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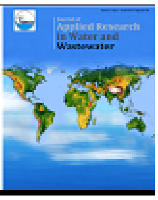

Overview of sugar distillery wastewater characteristics and the potential of nanomaterial adsorbents for treatment in Sindh, Pakistan

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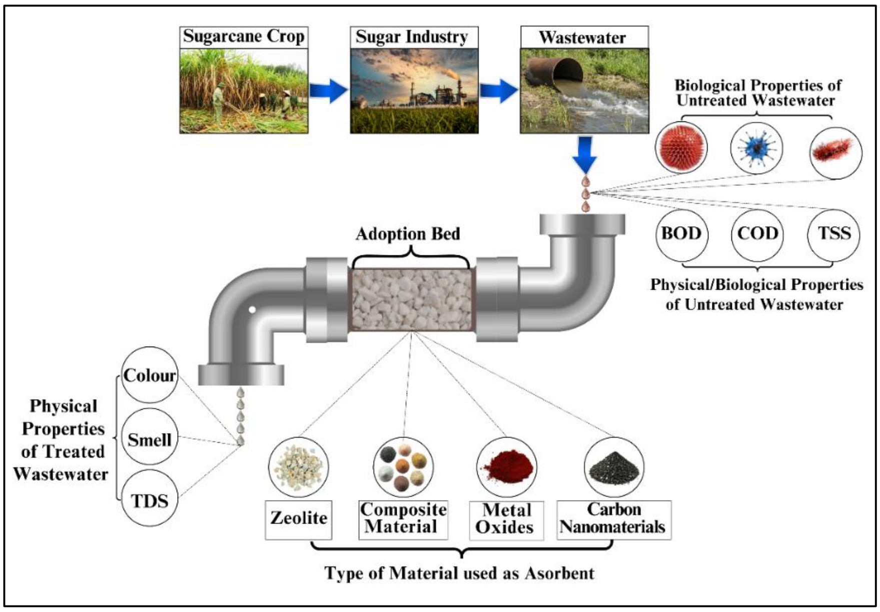
GRAPHICAL ABSTRACT



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ABSTRACT

Distilleries produce substantial amounts of wastewater containing high concentrations of organic and inorganic pollutants, leading to serious environmental concerns. In Sindh, Pakistan, water resources are at risk owing to the inappropriate disposal of industrial distillery effluents, contaminating land resources, water bodies, and groundwater. This has led to a notable increase in skin diseases and other health problems in Sindh, Pakistan. Therefore, effective and sustainable treatment strategies are required. We comprehensively reviewed the characteristics of sugar distillery wastewater from the Sindh region and highlighted its chemical composition, toxicity, and environmental impact. Conventional treatment methods often fail to achieve complete pollutant removal, necessitating the development of advanced alternatives. Nanomaterials, including nanoparticles, nanocomposites, and Nano-catalysts, have emerged as promising alternatives owing to their high surface areas, superior adsorption capacities, and reusability. This analysis examined a range of nanomaterials, such as metal oxides, carbon-based materials, and bio-inspired nanoparticles, and evaluated their potential for treating wastewater locally. This study aims to bridge the knowledge gaps and promote sustainable approaches for mitigating water pollution in the Sindh sugar distillery industry.

1. Introduction

Pakistan is an agricultural country and the production of agricultural commodities plays a vital role in its economy (Mahessar *et al.*, 2020). In recent years, distilleries have emerged as fast-emerging industries that produce ethanol and contribute immensely to Pakistan's economy due to the ubiquity of alcohol in other sectors, such as cosmetics, pharmaceuticals, and food (Lachenmeier *et al.*, 2008; Dao *et al.*, 2011). It is also used as a biofuel and is shared in the marketplace as an export product (Khan *et al.*, 2007). Sugar crops provide almost 61% of the

