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Review Article

Biological-Origin Materials for the Environmental Remediation of Tartrazine-Contaminated Water: A Review

Materiales de origen biológico para la remediación ambiental de aguas contaminadas con tartrazina: una revisión

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Abstract

Introduction: The persistent presence of tartrazine (FDC Yellow) in aquatic environments as a result of its widespread use in the food, textile, pharmaceutical, and cosmetic industries poses ecological and public health risks. Cheaper, eco-friendly alternatives are needed because conventional remediation technologies are costly to operate and have limited sustainability.
Objective: This narrative review evaluates research progress over the past 25 years in bio-based adsorption for tartrazine removal, aiming to assess bio-based adsorbents, identify high-efficiency materials, highlight technical bottlenecks, and identify knowledge gaps that hinder industrial application.
Methods: A literature search focusing on studies published between 2000 and 2025 was conducted using OpenAlex, Google Scholar, and DOAJ. The bio-adsorbents were categorised into agricultural by-products, biomass-derived carbons, and natural polymers, with emphasis on preparation methods, adsorption mechanisms, and performance under varying operating conditions.
Results: Chemically or thermally activated carbon-based adsorbents with capacities of 110-1136 mg g-1 offer better performance than unmodified agricultural residues such as rice husk and sugarcane bagasse, which exhibit moderate adsorption capacities between 1 and 91 mg g-1. However, substantial challenges remain in adsorbent regeneration, mechanical stability, batch-to-batch variability, and industrial scalability.
Conclusions: Bio-based adsorption has demonstrated considerable potential for tartrazine removal at the laboratory scale. Future research must focus on developing hybrid composite materials, continuous-flow systems, and comprehensive techno-economic assessments to transition these innovations into practical water treatment applications.

Keywords: Adsorption; Azo dyes; Biochar; Biopolymers; Tartrazine; Wastewater treatment.

Resumen

Introducción: La presencia persistente de tartrazina (FDC Yellow) en entornos acuáticos, derivada de su uso generalizado en las industrias alimentaria, textil, farmacéutica y cosmética, conlleva riesgos para el medio ambiente y la salud pública. Se requieren alternativas más económicas y respetuosas con el medio ambiente, dado que las tecnologías de remediación convencionales resultan costosas de operar y presentan una sostenibilidad limitada.
Objetivo: Esta revisión narrativa evalúa el progreso de la investigación en los últimos 25 años sobre la adsorción mediante materiales de origen biológico para la eliminación de tartrazina. El propósito es analizar dichos adsorbentes, identificar materiales de alta eficiencia, señalar los obstáculos técnicos y detectar las lagunas de conocimiento que dificultan su aplicación a escala industrial.
Métodos: Se realizó una búsqueda bibliográfica centrada en estudios publicados entre 2000 y 2025, utilizando las bases de datos OpenAlex, Google Scholar y DOAJ. Los bioadsorbentes se clasificaron en subproductos agrícolas, carbonos derivados de biomasa y polímeros naturales, prestando especial atención a los métodos de preparación, los mecanismos de adsorción y el rendimiento bajo diversas condiciones operativas.
Resultados: Los adsorbentes basados en carbono —activados química o térmicamente—, con capacidades de adsorción de 110 a 1136 mg g□¹, ofrecen un mejor desempeño que los residuos agrícolas sin modificar (como la cascarilla de arroz o el bagazo de caña de azúcar), los cuales presentan capacidades moderadas, situadas entre 1 y 91 mg g□¹. No obstante, persisten desafíos importantes en cuanto a la regeneración de los adsorbentes, su estabilidad mecánica, la variabilidad entre lotes y la escalabilidad industrial.
Conclusiones: La adsorción mediante materiales de origen biológico ha demostrado un potencial considerable para la eliminación de tartrazina a escala de laboratorio. La investigación futura debe centrarse en el desarrollo de materiales compuestos híbridos, sistemas de flujo continuo y evaluaciones técnico-económicas integrales, con el fin de facilitar la transición de estas innovaciones hacia aplicaciones prácticas en el tratamiento de agua.

Palabras clave: Adsorción; colorantes azoicos; biocarbón; biopolímeros; tartrazina; tratamiento de aguas residuales.

How to cite?

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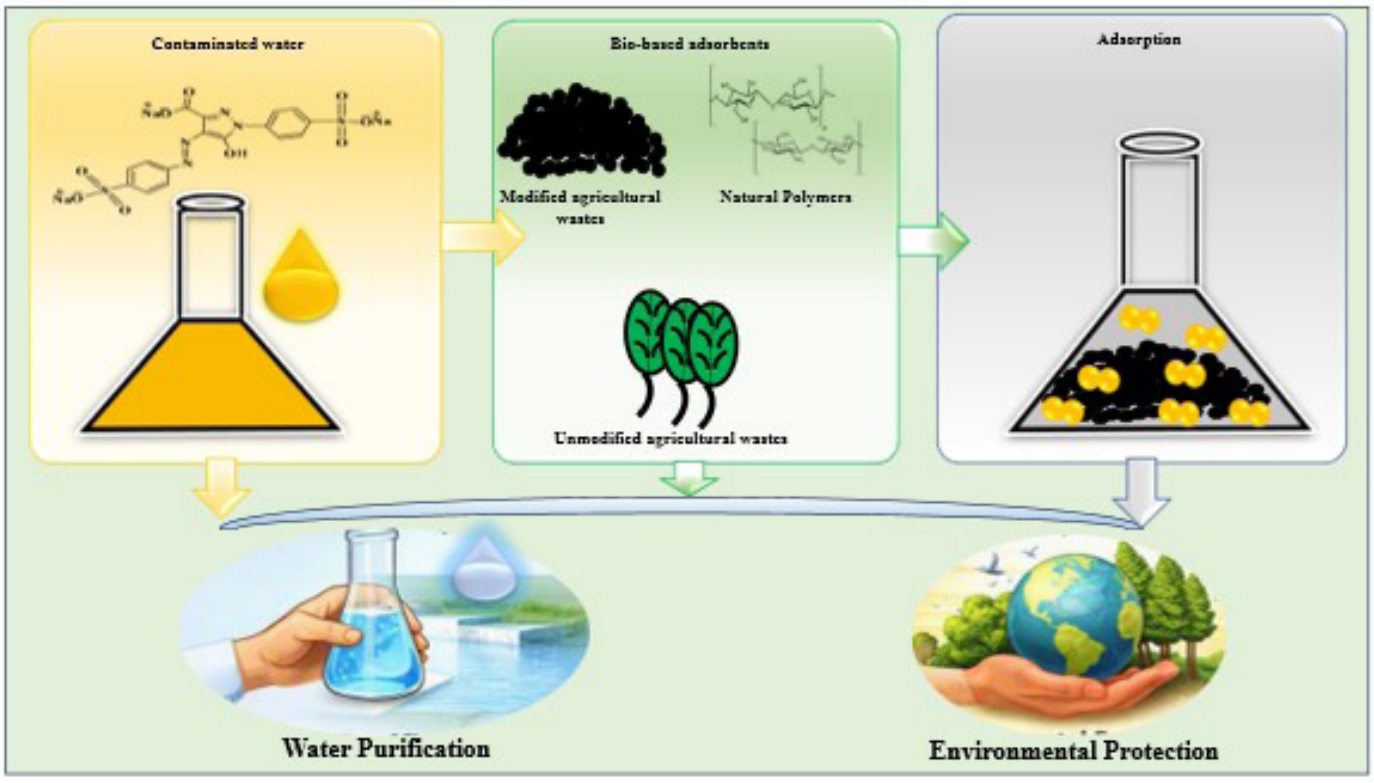
Why was the study conducted?
The review was prompted by concerns that tartrazine, a widely used synthetic azo dye, may pose risks to human health and aquatic ecosystems. It also reflects the growing need for effective, sustainable, and environmentally friendly ways to treat tartrazine-contaminated water. The study aimed to summarise recent advances in bio-based adsorption technologies for removing tartrazine and to assess their environmental applications, challenges, and future prospects.

