ISSN: 0975-833X

Available online at http://www.journalcra.com

International Journal of Current Research
Vol. 18, Issue, 01, pp.36057-36061, January, 2026
DOI: https://doi.org/10.24941/ijcr.50124.01.2026

INTERNATIONAL JOURNAL OF CURRENT RESEARCH

RESEARCH ARTICLE

FRUIT PEELS BASED NATURAL ADSORBENTS USED IN WASTEWATER TREATMENT: A REVIEW

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ARTICLE INFO

Article History:
Received 25th October, 2025
Received in revised form
20th November, 2025
Accepted 18th December, 2025
Published online 30th January, 2026

Keywords:

Adsorption, Agro-Waste, Dyes, Fruit Peels, heavy metals, Wastewater Treatment.

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ABSTRACT

The spontaneous urbanization development forced on industrialization evolution which increase the production of huge amounts of contaminated water. These contaminated water discharge in water reservoirs in untreated or semi treated form that contaminates the pure water containing dyes, heavy metals, nutrients, and emerging contaminants. Population growth cause stress to the need of fresh water for survival of life hence various conventional methods are applied for wastewater treatment. These methods have some limitation as expensive, energy-intensive, and may generate secondary pollution. In recent years, fruit peels based natural adsorbents that have abundant availability renewable agro-waste—have gained significant attention as low-cost, eco-friendly materials frequently applied for wastewater treatment. Some fruit peels like banana, orange, lemon, pomegranate, mango, and apple peels which rich in cellulose, hemicellulose, lignin, pectin, and various functional groups (–OH, –COOH, $–NH_2$), that empower effective adsorption of pollutants. This review emphasized about the sources, composition, alteration process, adsorption mechanisms, and applications of fruit peels in the removal of dyes, heavy metals, and other contaminants from wastewater. Advantages, limitations, and future prospects for large-scale application are also discussed.

Citation: Amar Nath. 2026. *"*Fruit peels based natural adsorbents used in wastewater treatment: A review.". ***International Journal of Current Research, 18, (01), 36057-36061.***

INTRODUCTION

Industrial development and urban extension have directed to the discharge of huge volumes of polluted wastewater into natural water system, posing crucial fears to aquatic ecosystems and human health (Nath, A. 2026; Rusprayunita, N. R. A. *et al*., 2025; Tella, T. A. *et al*., 2025). Amongstseveral pollutants, synthetic dyes (Nath, A. 2025B), heavy metals (Shetty, B. R. *et al*.,2025) pharmaceuticals and organic pollutants are of preciseanxiety due to their toxicity, staying potential and defiance to microbial degradations (Mondal, S. *et al*., 2024). Conventional treatment of wastewater technologieslike chemical coagulation (Ghzal, Q.et al., 2025), progressive oxidation (Vadivel, D. *et al*., 2025), membrane filtration (Mansor, E. *et al*., 2024), and adsorption with activated carbon (Nath, A. 2026A; Qin, W. *et al*., 2024) are though effective but faced to confines including muchoperative costs, energy consumption, production of secondary sludge and have restricted sustainability. These shortcomings haveinspiredrisingattention in affordable, eco-friendly, and renewable substances for wastewater treatment. Nowadays, fruit peels have arisen as auspicious natural materials applied for wastewater treatment due to their plentiful availability, inexpensive, biodegradability, and amusing surface chemistry (Halder, A. 2025). Banana (Yhon, J. *et al*.,2023) orange, pomegranate, mango, citrus, apple, and watermelon fruit peels are agro-waste (Shrivastava, R. *et al*., 2022) secondary products produced in hugeextents from households, markets, and food-processing industries. These materials are basicallyconstituted of cellulose, hemicellulose, lignin, pectin, and proteins, that contain hydroxyl (–OH), carboxyl (–COOH), amino ($–NH_2$), and phenolic (ph-OH) like functional groups (Datta, D. *et al*., 2025). The availability of such functional groups allows fruit peels to interact efficiently with several pollutants by mechanisms with electrostatic attraction, hydrogen bonding, ion exchange, complexation, and π–π interactions (Nath, A. 2025A, Nath, A. 2026B). The application of fruit peels as adsorbents makes even well with the principles of green chemistry and globular economy throughaltering agricultural waste into valuable materials for atmospheric remediation. Several studies have established the efficacy of raw and chemically or physically improved fruit peels in removing of dyes, heavy metals and other organic pollutants from aqueous solutions. Surface alterationprocedures like stimulation, acid/base treatment, carbonization, and composite formation and further boost their adsorption potential and selectivity. Theaims of this review to deliver a comprehensive outline of fruit peels as natural materials for wastewater treatment, concentrating on their physicochemical possessions, adsorption mechanisms, alterationapproaches, concert in contaminant removal, and future prospects for large-scale and sustainable applications.