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ethanol production worldwide (Berg *et al.* 2004). In Sindh, Pakistan, most distilleries collaborate with sugar mills and use molasses from cane sugar manufacturing as a feed for alcohol production (Arshad *et al.,* 2019). Currently, there are 21 distilleries in Pakistan with a production capacity of 240–270 liters per ton of molasses (Rashid and Altaf, 2008). Distillery is considered a highly contaminated industry because ethanol fermentation generates significant quantities of high-strength liquid effluents (Sultan *et al,* .2024; Siles *et al.,* 2011). Alcohol-based sectors require a large amount of raw water, which produces a large amount of wastewater (Kharayat *et al.,* 2012). The production of effluent streams from distilleries is termed sugarcane molasses wastewater (SCMW). High concentrations of contaminants, such as inorganic components such as sulfide and chloride, as well as volatile organic compounds (VOCs) such as ethanol and methanol, are characteristics of this type of wastewater. It typically exhibits a high chemical oxygen demand (COD) ranging from 80,000 to 160,000 mg/L, acidic pH, dark brown coloration, and a strong, unpleasant odor (Mikucka and Zielińska, 2020). The disposal of distillery wastewater without adequate treatment deteriorates the quality of the soil, water bodies, and, ultimately, groundwater, and the safe disposal of these effluents has become a growing concern as they negatively affect ecosystems and the health of residents (Ratna, Rastogi and Kumar, 2021).

Numerous treatment methods have been devised to control and degrade distillery wastewater toxicity, dark color, and high organic loads. These methods fall into three main categories: advanced oxidation processes (AOPs) (Fenton oxidation, ozonation, and photocatalysis), physicochemical (membrane filtration, coagulation and flocculation, and adsorption), and biological (aerobic, anaerobic, and fungal). Adsorption is an economically feasible, cost-effective, simple, and conventional process for producing high-quality products. Moreover, adsorption demonstrates high efficacy for the removal of a broad spectrum of contaminants, including both organic and inorganic compounds, underscoring its versatility as a wastewater remediation strategy (De Gisi *et al.*, 2016). Nanomaterials are well known and are frequently suggested for use as adsorbents because of their high surface area, which provides them with effective energy sites and efficient adsorption capability. Adsorbents with nano-scale structures are favored over prosaic materials because of their diverse nature, affordability, and environmental friendliness.

The objective of this review is to present a comprehensive analysis of the production, physicochemical characteristics, and environmental impacts of sugar distillery wastewater, with a focus on the industrial and ecological contexts of Sindh, Pakistan. To examine and evaluate the potential of adsorbents for the effective treatment of wastewater from sugar distilleries, and to offer a summary of the many nanomaterial adsorbents used in wastewater treatment, including information on their adsorption processes, types of nanomaterials used, treatment effectiveness, ideal operating parameters, and environmental sustainability. This study intends to critically evaluate distillery wastewater management within Sindh's socioeconomic and industrial setting by combining knowledge from the existing literature and contrasting regional treatment methods with international developments. It looks for gaps in local research activities, identifies limitations in current treatment technologies, and suggests possible avenues for further research and technological advancement. The ultimate goal of this review is to aid in the creation of ecologically friendly, scalable, and reasonably priced nanotechnology-based wastewater treatment solutions tailored to the needs of Sindh's sugar distillery industry, as well as other similar agro-industrial regions.

1.1. Background of sugar distillery industry and its wastewater

Ethanol (C2H5OH) from distilleries is in demand as a renewable fuel worldwide (Khan *et al.,* 2021). In Pakistan, the production of ethanol is increasing in large numbers (Khan *et al.,* 2019). Alcohol can be produced from various feedstock. Starch-based (corn, wheat, rice, and barley), sugar-based (sugarcane, beet molasses, and cane juice), and cellulosic (crop residues, sugarcane bagasse, wood, and municipal solid waste) materials (Rutz and Janseen, 2007). The feedstock was selected based on its cost, availability, carbohydrate content, and conversion efficiency into alcohol (Robak and Balcerek, 2018).

Ethyl alcohol production in distilleries is based on four main processes: feed preparation, fermentation, distillation, and packaging (Fig. 1). Initially, blackstrap molasses was diluted with water in proportion to attain 10-15% of sugar content in the solution. The diluted solution was then added to the fermenter, and the 5% active yeast culture (Saccharomyces cerevisiae) (Satyawali and Balakrishnan, 2008) was also fed to the column. The fermentation mixture was then treated using distillation columns. The ethanol obtained (95%) from fractional distillation is called rectified spirit, and the bottom product is a brownish liquid known as distillery stillage. This mixture of ethanol and water was further heated and refluxed for several hours to obtain the absolute alcohol (99%) (Senthamil Selvi, 2013). The probable reactions for ethanol production are given in Eq. 1–2.

$$C_{12}H_{22}O_{11}\,(\text{sucrose}) + H_2O \rightarrow C_6H_{12}O_6\,(\text{glucose}) + C_6H_{12}O_6\,(\text{fructose}), \quad (1)$$

$$C_6H_{12}O_6\,(\text{Glucose}) \rightarrow 2C_2H_5OH\,(\text{Ethanol}) + 2CO_2 \quad (2)$$