What were the key findings?
The review found that many bio-based adsorbents such as agricultural by-products, biomass-derived materials, and natural polymers effectively remove tartrazine from water. Adsorption is most effective in acidic conditions, and modified bio-based materials often have significantly higher adsorption capacities than unmodified materials. However, variability in adsorbent properties, regeneration challenges, and scalability remain barriers to industrial application.

What do these findings contribute?
The findings offer a comprehensive understanding of bio-based adsorption as a cost-effective, environmentally friendly, and sustainable approach to tartrazine remediation. They identify promising adsorbents, highlight existing limitations, and point to future research directions that could help develop scalable wastewater-treatment technologies and protect the environment.

Graphical Abstract



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Introduction

Tartrazine is a soluble, anionic, synthetic azo dye also known as FDC Yellow, which is widely used in the food, textile, paper, plastics, leather, cosmetics, and pharmaceutical industries (1). Its widespread application and persistence in aquatic media have made tartrazine-contaminated wastewater a pressing problem that traditional treatment options struggle to solve affordably (2,3). Several researchers have investigated the toxicological profile of tartrazine (Figure 1) over the years, and ecotoxicological studies have shown its toxic effects on aquatic organisms, including documented morphological abnormalities in embryonic development and oxidative stress responses in fish models (4).

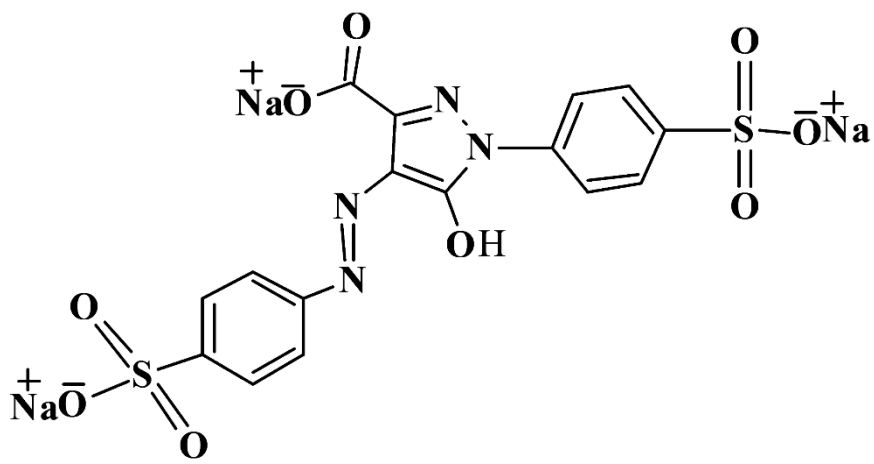

Figure 1. Structure of tartrazine (**Source:** Authors, redrawn from the PubChem structure).

Advanced techniques like membrane filtration and chemical oxidation, which can break down or trap the dye, often require high energy inputs or produce hazardous secondary waste, in addition to high costs (5). While standard adsorption circumvents these operational challenges, commercial activated carbon (AC) is costly for widespread use in resource-limited areas such as Africa (6). Conversion of raw agricultural and marine wastes into functional adsorbents for the remediation of tartrazine-contaminated aqueous media offers a practical way of producing sustainable, low-cost water treatment solutions and solving waste management challenges simultaneously (7,8).
This narrative review of research progress over the past two and a half decades on bio-based adsorption for tartrazine remediation is aimed at providing a structured evaluation of bio-based adsorbents, identifying the bio-sorbents with the highest removal efficacy for tartrazine, discovering the physicochemical mechanisms governing the adsorption of tartrazine onto these materials, and identifying the technical bottlenecks, structural limitations, and knowledge gaps currently existing in the literature that must be resolved to advance bio-based tartrazine adsorption technology. To this end, the review describes existing types of biomass, evaluates their operational behaviour, identifies challenges to widespread industrial adoption, and outlines future research priorities to support sustainable water management practices.

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Methodology

This review's literature was gathered through targeted searches across scholarly databases, primarily OpenAlex, supplemented by Google Scholar and the Directory of Open Access Journals (DOAJ). OpenAlex was chosen for its broad, interdisciplinary coverage and its open-access nature that allows barrier-free metadata retrieval (9). Google Scholar and DOAJ were used to capture additional relevant studies and open-access full texts. Rather than conducting a formal systematic review with rigid PRISMA screening frameworks or risk-of-bias quality scoring, we used a search-informed narrative approach (Figure 2) to identify, screen, group, and discuss key representative literature on bio-based tartrazine adsorption over the past two and a half decades.

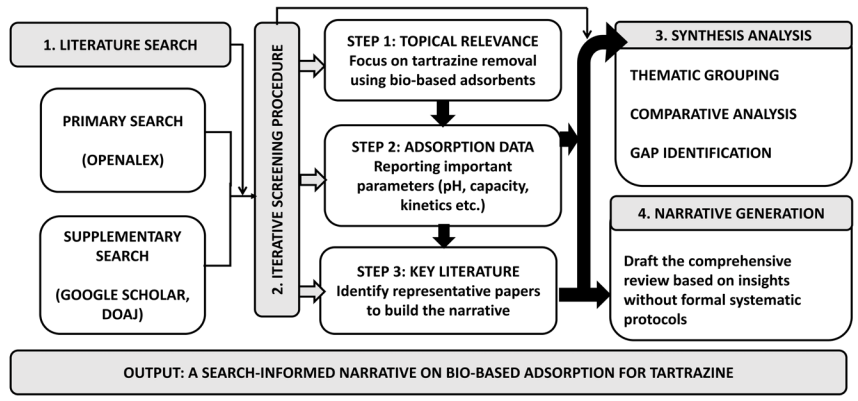

Figure 2. Methodological framework for the literature search.

The search was carried out from June to December 2025, using the search terms "tartrazine," "tartrazine adsorption," "tartrazine biosorption," "biomass-derived carbons," "bio-based adsorbents," "biochar tartrazine," "agricultural waste adsorption," "alginate tartrazine," "chitosan tartrazine," "natural polymers dye removal," "tartrazine remediation," "modified biosorbents" and "anionic dye adsorption," combined with the Boolean operators "AND" and "OR."
Eligibility criteria included peer-reviewed journal articles, conference papers, review articles, and book chapters published in English between 2000 and 2025. Studies unrelated to tartrazine dye adsorption, duplicate records, non-scholarly sources, and publications lacking sufficient experimental or review detail were excluded. Next, 65 articles were selected from an initial pool of 329 records for this review.