SOURCES AND AVAILABILITY OF FRUIT PEELS

The fruits peel is available plentifully in form of secondary products of fruit consumption and processing industries like juice, jam, and canned food production. Commonly studied fruit peels include:

Banana peels: This peel is the outer layer of a banana, that contains sufficient amounts of fiber, potassium, antioxidants, and other nutrients, offering uses from food (after preparation) and skincare to fertilizer and compost, transforming potential waste into an appreciated resource for health and sustainability (Emmanuel, J. K. *et al*.2025; Kumar, Y. *et al*., (2022), despite being fibrous and bitter shown in Figure1.

Figure 1. Banana peels

Orange, Lemon and citrus peels: These peels are ridiculous in nutrient, external coatings packed with fiber, Vitamin C, antioxidants such as phenolics, flavonoids, and d-Limonene essential oils showing assistances for skin care as brightening, digestion and flavoring foods drinks in teas, beers, roasted dishes, yet must be make appropriate as blanching and drying to minimize bitterness and remove pesticides if eaten or used in recipes the peels and flavonoids (Tahir, Z. *et al*., 2023; Wu, J. *et al*., 2023) are shown in Figure 2.

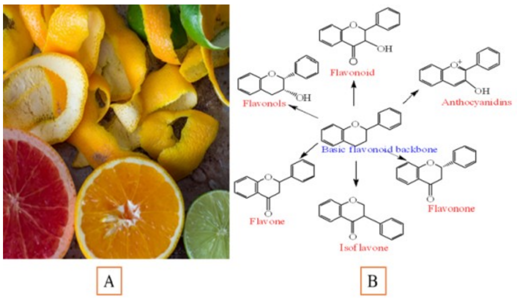

Figure 2. A. Citrus peels, B. Various flavonoid present in citrus peels

Pomegranate peels: This peel contains enough amounts of polyphenols such as punicalagin, ellagic acid, and gallic acid, shown in Figure 3, which provide several science-backed benefits to the skin and other human health (Saad, H. *et al*., 2025)

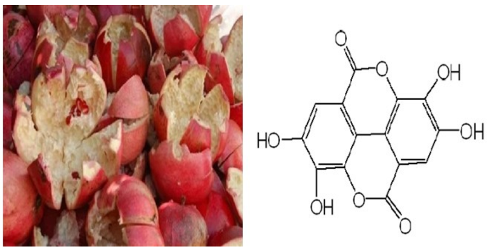

Figure 3. Pomegranate peels and chemical structure of polyphenols

Mango peels: This peel can be merged into numerous food stuffs to improve their nutritional profile, adding fiber, vitamins, and a unique flavor (Albaayit, S.F.A. *et al*., 2024) shown in Figure 4.

Figure 4. Mango peels

Apple peels: Apple peels that given in Figure 5, are a vastly nutritious and multipurpose fruit's part rich in fiber, vitamins, and antioxidants (Chauhan, S. *et al*., 2025). In its place of discarding them, they can be consumed directly or used in various culinary and household applications.

Figure 5. Apple peels

The world-wide availability, renewability, and negligible cost of these resources facilitate them attractive and extensively applied for wastewater treatment, particularly in developing countries.