Various by-products and pollutants are generated during these processes. Wastewater, as a potential pollutant in distilleries, is generated from different sources such as cooling water, column washing, and boilers. Unfortunately, waste streams from distilleries are acidic, dark brown recalcitrant compounds with high biological oxygen demand (BOD), chemical oxygen demand (COD), and total dissolved solids (Shinde *et al.*, 2020), as summarized in Table 1. It also contains various salts, endocrine-disrupting chemicals (EDCS), and toxic heavy metals (Tripathi *et al.*, 2021). The large quantity of discharged effluents is a serious threat to terrestrial ecosystems.

Table. 1. Characteristics parameters of sugar Distillery wastewater

Parameters	Values
Volume (L/L alcohol)	10-15 l
pH	3.8-4.4
Temperature	Very high
Colour	Blackish Brown
BOD	40,000-60,000 mg/L
COD	80,000-100,000 mg/L
Total solids	90,000-120,000 mg/L
Total dissolved solids	30,000-40,000 mg/L
Total volatile solids	60,000-70,000 mg/L
Sulphates	4000-8000 mg/L
Chlorides	5000-6000 mg/L

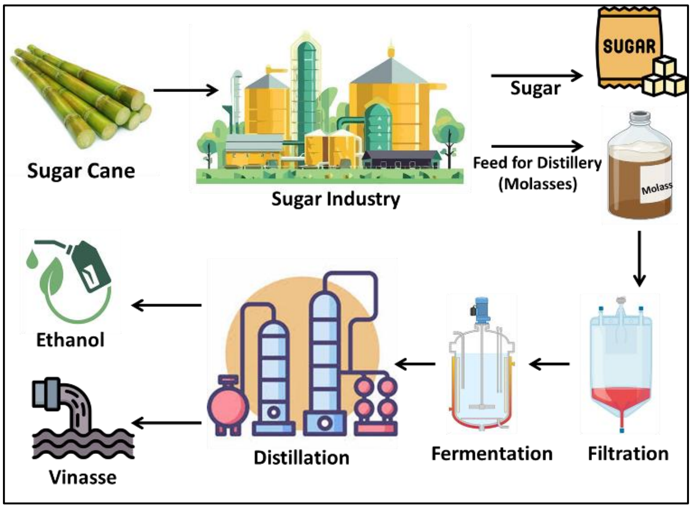

Fig. 1. Process description of sugar distillery industry and its wastewater.