Results and discussion

Recent research has focused on developing alternative, affordable sorbents with consistent adsorbent properties, high regeneration potential, stability over repeated adsorption-desorption cycles, and performance in real wastewater effluents to reduce reliance on expensive adsorbents materials that lack these properties (10,11). Yet, selecting an appropriate adsorbent for

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removing tartrazine from aqueous solution requires a good understanding of the adsorbent's physicochemical nature and properties to improve dye-removal effectiveness (8,12). Investigators have studied different categories of bio-based adsorbents for removing tartrazine from aqueous media with varying degrees of success. But in this paper, biomass-derived adsorbents are materials obtained from renewable biological feedstocks, though their physicochemical properties may have been modified through thermal or chemical processing. For this review, they were classified as agricultural by-products, biomass-derived materials, and natural polymers. Each of these categories is discussed in the sections following.

Agricultural By-products

Investigations of tartrazine adsorption using agricultural by-products were relatively scarce before 2010. Initially, investigations into dye adsorption using untreated agricultural materials did not focus specifically on tartrazine. Still, they established the mechanistic basis for later applying unmodified biomass in tartrazine remediation.

In one such study in the last two decades, Annadurai et al. (13) demonstrated that untreated banana and orange peels could effectively adsorb several synthetic dyes from aqueous solution, with adsorption capacities reaching 17.2 mg g^{-1} for methyl orange under optimised conditions. The authors attributed the adsorption behaviour to the porous lignocellulosic matrix and the naturally occurring oxygen-containing functional groups on the biomass surface. Although the study did not directly investigate tartrazine, it provided supporting evidence that untreated agro-residues can adsorb anionic azo dyes without extensive modification.

The past decade has seen substantial growth in this research area, reflecting increased awareness of tartrazine's environmental persistence and the potential of renewable adsorbent materials. The following sections therefore focus on the past decade, which accounts for most of the available literature.

Masau stones exhibited capacities of 51.3-65.1 mg g^{-1}, with FTIR confirming hydroxyl and carboxyl groups as binding sites for electrostatic and hydrogen bonding interactions (14). Recent studies on tropical residues such as rice husk, sugarcane bagasse, peach palm, cassava, and coconut mesocarp report moderate capacities of 1.24 to 3.55 mg g^{-1} and 74 to 95 % removal efficiencies, respectively (5,15). Composite adsorbents combining Capparis decidua and eggshell achieved 50.97 mg g^{-1} for tartrazine in mixed dye systems (16).

As shown in Table 1, most studies report that tartrazine adsorption is favoured at pH 2-3 due to electrostatic attraction between protonated adsorbent surface sites and the negatively charged sulfonate groups of tartrazine (17). Maximum adsorption capacity (Q_{max}) varies widely among adsorbents, from 1.24 mg g^{-1} for rice husk to 91.27 mg g^{-1} for Moringa oleifera. These differences result from variations in surface area, pore structure, surface functional groups, and the adsorbent's affinity for tartrazine.

Substantial differences in adsorbent dosage were also observed (0.2-25 g). This indicates variations in adsorption efficiency and in the researchers' experimental design. The low dosage of Moringa oleifera (0.2 g) yielded the highest reported adsorption capacity (91.27 mg g^{-1}), indicating that the

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adsorbent utilises its adsorption sites more efficiently than other adsorbents such as sugarcane bagasse, which achieved a maximum adsorption of 2.5 mg g^{-1} with 10 g of adsorbent.

Initial tartrazine concentrations (10-100 mg L^{-1}) also differ across different adsorbent studies. This can affect apparent adsorption capacity because higher concentration gradients provide a stronger driving force for mass transfer from solution to the adsorbent surface (18). Equilibrium times range from 60 to 240 min, suggesting differences in adsorption rates due to variations in pore properties or diffusion resistance. Most studies found that adsorption followed the pseudo-second-order kinetic model, an indication that the adsorption rate depends on the availability of adsorption sites. Although the best-fitting isotherm model varies among adsorbents, the frequent applicability of the Langmuir and Freundlich models suggests that, depending on adsorbent characteristics, both monolayer adsorption and surface heterogeneity contribute to tartrazine uptake.

Table 1. Agricultural by-products for tartrazine removal.

Adsorbent	Q_{max} (mg g^{-1})			C_o (mg L^{-1})	T_{eq} (min)	Isotherm	Kinetics	Reference
Masau stones	65.1	2	4	100	NR	Freundlich and Redlich-Peterson	PSO	(14)
Moringa oleifera	91.27	3	0.20	15	240	Freundlich	PFO	(19)
Rice husk	1.24	2	1	50	120	Langmiur	PSO	(5)
Coconut shell	NR	4	25	70	NR	Langmuir & Freundlich	NR	(11)
Sugar cane bagasse	2.45	2	10	10	120	Brouers-Sotolongo	PSO	(20)
Rice husk	3.55	2	10	10	120			

NR = not reported; Q_{max} = maximum adsorption capacity; PSO = pseudo-second-order; PFO = pseudo-first-order; C_o = initial dye concentration; t_{eq} = equilibrium time.

Biomass-derived materials

Agricultural by-products can be modified or functionalized to produce biomass-derived adsorbents with improved tartrazine affinity. Chemical modification and thermal activation may also increase surface area and porosity and alter surface chemistry to introduce functional groups that enhance dye adsorption.

Studies investigating carbon-based adsorbents derived from biomass for tartrazine removal report that they offer high adsorption capacities and better regeneration characteristics than their unmodified counterparts (6). Because they rely on inexpensive, carbon-rich precursors with relatively low inorganic content, agricultural residues are suitable feedstocks for AC and biochar production, which are the most extensively studied materials in this category (20). Generally, biomass is pre-treated by drying and milling, followed by chemical activation before carbonization at elevated temperatures, generally below 1,073 K, under an inert atmosphere (21,22,24). The

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resulting carbonaceous material may be used directly or further activated physically or chemically to improve adsorption performance (20).

Figure 3 shows a schematic of a typical procedure for preparing AC from bio-based precursors, and Table 2 summarises representative modified biomass-derived materials used in tartrazine remediation. A combination of raw materials with appropriate characteristics and suitable preparation processes leads to the formation of carbons with favourable textural properties for tartrazine removal (19,20,23).

Table 2. Preparation conditions and adsorption performance of biomass-derived ACs and biochar for tartrazine removal.

Raw Material	Pyrolysis T (K)	Activation Time (min)	Activating agent	BET surface area ($m^2 g^{-1}$)	Q_{max} (mg g^{-1})	pH_{Opt}	pH_{PZC}	Reference
Alligator weed (Alternanthera philoxeroides)	873	120	H_2SO_4	303	183	2	6.10	(24)
Lantana camara weed	873	120	H_2SO_4	268	91	2	6.40	(25)
Pecan (Carya illinoinensis) nut shells	873	NR	Steam	5	5	7	9.00	(26)
Pecan (Carya illinoinensis) nut shells	1130	NR	Steam	446	14	7	10.50	(26)
Apricot Stones[a]	973	180	H_3PO_4	774	76	6.80	NR	(27)
Corn cob	673	60	Triethylenetetramine	7	3	2	NR	(28)
Cassava sievate	823	60	H_3PO_4	NR	21	1	NR	(29)
Wheat straw	873	60	$ZrFe_2O_5$ nanoparticles	NR	89	2	NR	(30)
Commercial biochar	NA	NA	NA	67.20	3.28	2	6.50	(31)

NR = not reported; NA = not applicable; T = temperature; BET = Brunauer-Emmett-Teller; Q_{max} = maximum adsorption capacity; [a]= fixed bed adsorption study.