CHEMICAL COMPOSITION AND SURFACE CHARACTERISTICS: Fruit peels are basically composed of natural polymers like cellulose, hemicellulose, lignin, starch, and pectin. These compounds' structure that contains plentiful functional groups such as hydroxyl (–OH), carboxyl (–COOH), ketonic (>CO),and amine ($–NH_2$) groups. These functional groups performance as active positions for binding of contaminants by several physicochemical interactions (Tolkou, A. K. *et al*., 2024). The availability of phenolic compounds and organic acids again boost the fruit peels affinity toward pollutants as metal ions and dye molecules. The external fruit peels morphology frequently shows irregular pores and rough surfaces, contributing to wide surface area and adsorption potential (Thakur, A. *et al*., 2025).

PREPARATION AND MODIFICATION OF FRUIT PEEL ADSORBENTS: Generally raw fruit peels need humble pre-treatment before applied in form of adsorbents. Usual preparation stage involved as washing, drying, grinding, and sieving. For improvement of adsorption concert, a variety physical and chemical techniques have been employed details mechanism (Nath, A. 2026A; Nath, A. 2026B; Tolkou, A. K., *et al*., 2024) shown in Figure 6:

Physical activation: Thermal treatment or carbonization process of fruits peels that enhance the porosity and surface area.

Chemical activation: Treatment of fruits peels with acids as HCl, H_2SO_4, bases like NaOH, KOH, or salts that helped in incorporation of additional functional groups into the peels.

Composite formation: Applied blending of fruit peels with polymers, clays, or metal oxides which improved the durability and adsorption potential. Hence it can be seen that tailored fruit peel adsorbents extensively show significantly more removal efficiencies as compared to raw materials.

Figure 6. Preparation mechanism of activated carbon from fruit peels

MECHANISMS OF POLLUTANT REMOVAL: The removal of pollutants through the fruit peels occurs by various mechanisms that depend on the nature of the pollutant and solution conditions:

Electrostatic interactions: These interactions are a basic mechanism for removal of dye from contaminated water by using activated carbon derived from fruits peels in which attraction and repulsion forced produced in between charged activated surface and ionic dye molecules shown in Figure 7. Some main mechanisms of electrostatic interaction which are (Nath, A. 2025A, Nath, A. 2026B) depends on as-

Surface Charge and pH dependence: The activated carbon surface charge depends on the pH of the solution that comparative to its Point of Zero Charge (pH_{PZC}), when$pH < pH_{PZC}$, the activated carbon surface is becomes cationic in naturethat favour the adsorption of negatively charged dyes as Congo Red, Reactive Black,that involved strong electrostatic attraction. While$pH > pH_{PZC}$ the surface makes negatively charged by deprotonation mechanism, that boost the attraction of positively charged (basic) dyes as Methylene Blue or Crystal Violet (El-Nemr, M. A., *et al*., 2024).

Zeta Potential Effect: The adsorption capacity is strongly related with the zeta(ζ)potential, more negative zeta potential (< -30 mV) significantly rises the attraction of cationic dye, while morepositive zeta potential (> +60 mV) shows electrostatic repulsion hence decreases attraction capacity of cationic dye (Shukla, A. K. *et al*., 2024)

Functional Group Interactions: Activated carbon surface have oxygen-containing functional groups as carboxyl, phenolic-hydroxyl and nitrogen-containing function groups that offer precise charged sites which interact to the polar or ionized groups of dyes (Nath, A. 2025A, Nath, A. 2026B).

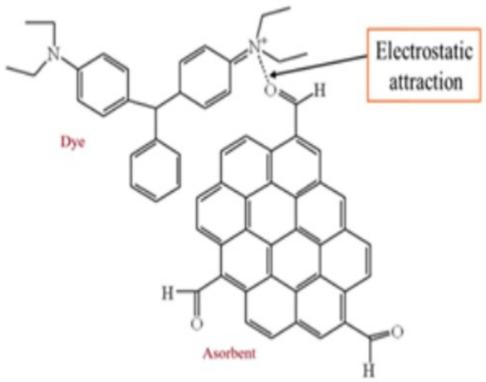

Figure 7. Electrostatic attraction between dye and adsorbents

Hydrogen bonding: The presence of various functional groups in fruits peels bases natural adsorbents and dye molecules as hydroxyl (-OH), carboxylic (-COOH) functional groups containing oxygen (O) and amine groups contains nitrogen (N) during the removal of dye with adsorbent the hydrogen atoms of the dye and adsorbents both interact with high electronegative atoms in between both dye and adsorbents form hydrogen bonding shown in Figure 8 that facilitate the pollutant like dye molecules and other contaminant form contaminated water (Nath, A. 2025A, Nath, A. 2026B).