1.2. Overview of sugar distillery wastewater, its characteristics & effects in Sindh, Pakistan

Wastewater generation from distilleries and fermentation industries is a major concern because of water scarcity and the huge volumes of wastewater management. The effluent generated from distilleries, also termed spent wash, is approximately 10-15 times the amount of alcohol produced per liter (Sankaran *et al.*, 2014). The physicochemical properties of distillery stillage differ based on the raw materials used and the operational processes involved in alcohol production, resulting in wastewater characteristics that vary among distilleries (Mohana, Acharya, and Madamwar, 2009). Wastewater contains high chemical oxygen demand (COD), biological oxygen demand (BOD), dissolved organic nitrogen, phenolics, total dissolved solids, phosphates, and sulfates because of the high load of organic compounds such as proteins, waxes, polysaccharides, and heavy metals (Chaudhari, Mishra and Chand, 2007). The dark brown color of the effluent stream is due to the presence of condensation products of amino acids, proteins, and carbohydrates, termed melanoidin (Chandra, Bharagava, and Rai, 2008). Melanoidin constitutes approximately 2% of distillery wastewater (Kaushik *et al.*, 2018). The obnoxious smell in the spent wash is due to the presence of sulfur compounds such as indole and skatole (Bhardwaj *et al.*, 2019). Some Distilleries in Sindh, Pakistan, treat spent wash through anaerobic digestion (Salahuddin Panhwar *et* *al.*, 2019). Although COD and BOD are removed to a great extent through anaerobic digesters, the color remains because the colored compounds are non-biodegradable (Malik *et al.*, 2018). Melanoidin also possesses antioxidant properties that are toxic to microorganisms present in conventional wastewater treatment (Pant and Adholeya, 2007). Distillery wastewater also contains endocrine-disrupting chemicals (EDCS), which lead to hormonal irregularities that trigger different metabolic and physiological disorders, ultimately compromising reproductive fitness in both humans and animals (Chowdhary, Raj and Bharagava, 2018), (Gonsioroski, Mourikes, and Flaws, 2020). A large volume of dark-colored wastewater pollutes both water bodies and landfills. They hinder sunlight penetration, disrupt photosynthetic activity, and lead to the depletion of dissolved oxygen, posing a serious threat to aquatic life. When exposed to vinasse, Oreochromis niloticus (tilapia) exhibited dose-dependent acute toxicity, distinguished by cytoplasmic degeneration and a substantial decrease in hepatic polysaccharide accumulation, indicating a major metabolic disturbance (Urbano *et al.*, 2014). Additionally, their high organic loads can cause eutrophication when discharged into water bodies (FitzGibbon *et al.*, 1998). Distillery wastewater can adversely affect landfills in Pakistan (Bano and Arshad, 2017) by inhibiting seed germination due to Mn deficiency and soil alkalinity (Fuess and Garcia, 2014). Prolonged irrigation with post-methane distillery effluent (PMDE) increases soil fertility by increasing phosphorus, potassium, total organic carbon (TOC), total Kjeldahl nitrogen (TKN), and enzymatic activity. However, it also causes Na to accumulate in the soil, which could be harmful to the long-term viability of agriculture (kaushik *et al.,* 2005). The amounts of Fe, Zn, Ni, Cd, and Cr in Spinacia oleracea (spinach) plants and the surrounding soil have been reported to increase when distillery effluents, particularly vinasse, are used for irrigation. This study suggests that prolonged application of vinasse poses a significant risk of heavy metal accumulation in crops, thereby raising concerns regarding the potential adverse effects on food safety and human health (Pathak *et al.*, 2014). The textual description was supplemented with a graphic overview of this pathway (Fig. 2).