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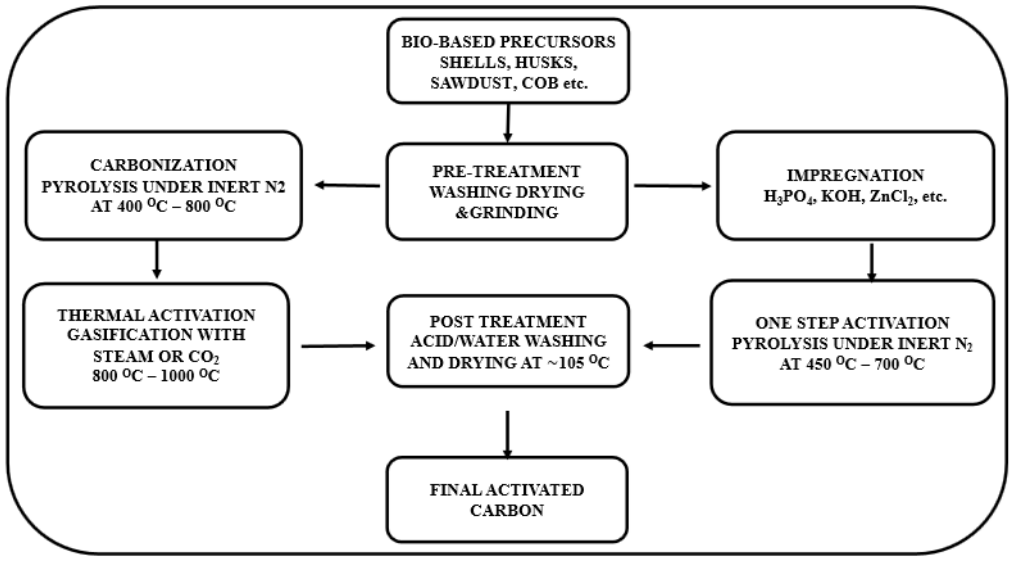

Figure 3. Preparation of AC from bio-based precursors (**Source:** Authors).

The literature on biomass-derived carbons for tartrazine, presented in Table 2, shows distinct performance variations driven by the choice of activating agent, thermal processing history, and solution electrokinetics. Higher pyrolysis temperatures (973-1,130 K) produced carbons with higher surface areas (26,27). This is understandable since higher activation temperature and time generally improve pore development (20). However, higher surface area was not consistently associated with greater tartrazine adsorption capacity, meaning that the adsorption of tartrazine is not solely dependent on the surface properties of the adsorbents. For instance, AC produced at higher temperatures (1130 and 973 K) with BET surface areas of 774 and 446 $m^2\ g^{-1}$ had adsorption capacities of 76 and 14 mg g^{-1}, respectively. ACs with BET surface areas of 268 and 303 m2 g-1 exhibited higher adsorption capacities of 91 and 183 mg g-1, respectively.

Adsorption of tartrazine is affected by the activation method and duration. Chemical activation with H_2SO_4 and H_3PO_4 at longer durations (120-180 min) led to higher adsorption capacity (76-303 $m^2\ g^{-1}$), while activation with H_3PO_4 at 60 min produced adsorbents with an adsorption capacity of 21 $m^2\ g^{-1}$. This is because chemical activation with H_2SO_4 and H_3PO_4 introduces acidic functional groups that increase overall surface acidity. This increases electrostatic attraction to the anionic dye under acidic conditions, and longer durations also increases the density of functional groups on the AC surface (32). The steam-activated adsorbents (Carya illinoinensis nut shells) exhibited comparatively low adsorption capacities, possibly because steam activation mostly increases porosity and surface area but introduces fewer acidic surface functional groups, thus limiting electrostatic interactions.

The pH at the point of zero charge (pHpzc) is important for understanding electrostatic interactions between adsorbent surfaces and ionic adsorbates. At pH below pH_{pzc}, the adsorbent surface acquires a net positive charge due to protonation of surface functional groups, favouring the uptake of anionic dyes such as tartrazine. Conversely, at pH above pH_{pzc}, the surface becomes negatively charged, inducing electrostatic repulsion and reduced adsorption (33).

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Table 2 shows that pH_{pzc} values vary considerably by precursor material and activation method. Commercial biochar (pH_{pzc} = 6.5), acid-activated carbons from Alligator weed (pH_{pzc} = 6.1), and Lantana camara pH_{pzc} = 6.4) exhibit moderately acidic surfaces. Pecan (Carya illinoinensis) nut shells, however, exhibit moderately basic surfaces.

The relationship between pH_{pzc} and adsorption behaviour is well-demonstrated in tartrazine removal studies. For Alligator weed AC (24), adsorption capacity of 183 mg g^{-1} was achieved at pH 2, well below the pH_{pzc} of 6.1, where the surface is positively charged and electrostatically attracts the anionic sulfonate groups of tartrazine (24). Similarly, for Lantana camara AC and the commercial biochar (pH_{pzc} = 6.4 and 6.5, respectively), the optimal pH values are well below the pH_{pzc}, consistent with protonation of surface functional groups and electrostatic attraction. The adsorption capacity for the two (Carya illinoinensis) nut shells prepared at different temperatures are much lower (5 and 14 mg g^{-1}) than that of Lantana camara as pH increased above the $pH_{pzc,}$ consistent with deprotonation of surface functional groups and electrostatic repulsion.

These results prove that biomass-based carbons are high-performance adsorbents from renewable resources, but their production raises sustainability concerns. Their environmental advantage arises mainly from using renewable waste biomass rather than from the preparation process itself, which often carries considerable life-cycle burdens. Since processes such as high-temperature carbonisation and chemical activation using strong acids, bases, or salts significantly reduce net environmental benefits through high energy consumption and secondary chemical pollution, the overall sustainability of these materials is evaluated alongside the energy demand of carbonisation, the use of activating agents, chemical consumption, and the potential for adsorbent regeneration and reuse. This is especially important since some unmodified agricultural residues outperformed some AC adsorbents (Tables 1 and 2). Therefore, considering adsorption performance alongside production requirements is necessary when assessing practical and environmental merits, and comprehensive life-cycle assessment is required to determine whether improved capacity outweighs the environmental costs.

Natural Polymers

Natural polymers such as chitosan and alginate have also been used as efficient, eco-friendly adsorbents to remove tartrazine. Functional groups such as hydroxyl and amino groups along their polymer chains contribute to their biodegradability and other environmentally favourable properties (34). Though these materials are derived from biological resources, for example, chitin is obtained from crustacean processing residues, and alginate is extracted from brown seaweed, they differ from crude biomass adsorbents because they are isolated biopolymers with relatively well-defined chemical structures. This higher level of purification allows controlled chemical modification through crosslinking, grafting, or functionalization. It allows their adsorption properties to be tailored more methodically than is possible with heterogeneous agricultural residues. For this reason, this review treats natural polymers separately while keeping them within the broader category of bio-based adsorbents. Depending on their biological origin, these polymers may be derived from animals, fungi, algae, or plants (35,36). The subsequent sections examine these natural polymers and their applications in tartrazine adsorption.