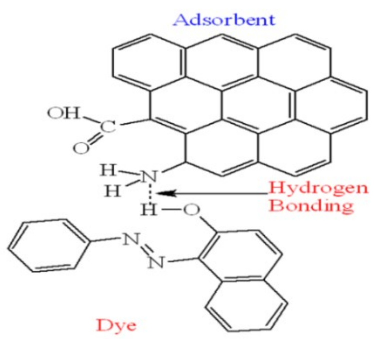

Figure 8. Hydrogen bonding between dye and adsorbents

Ion exchange: This is also an important process that extensively applied for the removal of dye from contaminated water. In this process activated carbon packed into a column and dye contaminated water passed through the column, the functional groups available on the activated carbon having cationic, anionic charge and it also bears hydroxyl, carboxylic oxygen containing functional groups and nitrogen containing functional groups attract anionic, cationic and polarised dye molecules and dye free water obtained the process (Akpomie, K.G. *et al*., 2024) are shown in Figure 9.

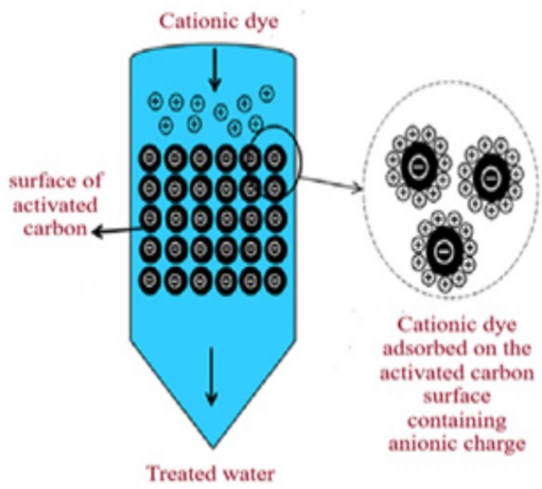

Figure 9. Removal of dye pollutant by ion exchange process

***π–π* interactions:** The activated carbon which derived from fruits peels contains aromatic structure with nitrogen and oxygen containing functional groups. The aromatic structure and carboxylic group contain pi electrons. The most of dye also structured with aromatic compounds in azo form and some other functional groups depending on the nature of dye. During the removal of dye removal, the pi electrons of both dye and adsorbents also interacts with each other shows $\pi - \pi$ interactions shown in Figure 10, that facilitate the efficient dye removal from wastewater (Nath, A. 2025A, Nath, A. 2026B).

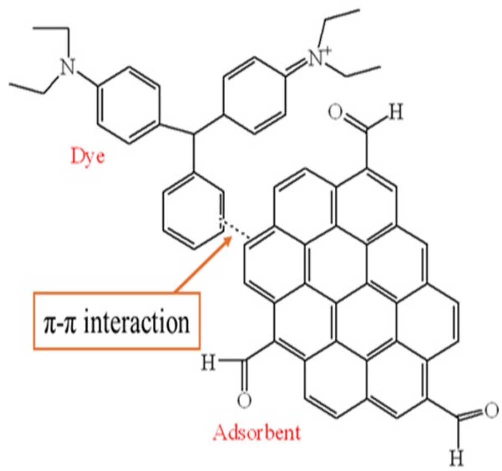

Figure 10. *π-π* interaction in between dye and adsorbents

Complexation: Activated carbon which are derived from naturally occurring fruits that contains huge amount of nitrogen and oxygen containing functional groups on the surface. These atoms contain lone pair of electrons which can easily donate their electrons to the electron deficient atoms. During the removal process of metal ion from wastewater, oxygen and nitrogen atom of available functional group easily donate their lone pair electrons to the metal ions present in water that formed complex shown in Figure11. These complex compounds easily settled down in water and removed by simple filtration process.