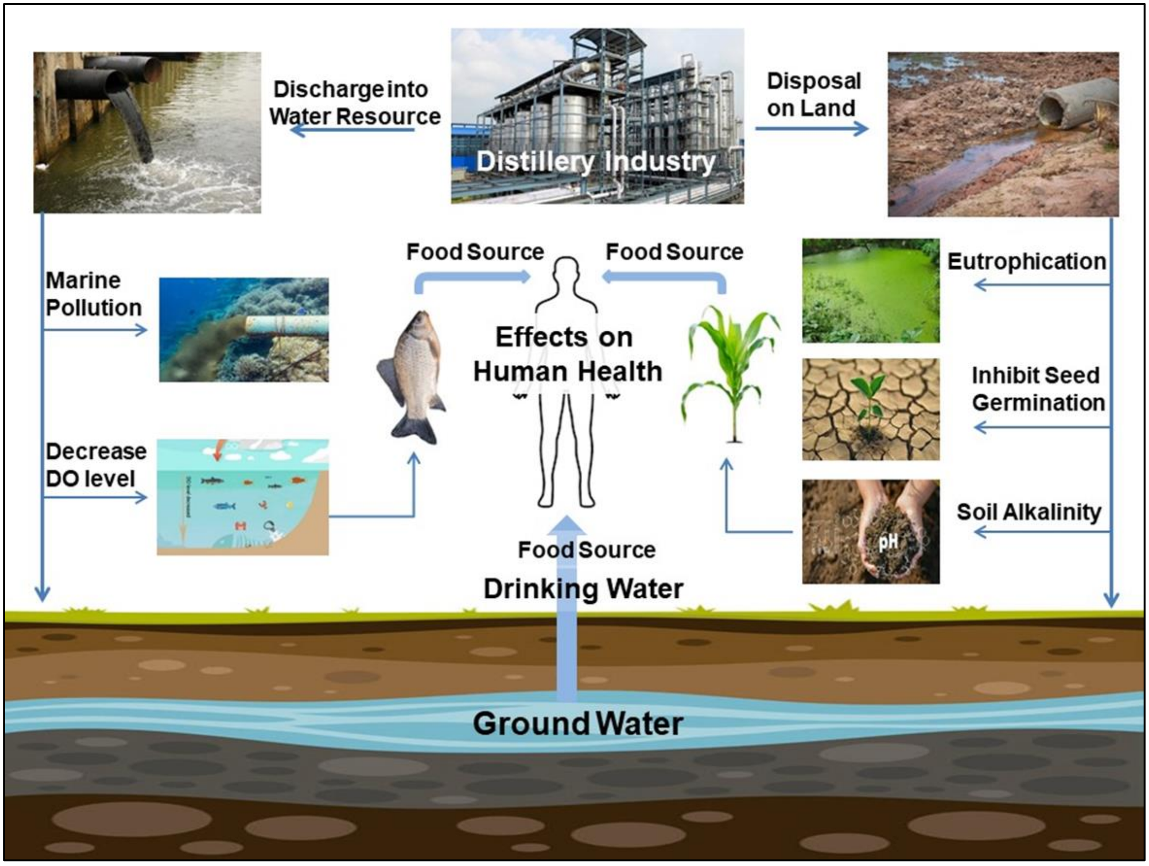

Fig. 2. Distillery wastewater, characteristics and effects.

In Pakistan, untreated wastewater from distilleries is often dumped into rivers, streams, and other waterways, severely damaging the groundwater. Studies have shown that the quality of groundwater has decreased in places where sugar manufacturers release wastewater with high concentrations of total dissolved solids (TDS) and other pollutants. This contamination poses a serious risk to local communities due to skin disorders and waterborne diseases (Qureshi *et al.*, 2015). Additionally, research indicates that groundwater pollution from industrial activities in Pakistan affects drinking water quality and puts human health at risk (Soomro *et al.,* 2011). Therefore, the removal of color and a high organic load from distillery wastewater is necessary for a better environment and sustainable development (Chowdhary *et al.*, 2017). The inability of the current practices and concentration achieved in the laboratory is quite low in comparison to the guidelines put forth by environmental standards, as well as the first international guidelines for water reuse in agriculture (Directive EU *et al.,* 2020). In an effort to satisfy the stringent government pollution control regulations, industries are being compelled to implement remediation technologies that are both economically viable and environmentally favorable in order to achieve more sustainable and efficient outcomes. (Faruqee and Kemal, 1996).

1.3. Importance of color removal and enhancement of physical and biological properties of sugar distillery wastewater in Sindh

The disappearance of color and enhancement of physical and biological qualities are of foremost importance and cannot be surpassed (Shahnawaz *et al.*, 2020; Collivignarelli *et al.*, 2019). The vision of an environmental engineer is referred to as visual engineering. The removal of color is of great importance, as it refines water. Color significantly contributes to aesthetic excellence and blemishes water quality for application in irrigation and effluent discharge into local water bodies (Mehmood, Batool, and Qazi, 2013). The deep coloration of distillery wastewater is caused by organic compounds such as phenolics, melanoidins, furfurals, and caramels (Miranda *et al.*, 1996). Melanoidin is the main contributor of the dark brown pigment in wastewater (Arimi *et al.*, 2015). The dark color of wastewater impedes photosynthesis, leading to a reduction in the levels of dissolved oxygen in water (Tariq *et al.,* 2022; Tirphati *et al.,* 2021). With regard to aquatic life, a decline in dissolved oxygen supports anaerobic organisms in aerobic digesters, which in turn produce hydrogen sulfide (Muller *et al.* 2022). Hydrogen sulfide can deteriorate the canal structure (Zhang *et al.*, 2023). Consumption of untreated wastewater can lead to skin allergic effects and possibly other waterborne diseases in the concerned population (Afzal *et al.*, 2018). Distillery wastewater is naturally turbid (Bezueh and Kebede, 2015). Turbidity is caused by the presence of soluble organic matter and suspended matter (Momeni *et al.,* 2018; Kumar *et al.,* 2014). Conversely, an increase in turbidity reduces the amount of solar radiation (Shedayi *et al.,* 2016). Improvements in the physical properties will not only refine the color but can also elevate the organic configuration in wastewater, making it useful for further applications (Zielińska, Bułkowska, and Mikucka, 2021).