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Chitin and chitosan

Chitin is a linear polysaccharide composed mainly of β-(1→4)-linked N-acetyl-D-glucosamine units, and is recognized as the most abundant nitrogen-containing natural biopolymer after cellulose (37). It is a major structural component of the cell walls of fungi such as edible mushrooms, Aspergillus spp., and Penicillium spp. (35). It is also found in the exoskeletons of arthropods and crustaceans (Figure 4).

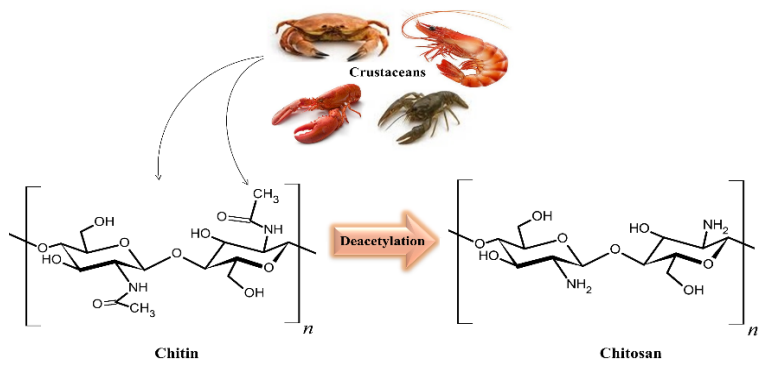

Figure 4. Sources of chitin and the structure of chitin and chitosan (**Source:** Authors).

Chitin and chitosan share a β-(1→4)-linked polysaccharide backbone with structural similarities to cellulose. The major difference is that chitin substitutes the hydroxyl group at the C-2 position of cellulose with an acetamido (-$NHCOCH_3$) group (Figures 4 and 5), which, upon deacetylation, becomes an amino (-NH_2) group in chitosan. The degree of deacetylation determines the density of free amino groups and, consequently, the adsorption capacity.

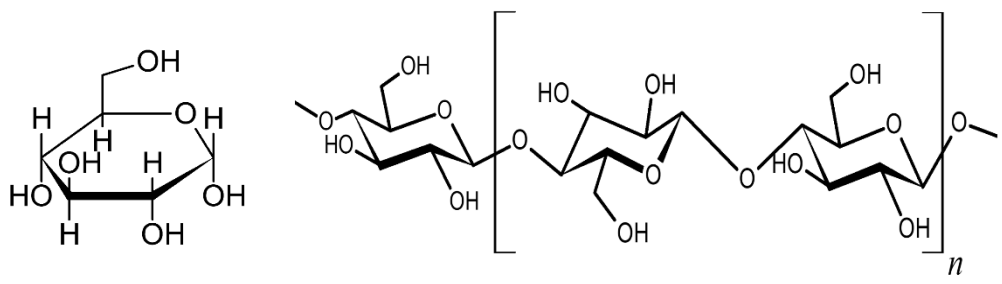

Figure 5. Structure of (a) glucose and (b) cellulose (**Source:** Authors).

From the data displayed in Table 3, chitin- and chitosan-based materials are promising sustainable adsorbents for tartrazine removal. The improved effectiveness of chitosan relative to chitin is

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mainly a function of the presence and density of amino groups capable of protonation under acidic conditions, which results in chitosan's stronger ionic attraction toward tartrazine.

Table 3. Summary of natural polymer-based adsorbents for tartrazine removal from aqueous solutions.

Base polymer	Adsorbent form	C_o (mg L^{-1})	Q_{max} (mg g^{-1})	pH_{Opt}	T_{Opt} (K)	Isotherm	Kinetics	Regeneration cycle	Ref
Chitosan/carbon nanotubes	Films	NR	660	2	318	Freundlich	PSO	4	(38)
TiO_2-Chitosan nanocomposites	Membranes	10	83	Free	NR	NR	NR	4	(39)
Chitosan-bentonite	Bead	60	294.10	2.50	320 K	Langmuir	PSO	NR	(40)
Chitosan-Arthrospira spirulina sp.	Films	100	110	4	298	NR	NR	NR	(41)
Chitosan/ polyaniline composite	Powder	100	584	7.20	298	Freundlich	PSO	4	(42)
Chitosan	Powder	100	1066	3	328	NR	NR	NR	(8)
Chitosan	Chitosan-coated sand[a]	90[b]	595	3	298	NR	Thomas and Yoon-Nelson	NR	(43)
Chitosan	Chitosan-coated sand[a]	90 [c] 30 [c]	497	3	298	NR	Thomas and Yoon-Nelson	NR	
Chitosan	Chitosan-coated sand[a]	89 [d] 17 [d]	191	3	298	NR	Thomas and Yoon-Nelson	NR	

[a] = fixed bed adsorption study; [b] = single system; [c] = binary system (90 mgL^{-1} of tartrazine + 20 mgL^{-1} of SY); [d] = real effluent (89 mgL^{-1} of tartrazine + 17 mgL^{-1} of SY); NR = not reported; PSO = pseudo-second-order; SY = sunset yellow; C_0 = initial dye concentration

A key quantitative advance in the field is the study by Zhang et al. (8). Using chitosan prepared from pink shrimp waste with a degree of deacetylation of 85 ± 1 %, the authors reported exceptionally high tartrazine adsorption values ranging from 611.27 to 1065.55 mg g^{-1}. These values are considerably higher than those of many conventional ACs and demonstrate protonated chitosan's strong affinity for tartrazine. The adsorption process was interpreted using a multilayer statistical physics model rather than traditional Langmuir or Freundlich equations alone, and the analysis suggested horizontal orientation of dye molecules on the chitosan surface and multilayer formation

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at higher concentrations. Thermodynamic analysis of the adsorption process indicated exothermic physisorption behaviour dominated by van der Waals forces and electrostatic attractions.

The benefits of combining chitosan with nanostructured materials are also evident in studies employing inorganic nanoparticles and carbon nanomaterials. For example, composite films obtained from chitosan/carbon nanotubes at 0.1, 0.3, and 0.5% w/w^{-1} were investigated by Lessa et al. (38). The maximum tartrazine adsorption capacity of 660 mg g^{-1} was achieved with the composite with 0.1% nanotubes. The composite maintained adsorption performance for four regeneration cycles before a 5% reduction. The adsorption isotherm fitted the Freundlich isotherm, while the kinetics were best described by the pseudo-second-order model. This improved the surface characteristics of the chitosan matrix, increased the adsorption capacity of pristine chitosan, and increased the availability of active adsorption sites. Similarly, Zioui et al (39) produced photocatalytic TiO_2-chitosan nanocomposite membranes that demonstrated successful tartrazine removal with an adsorption capacity of 83 mg g^{-1} under free-pH conditions and which also retained functionality for four regeneration cycles. The adsorption capacity of the TiO_2-modified membrane was lower than that of carbon nanotube-reinforced systems, but incorporating photocatalytic TiO_2 nanoparticles improved the membrane's thermal stability, reduced the contact angle of the pristine chitosan from 71 to 46°, and provided additional surface interaction sites. These results show that incorporating nanoparticles can modify the adsorption behaviour of chitosan matrices by improving structural stability and reusability, which, in turn, enhances adsorption capacity.