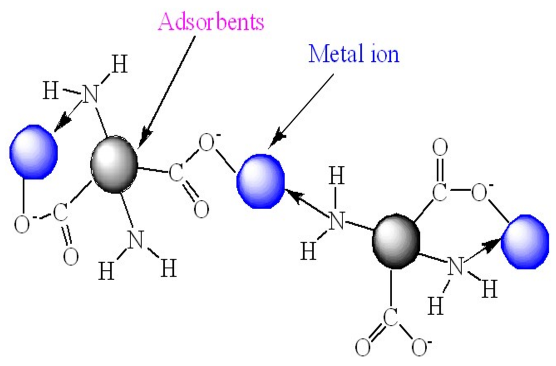

Figure 11. Formation of complex in between metal ions and adsorbent

These mechanisms often act simultaneously, that facilitate the efficient pollutant uptake, hence improved the removal of dye by activated carbon which obtained from fruits peels (Nath, A. 2025A, Nath, A. 2026B).

APPLICATIONS IN WASTEWATER TREATMENT

Dye Removal: Due to the availability of various functions groups like hydroxyl (-OH), carboxyl (-COOH), ketonic (>CO) and amine (-NH_2) the fruit peels have been extensive potential for the removal of cationic and anionic dyes such as methylene blue, crystal violet, Congo red, and reactive dyes. High removal efficiencies are attributed to strong electrostatic attraction and surface interactions (Nath, A. 2025A, Nath, A. 2026B).

Heavy Metal Removal: The fruit peels contain nitrogen containing groups as amine (-NH_2) and oxygen containing functional groups as hydroxyl (-OH), carboxyl (-COOH), ketonicl (>CO) in which N and O atom contains lone pair electrons that easily donate their electrons to the electron deficient atom or having acceptor capacity. Hence fruits peels demonstrate excellent affinity toward heavy metals including Pb (II), Cd (II), Cr (VI), Cu (II), and Ni (II). The abundance of carboxylic and hydroxyl groups facilitates metal binding through chelation and ion exchange mechanisms (Mkilima, T. *et al*., 2024).

Removal of Other Pollutants: In addition to dye activated carbon derived from fruits peels efficiently eliminates numerous organic pollutants, odors, chlorine, and some heavy metals from contaminated water and air by adsorption, trapping pollutants in its enormous system of apertures, but it's lower efficiency towards inorganic ions as nitrates (NO_3^-) or fluoride (F^-) and desires replacement as its surface becomes saturated. It's used in filters and purifiers which can improve water quality, removing volatile organic compounds (VOCs), pesticides, and refining taste/odor, depending on its large surface area to fascinate and grasp molecules (Tolkou, A. K. *et al*.,2024).

ADVANTAGES AND LIMITATIONS

Advantages

- Low cost and abundant availability
- Renewable and biodegradable
- Simple preparation methods
- Minimal secondary pollution

Limitations

- Lower mechanical strength compared to commercial adsorbents
- Limited regeneration and reusability in some cases
- Performance variability depending on wastewater composition

FUTURE PERSPECTIVES

Future research activated carbons derived from fruits peels should emphasize on enhancing the durability, renaissance capacity, and scalability of such adsorbents. Development of hybrid materials, column studies, and real wastewater applications are crucial for industrial application. Life cycle valuation and techno-economic investigation will further support their feasibility as sustainable wastewater treatment materials.

CONCLUSION

Fruit peels are primarily converted into activated carbon that represent an auspicious class of natural materials for wastewater treatment due to their inexpensive, ecofriendly, and availability of nitrogen and oxygen containing function groups improved their effectiveness to adsorption capacity. These materials involved electrostatic interactions, hydrogen bonding, ion exchange, π–π interactions mechanism during the removal of dye while complexation process involved for removal of metal ions from wastewater. Their use not only applicable for the treatment of wastewater but also contributes to the valorization of agricultural waste. Due to the further alteration and optimization, fruit peel-based adsorbents show strong potential for practical and sustainable water treatment applications.

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