A reduction in the turbidity of wastewater will also contribute to a reduction in the chemical oxygen demand (COD), as highly turbid wastewater allows for higher COD values during analysis (Nguyen, Ward, and Lewis, 2014). It is envisaged that the backbone of any treatment facility is its treated effluent, which experiences improvement not only in terms of organic and inorganic configuration, but also in other general parameters (Lako and Çomo 2024). The agricultural sector is largely dependent on water from rivers and natural rain-fed canal streams, which, on their way, capture and flow through the open drains of big cities. The use of effluents in sewer drains with high total suspended solids (TSS) and TDS values imperils irrigated cultivation, fruit trees, vegetation, and traditional livestock (Awan *et al.*, 2012). Wastewater treatment technologies should not only be environmentally friendly, but also cost-effective, as environmental measures can burden the socio-economy of the country (Khan *et al.,* 2022). The drainage of undiluted wastewater can also impose a percentage of the total country water resources to dilute and sustain existing natural water flow in streams and rivers. A grassroots-level approach is required to tackle this issue (Martí, Riera, and Sabater, 2009). Therefore, management measures require effective design and implementation of advanced wastewater treatment systems (Zhou and Smith, 2002). The subject wastewater should comply with the effluent standards for two reasons: one is self-imposed, and the second is that in the best national scenario, the same water could be utilized for irrigation techniques that can increase the number of crops and land with the same output (Ali, Pervez and Khan, 2020). Proper management of the effluent stream enhances its physical and biological properties, and it can be utilized as a soil fertilizer (Cerri *et al.*, 2020). It is anticipated that effluents from advanced treatment technologies can be used for the growth of hardwood trees, aquarium fish culture, environmental aesthetics, landscape water bodies, golf courses, surface gardening, and dust suppression in mining and construction. Ultimately, the paramount objective of environmentalists is to maintain a healthy environment (Khalid *et al.,* 2018; Hanjra *et al.,* 2012).

1.4. Potential of nanomaterial adsorbents for wastewater treatment in the context of Sindh

Nanomaterials are tiny artificial structures that are nanometers in size. They are more efficient than conventional materials and can be used to remove organic and inorganic compounds from wastewater (Younas *et al.*, 2021). Nanomaterials exhibit exceptional properties and show promising results as adsorbents for contaminant removal from wastewater. These adsorbents are capable of treating a variety of pollutants, such as organic pollutants (e.g., color, medications, and insecticides) and heavy metals (e.g., lead and mercury). Innovative adsorbent research also encompasses emerging contaminants such as per- and poly-fluoroalkyl substances (PFASs), microplastics, and endocrine-disrupting chemicals (Akhtar, Ali, and Zaman, 2024). The structural characteristics of nanomaterials, such as their high surface area and reactivity, enhance their effectiveness in removing heavy metals (Fu and Wang, 2011). Nanotechnology has been explored as a transformative approach to wastewater treatment. nanomaterials are categorized into three groups: nano-adsorbents, nanomembranes, and nano-catalysts (Anjum *et al.*, 2019). Various types of nanomaterials, including metals, metal oxides, carbonaceous materials, and bio-based nanomaterials, have demonstrated significant color-removal efficiencies (Umar *et al.*, 2023; Saleem, 2023). In particular, magnetic-based nanomaterials can remove more contaminants in less time and can be reused (Asghar *et al.*, 2024; Karnwal and Malik, 2024). Surface-modified magnetic nanoparticles with tridentate ligands effectively remove heavy metals. The Pb2+ and Cd2+ adsorption capacities were 93.5 mg/g and 83.5 mg/g respectively. (Masjedi, Askarizadeh and Baniyaghoob, 2020). Sarwar *et al.* (2024) examined the potential of biopolymeric nanocomposites for wastewater remediation by focusing on their production methods, properties, and applications. Despite the potential of nanomaterials, there are challenges such as environmental toxicity, cost, and operational issues that need to be addressed on a large scale (Muzammil *et al.*, 2023). Future research should focus on developing improved nanomaterials and composite materials with high adsorption capacity, selectivity, and durability to provide durable and recyclable solutions for the treatment of sugar distillery wastewater in Sindh (Shahzad *et al.,* 2025; Saleem *et al.,* 2020).

2. Synthesis, type and characterization of nanomaterial adsorbents

2.1. Synthesis of nanomaterial adsorbents

The synthesis of nanomaterial adsorbents should be developed to achieve a green, time-saving, scalable, and simple approach to prepare nano adsorbents with high surface areas and good stabilities for wide applications (luo *et al.,* 2021). Nanomaterial adsorbents are commonly synthesized by chemical, physical, and biological processes and are widely used for the fabrication of nanomaterials (Ullah *et al.,* 2019) (ref to Fig. 3).

They (the methods of synthesis of nanomaterials) can be broadly classified into two scientific approaches: (i) top-down and (ii) bottom-up. The breakdown of bulk materials into their nanosized structures is equivalent to the top-down approach. In contrast to the bottom-up approach, nanostructures are constructed from atomic or molecular units (saleh *et al.,* 2021).