Another major trend in the reviewed literature is the growing use of composite materials to overcome the limitations of pristine chitosan, as noted earlier. Accordingly, recent studies have focused on hybridizing chitosan with materials such as silica and metal-organic frameworks (MOFs). To this end, Abd El-Fattah et al. (44) synthesized a chitosan/MOF composite that demonstrated enhanced adsorption performance, attributed to the high porosity and tuneable surface chemistry of MOFs. Similarly, Wan Ngah et al. (40) also showed that incorporating silica phases improved chitosan stability and adsorption behaviour toward tartrazine dye.

Surface functionalization is another strategy to enhance adsorption capacity, as Tan et al. (45) did. They increased the density of protonatable amino groups by modifying chitosan with polyethyleneimine. This modification amplified electrostatic attraction to anionic tartrazine molecules and substantially improved adsorption performance. The results confirmed that adsorption efficiency depends not only on surface charge density but also on the accessibility of functional groups, and are consistent with the well-established mechanism of tartrazine adsorption, which is driven by ionic interactions between sulfonate groups in the dye molecule and protonated amino groups on chitosan (Figures 1 and 4).

In a study by Ayala-Gutierrez et al. (46) they investigated morphological differences as another research direction and reported that adsorption performance varies with adsorbent morphology, and that chitosan film thickness strongly influences adsorption kinetics. Thin films facilitated faster mass transfer, while thicker films increased total adsorption capacity, an indication that adsorption efficiency depends not only on chemical composition but also on structural architecture.

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A highly attractive system for continuous wastewater treatment that combines high porosity, large surface area, and improved operational durability was recently developed by Liu et al. (47). They achieved this by synthesising MOF-stabilized bio-based aerogels with anti-biofouling properties.

Alginate

Alginate is an effective, environmentally friendly biopolymer for removing tartrazine from aqueous systems. The biopolymer backbone consists of β-D-mannuronic acid and α-L-guluronic acid units, which carry carboxyl and hydroxyl groups (Figure 6). Because pure alginic acid is water - soluble, and Na-alginate forms gels in solution (48), it is frequently crosslinked with calcium ions. Divalent Ca^{2+} coordinates with guluronate blocks to form three-dimensional "egg-box" hydrogel networks to improve its mechanical strength (49,50). Beyond conferring structural stability and preventing premature dissolution, bound calcium ions act as ionic bridges. These positively charged metallic centres partially shield the polymer matrix's negative background charge and interact directly with tartrazine sulfonate anions through electrostatic coordination (51).

Integrating functional materials or photocatalytic composites further increases accessible adsorption sites and dye-removal efficiency.

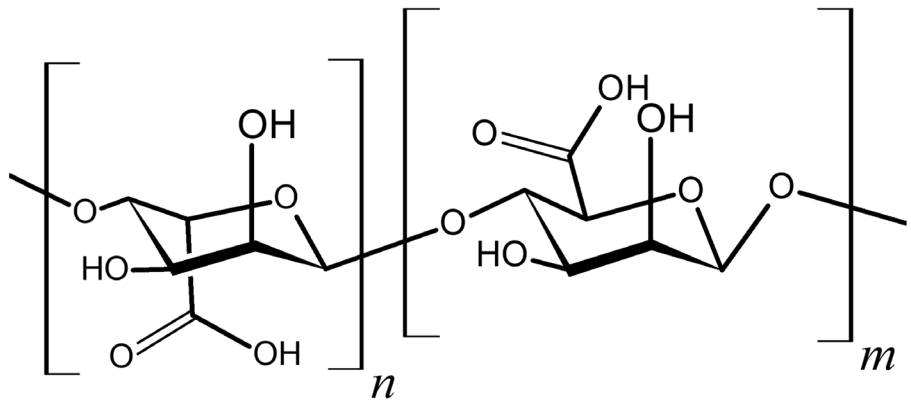

Figure 6. Chemical structure of alginate (**Source:** Authors).

One example is immobilizing Spirulina platensis biomass in calcium alginate beads (Alg-SP). Saloglu and Sahin (52) synthesized composite beads with varying biomass loadings and showed that incorporating 3% (w/v) Spirulina improved tartrazine adsorption compared with alginate alone.

The composite's enhanced performance was attributed to amino, phosphate, sulphate, hydroxyl, and carboxyl groups in the microalgal biomass, which provided additional binding sites for tartrazine molecules. Under optimal conditions (100 mg adsorbent, 2 h contact time, and 3% biomass loading), the Alg-SP beads removed approximately 98% of tartrazine from solution. FTIR, XRD, SEM, TGA, and DSC confirmed successful immobilisation of Spirulina within the alginate matrix. At the same time, SEM also revealed that immobilisation produced a rougher, more homogeneous surface morphology that favoured adsorption by increasing active binding sites.

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Another promising approach combines alginate-based adsorption with photocatalytic degradation. Dalponte et al. (53) synthesised floating TiO_2-organobentonite/calcium alginate (TiO_2-NaOB/CaAlg) composite beads via ionotropic gelation. In this multifunctional material, alginate served as the immobilisation matrix, organobentonite increased surface area and adsorption capacity, and TiO_2 nanoparticles provided photocatalytic activity. FTIR, BET, SEM, and EDS confirmed successful incorporation of all components, yielding mesoporous beads with a pH_{pzc} of approximately 6.4, making them suitable for adsorbing anionic tartrazine under acidic conditions. Adsorption alone removed approximately 23.5% of tartrazine, and the combined adsorption-photocatalysis process achieved ~95% dye removal within 180 min. The beads also maintained more than 80% tartrazine removal after seven reuse cycles, demonstrating good stability and the advantages of alginate composites that integrate adsorption with advanced oxidation processes.

Plant-based natural polymers

Plant-based natural polymers like cellulose, starch, and their derivatives have been used to remediate tartrazine-polluted wastewater. However, this application is relatively new compared with the use of treated and untreated crude agricultural wastes. As the most abundant renewable organic material on Earth, cellulose in its various forms has been used for numerous aqueous dye remediation applications.

Most biosorbent materials derive their sorption ability from cellulosic components in plants and microbes, the major sources of cellulose. This section, however, focuses on plant-based natural polymers and their modified derivatives for remediating tartrazine-contaminated aqueous solutions. Although plant-based biopolymers in their natural state are proven eco-friendly adsorbents for wastewater remediation (54), modification increases their adsorption capacity. For instance, quaternization of wheat cellulose by Villabona-Ortíz et al. (55) using cetyltrimethylammonium chloride (CTAC) led to more than an 88% increase in the adsorption capacity of the quaternized derivative (13.3 mg g^{-1}), relative to the neat cellulose (1.49 mg g^{-1}) obtained from wheat residues. They also found that the modified sample reached equilibrium faster (120 min) than its natural counterpart (480 min), but this was more than offset by the improved adsorption capacity of the quaternized adsorbent. Although they didn't study the mass transfer mechanisms, they attributed the results to increased protonation of the adsorbent surface due to CTAC modification.

Similarly, Dai et al. (56) investigated tartrazine removal from aqueous solutions using hydrogel beads derived from corn starch, oxidized corn starch, and a composite of oxidized corn starch crosslinked with gelatine. The study compared the removal capacities of these starch-based adsorbents for tartrazine remediation in aqueous environments and found that the adsorbents exhibited uniform porosity and formed stable, compatible Schiff base structures in electrolyte solutions. The gelatine concentration was varied, and its effect on maximum tartrazine uptake capacity was investigated. The highest maximum adsorption capacity (165 mg g^{-1}) was observed at a 5:5 (gelatine:starch) ratio. However, because the hydrogels have high water-absorbing capacity, the adsorbent's recyclability was reduced due to partial dissolution in aqueous media with long residence times (above 18 hours). Thus, researchers usually modify biopolymers through

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crosslinking or functionalization to improve adsorption rate, increase uptake capacity, enhance selectivity for tartrazine in the presence of other dyes, and promote recyclability.

Cellulose nanosponge modified with methyltrioctylammonium chloride was developed by Shiralipour and Larki (57). They used it to preconcentrate and remove tartrazine from aqueous media. According to the BET isotherm, which best fit the adsorption data, the maximum adsorption capacity of the nanosponges was 180 mg g^{-1} of adsorbent, using 0.005 g of adsorbent.

A simple method to produce an amine-rich porous adsorbent with improved recyclability for anionic dye decontamination has been reported by Chen et al. (58). They prepared the adsorbent by crosslinking glucose and diethylenetriamine with epoxy chloropropane and tested its effectiveness using amaranth and tartrazine. Their results showed that adsorption reached equilibrium within 20 min, with a maximum adsorption capacity of 534.76 mg g^{-1} for tartrazine. In addition to its relatively high adsorption capacity, the bio-sorbent showed high selectivity for tartrazine, as shown by its ability to selectively adsorb tartrazine from a solution of tartrazine and amaranth, a property necessary for real-world applications since industrial effluents are always composed of several dyes. Their results also showed that the adsorbent could be recycled for up to five consecutive adsorption and desorption cycles while maintaining a high percentage removal of tartrazine (78.90%), making it a viable material for environmental remediation of tartrazine-polluted wastewater streams.

Quaternized, crosslinked peach gum polysaccharide prepared by adding

glycidyltrimethylammonium chloride has been studied for its tartrazine removal efficiency (59). A study of the adsorption properties of the natural peach gum polysaccharide and its modified derivatives revealed that they exhibit high selectivity for tartrazine, are spontaneous and endothermic, and follow pseudo-second-order kinetics. According to the Langmuir isotherm, the maximum adsorption capacity of the crosslinked analogue was calculated to be 814.5 mg g^{-1}, while the adsorption capacity increased to 1136.7 mg g^{-1} for the quaternized derivative. In addition to its higher adsorption capacity, the quaternized analogue also showed a higher adsorption rate (equilibrium time of 10 min), better environmental stability, adsorption selectivity, and regeneration efficiency than its counterparts.

Comparative Summary of Natural Polymers

Assessing the effectiveness of natural polymers in removing tartrazine shows a clear order of adsorption capacity. Modified plant polymers (110-1136 mg g^{-1}) and chitosan-based materials (30-1065 mg g^{-1}) exhibit the highest capacities. Activated carbon (AC) and biochar (100-183 mg g^{-1}) possess moderate to high adsorption capacities, while unmodified agricultural residues (1-91 mg g^{-1}) have the lowest removal efficiencies.

The performance difference between chitin (30 mg g-L) and chitosan (350-1065 mg g^{-1}) emphasises the importance of deacetylation, which introduces protonatable amino groups that promote electrostatic attraction between the positively charged polymer surface and tartrazine's sulfonate groups. This high efficiency makes chitosan the most thoroughly researched and effective natural polymer for tartrazine capture.

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Plant-derived polymers exhibit comparable adsorption potential when appropriately modified, though their mechanisms and functions vary. To achieve competitive capacities, chemical modifications such as quaternization or crosslinking are often necessary, which can increase complexity and environmental impact. While alginate alone has a limited capacity, its compatibility with composite matrices makes it an ideal backbone for developing composite materials.

Although adsorption capacity alone does not determine practical suitability, reported maximum adsorption capacities for modified plant-based polymers have reached values comparable to, and in some cases higher than, those of several chitosan-based systems. For example, quaternized peach gum polysaccharide showed a Langmuir adsorption capacity of 1136.7 mg g^{-1}, while chitosan-based materials have reported capacities between 110 and 1065.55 mg g^{-1}in acidic conditions. Chitosan performs well at low pH because protonation of amino groups enhances tartrazine binding, whereas modified plant polymers may offer broader operational flexibility depending on the introduced functional groups. Regeneration behaviour also matters, as some chitosan materials, such as the chitosan/polyaniline composite powder investigated by Sahnoun & Boutahala (42), show good recyclability, unlike some starch-based adsorbents that swell or partially dissolve during prolonged aqueous exposure. Therefore, the selection between chitosan and plant-derived polymer adsorbents depends not only on adsorption capacity but also on structural stability, regeneration ability, preparation requirements, and performance under realistic wastewater conditions.

Challenges and Future Directions of Bio-Based Adsorption

The review of existing research shows that bio-based adsorbents effectively remove tartrazine from water. Agricultural residues, being inexpensive and readily available, serve as moderately effective adsorbents suitable for low-concentration wastewater in resource-limited settings. Biomass-derived carbons, enhanced through thermal and chemical activation, can attain higher adsorption capacities but require energy-intensive production. Natural polymers like chitosan offer the highest capacities because of their numerous functional groups, but they require purification and modification. While composite materials combine benefits, they also involve more complex manufacturing and raise sustainability issues.

The laboratory results reported are encouraging, but adopting these materials for industrial wastewater treatment presents several challenges. Major issues include inconsistent adsorbent performance, mechanical instability, poor regenerability, and a lack of standardised evaluation methods.

Current Challenges

1. Material Variability and Reproducibility

The physicochemical properties of adsorbents made from agricultural waste vary greatly. This variation depends on factors like plant species, geographic origin, cultivation methods, and processing techniques. For chemically activated or thermally treated materials, the activation agent and preparation conditions influence surface area, pore structure, and functional-group distribution. Consequently, this variability leads to inconsistent adsorption capacity and kinetic performance

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across batches, and complicates quality control and reproducibility compared with traditional adsorbents with more uniform compositions.

2. Mechanical Stability and Handling

Natural polymers like hydrogel materials from starch and alginate swell or lose their structure when in prolonged contact with water (60). Chitosan-based materials may undergo structural changes after multiple adsorption-desorption cycles, especially when regenerated with acidic or alkaline agents (61). Additionally, processing agricultural residues into fine particles can complicate adsorbent recovery.