Top-down synthesis is mostly carried out using physical methods, such as electron beam lithography (Avoyan, Rupprechter, and Eppler 2000), etching (Du *et al.,* 2014), high-energy ball milling (Amusat *et al.,* 2021), inert gas condensation (Turker *et al.,* 2004), and sputtering (Verma *et al.,* 2017). These techniques are highly effective for producing well-ordered structures with macroscopic crossovers; however, the surface morphology may not be ideal. However, bottom-up synthesis is mostly done chemically through sol-gel synthesis (Tabesh, Davar, and Loghman-Estarki, 2018), hydrothermal synthesis (liu *et al.,* 2014), H_2O_2 synthesis (Li *et al.,* 2012), CVD (alyan *et al.,* 2018), solvothermal synthesis (Chella *et al.,* 2014). One of the most popular methods for synthesizing nanomaterials, such as metal/metal oxide nanoparticles and carbon-based nanomaterials, is the use of these methods because they can form uniform, small particles and include both inorganic and organic components (Patricio, López, and Thirumuruganandham, 2023).

Following the bottom-up pathway, biological methods use microorganisms, plants, and enzymes for the synthesis of nanomaterials, providing the advantages of biological friendliness, low cost, and high biosafety (Jamshed *et al.*, 2023). In particular, for synthesizing eco-friendly adsorbents, such as biosynthesized metal nanoparticles and plant-based carbon nanomaterials, these methods are convenient and an ideal choice for synthesis in areas with resource constraints (Rafatullah *et al.,* 2010). Biological synthesis using naturally occurring substances is safer and more sustainable than physical and chemical methods based on secondary chemicals, often toxic chemicals, and expensive reagents (Ijaz *et al.,* 2020). With the significance and environmental problems of the Sindh province, biosynthesis is expected to be a promising arena for future research in material synthesis and environmental purification. Local organic resources and biomass waste are emphasized as proper advancements in green nanotechnology to synthesize wastewater adsorbents suitable for local applications (Akhtar, Sarfraz, and Ahmad, 2024). Effective remediation requires novel synthetic strategies appropriate for the climate of Sindh. Ikram *et al.* (2023) demonstrated the feasibility of conventional synthesis methods for producing nanomaterials suitable for Sindh. The conversion of biomass waste to nanomaterials is advantageous from both environmental and economic perspectives, particularly for the development of adsorbents such as carbon nanomaterials and nanocomposites for industrial applications (Mubarak *et al.,* 2021; Tariq, Yahaya, and Sajid, 2024).

2.2. Types of nanomaterial used for distillery wastewater remediation

Nanostructured adsorbents, owing to their remarkably high surface areas compared to conventional materials, have become relatively common because of their faster adsorption rates and efficiencies. These top-down, bottom-up, and green synthesis nanomaterials are broadly categorized as carbon-based, metal/metal oxide, oxide-based, composite, and zeolite-based nanomaterials. Furthermore, some of these nanomaterials, which have distinctive functions, can be employed for the detoxification of distillery wastewater, which is differentiated as carbon-based (Nure *et al.*, 2017), metal/metal hybrid nanoparticles (Manikandan *et al.*, 2022), oxides, composite materials (El-Dib *et al.*, 2016) and nanoscale zeolite materials (Apollo *et al.*, 2019). Consequently, these nanomaterials can be effectively applied to degrade the majority of pollutants residing in distillery effluents, that is, color, COD, BOD, organic phenols, and heavy metals.

For effective waste management, the focus is on locally obtained carbon-based and metal/metal oxide nanoparticles in the Sindh Province (Ahmad *et al.*, 2020). Activated carbon, carbon nanotubes, and graphene are potential candidates for remediating distillery wastewater because of their high surface area and high adsorption capacity. Specifically, adsorbents such as activated carbon (AC) are frequently employed owing to their relatively high surface area and porosity, as well as their strong affinity for organic compounds.