3. Chemical leaching

Research has shown that chemical leaching from modified biosorbents introduces secondary contaminants into the treated water (64). Potential leachates include residual activators, unreacted cross-linkers such as gelatine, soluble organic components, incorporated metals such as titanium, and modifiers. Zioui et al. (39) attributed the 5% loss in photocatalytic efficiency of the chitosan-TiO_2 composite to TiO_2 washing off the chitosan biopolymer's surface during its first use and subsequent cleaning. Leaching should therefore be evaluated under relevant operating pH conditions and over repeated adsorption-regeneration cycles. Thorough washing alone does not establish safety, so the released substances should be analysed, and, where appropriate, toxicity testing should be conducted.

4. Regeneration and Reuse

Tartrazine is a highly water-soluble anionic dye. When regeneration is reported, efficiencies typically decline after 2-7 cycles. Tartrazine binds strongly to adsorbents such as chitosan-coated sands, so complete regeneration is rarely achieved. Attempts to desorb tartrazine using 0.1 M H_2SO_4, EDTA, and NaOH yielded less than 30 % recovery (40). Thus, regeneration from adsorbent surfaces often requires strong eluents such as NaOH or HCl, which may degrade adsorbent surface functionality, reduce the number of accessible adsorption sites, promote leaching of organic components (for unmodified biomass), and generate secondary waste streams, making the long-term stability of bio-based adsorbents under industrial operating conditions uncertain.

End-of-life management therefore must address both exhausted biosorbents and dye-containing regeneration solutions, since direct land application or composting is not safe because adsorbed dyes, modifiers, crosslinkers, or their transformation products may remain mobile or toxic (62).

5. Lack of Standardised Evaluation

Variations in experimental conditions and reporting methods complicate cross-study comparisons. Some studies report removal percentages based on concentration, while others focus on adsorbent capacity. The choice of isotherm and kinetic models also differs. Factors such as pH, temperature, and initial concentration vary widely, and regeneration performance frequently goes unreported or lacks detail.

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6. Knowledge Gaps in the Literature

Several gaps exist in the current literature.

Industrial effluents contain dyes, salts, surfactants, and organic compounds that may compete for adsorption sites or disrupt surface interactions. Dissolved salts screen electrostatic attraction between anionic tartrazine and positively charged adsorbent surfaces, while competing anions may reduce the availability of adsorption sites (63). However, salt effects depend on the adsorbent and solution chemistry. Among the studies reviewed, only chitosan-coated sand has been tested with real effluent (44), achieving a Q_{max} of 237 mg g^{-1}. This is significantly lower than the capacities observed in single systems (595 mg g^{-1}) and binary systems (497 mg g^{-1}). In light of these differences, realistic matrix testing is important. However, it does not isolate salt interference, thus, a systematic evaluation of representative salt compositions and ionic strengths is needed to distinguish salt effects from other matrix interactions.

Laboratory studies mostly employ batch adsorption, and fixed-bed and fluidised-bed studies, which are essential for scale-up, are limited to a few reports (27,43). Therefore, continuous flow testing using real effluents is needed to validate performance under industrial conditions.

Many studies do not report regeneration data. When reported, the number of cycles is limited (2-7), and the effect of regeneration eluents on adsorbent structural integrity is rarely addressed.

Limited comprehensive techno-economic analyses exist for bio-based tartrazine adsorbents. Production costs, raw material logistics, adsorbent lifetime, and waste disposal costs are not systematically evaluated. This limits comparisons between bio-based adsorbents and commercial alternatives.

Future Prospects of Bio-Based Adsorption

Despite these challenges, the field is rapidly evolving, with several promising directions that could redefine the role of bio-based adsorption in wastewater treatment.

1. Continuous Flow Systems

Few studies have explored tartrazine removal in fixed-bed or fluidised-bed systems. Future research should focus on breakthrough-curve modelling to understand how adsorption behaves dynamically under flow, analyse mass transfer to pinpoint rate-limiting steps like film diffusion, intraparticle diffusion, and surface reactions, develop column-regeneration protocols for efficient in situ regeneration, and conduct pilot-scale tests using real industrial effluents.

2. Real Wastewater Validation

Single-dye solution studies are essential but not enough. Future research should explore how tartrazine competes for adsorption when other dyes and characteristic wastewater components, such as salts and natural organic matter, are present, since ionic strength can affect electrostatic interactions. Additionally, competition by dissolved organic matter for adsorption sites might decrease the adsorbent's effectiveness.

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3. Waste-to-Energy Pathways

Non-regenerable spent adsorbents require proper management. Effective strategies include converting spent biomass into biochar through carbonisation, incinerating dye-loaded adsorbents to recover energy, utilising spent adsorbents in catalytic applications where they may serve as catalysts for other reactions, and disposing of them in landfills as a last resort. However, regeneration should minimise this need. When reuse is no longer feasible, options such as controlled thermal treatment with appropriate emission controls or stabilised disposal should be employed, subject to residue characterisation and applicable regulations.

4. Techno-Economic and Life Cycle Assessment

Future research should go beyond just measuring adsorption capacity. It should also evaluate production costs, from raw material procurement, transportation, processing, activation, to waste disposal, along with energy use during drying, milling, carbonisation, and regeneration. Additionally, assessments should consider environmental impacts like global warming potential, water use, and ecotoxicity, as well as a cost-benefit analysis comparing these materials with commercial AC based on capacity per unit cost.

Conclusion

The quest for effective and sustainable remediation methods for tartrazine-contaminated wastewater is driven by concerns about its effects on human health and ecosystems. This review presents bio-based adsorption as a viable option for removing tartrazine, as biological materials are plentiful and structurally varied. Agricultural residues, biomass-derived carbons, and natural polymers have all shown the ability to extract tartrazine from water. Nonetheless, their effectiveness varies with material source, surface chemistry, modification techniques, and operating conditions.

Chemically modified natural polymers and engineered biomass-derived carbon materials generally exhibit the highest adsorption capacities among the adsorbent classes. This is because they incorporate additional functional groups that enhance access to adsorption sites. However, these advantages do involve more complex preparation methods and increased chemical use.

Across adsorbent categories, electrostatic attraction between positively charged adsorption sites and tartrazine's anionic sulfonate groups is the most consistently reported mechanism, with hydrogen bonding, pore diffusion, and hydrophobic interactions contributing to varying degrees depending on the specific adsorbent structure. However, because this predominant electrostatic mechanism relies on extensive surface protonation, high removal efficiencies are limited to strongly acidic conditions (pH 1.5-3.0).

This dependence on low operational pH imposes a practical constraint. Acidifying industrial effluent requires substantial chemical input, and neutralising it before discharge increases chemical consumption, raises costs, and risks equipment corrosion and salinizing receiving waters. Consequently, unless adsorbents are specifically engineered to maintain positive surface charges or high adsorption capacities around neutral pH, or are integrated into fully regenerable, closed-loop systems, the environmental benefits of these treatments are limited for large-scale applications.

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Although laboratory results are promising, the main obstacle to scaling up is not the scarcity of high-capacity adsorbents but the absence of standardized testing and validation under realistic wastewater conditions. Variations in precursor sources, preparation methods, adsorption settings, and reporting practices hinder meaningful comparison of studies. Future research should focus on developing mechanically stable, regenerable bio-based adsorbents; conducting continuous-flow tests with actual effluents; enhancing mechanistic understanding; and thoroughly evaluating environmental and economic impacts.

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Conflict of Interest

The authors declare no conflict of interest.

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