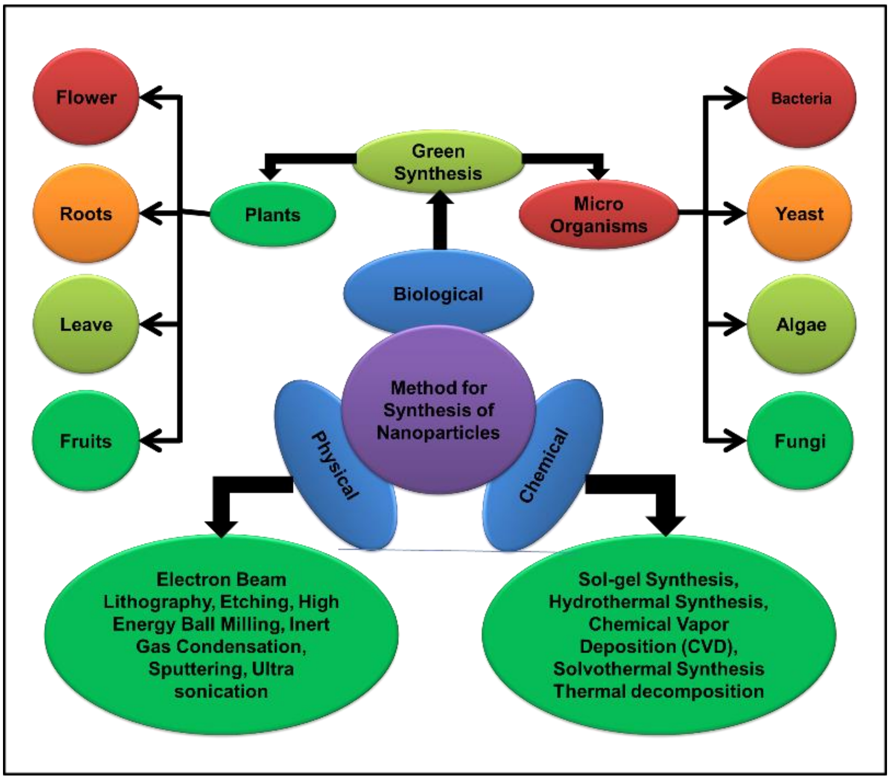

Fig. 3. Synthesis methods of nanomaterial adsorbents.

AC can be synthesized from abundant and economical materials such as agricultural residues (Almadani *et al.*, 2023), AC can be synthesized and has been found to efficiently adsorb pollutants such as organic phenols, COD, and color. Inorganic nanomaterials, such as metal or metal oxide-based nanomaterials, are widely used for wastewater treatment because of their catalytic properties and factors for specific pollutant removal (Naseem & Durrani, 2021). Therefore, detoxification of distillery effluents using magnetic nanoparticles (Fe_3O_4) has been demonstrated through the use of heavy metals as well as the removal of organic compounds and COD (Mahmoudabadi, Rashidi, and Maklavany, 2022). Propagation studies have also been conducted on distillery wastewaters. Contaminants have been removed using nanomembranes, nanofibers, and other nanomaterial-based membranes (Nataraj, Hosamani, and Aminabhavi, 2006).

Nanocomposites (NCs) are innovative materials formed by the combination of two or more different components, namely, the matrix and reinforcing phase, to produce a comprehensive set of properties superior to the properties of the individual constituents. These materials are also used to enhance the adsorption capacity and stability of the process for the removal of complex pollutants, such as aromatic compounds, COD, and color from distillery wastewater treatment (Ashraf *et al.*, 2024; Nadeem *et al.*, 2021).

2.3. Characterization techniques of nanomaterial adsorbents

Characterization of nanomaterials is crucial for the development of repeatable synthesis techniques. Characterization involves examining the structure, composition, and range of electrical, magnetic, chemical, and physical characteristics. Numerous methods are available for characterizing nanomaterials (Kumar *et al.,* 2019). The characterization techniques can be classified into three categories (Tables 2, 3, and 4): chemical, physical, and thermal characterizations. (Pellenz *et al.,* 2023).

Table 2. Chemical characterization techniques for nanomaterials.

	Technique	Purpose	Key outputs	References
Chemical characterization	X-Ray Photoelectron Spectroscopy (XPS)	Determines surface elemental composition, oxidation states, and chemical bonding.	Binding energies, oxidation states.	Steve and Donley 2020
	Fourier-Transform Infrared Spectroscopy (FTIR)	Identifies functional groups and surface chemical bonding.	IR absorption spectra.	Smith, 2011
	Raman Spectroscopy	Probes molecular vibrations and chemical structure.	Raman shifts, peak intensity.	Ferrari and Basko 2006
	Inductively Coupled Plasma Mass Spectrometry (ICP-MS)	Quantifies trace elements with high sensitivity.	Concentration of metal ions.	Wu et al, 2009
	UV-Visible Spectroscopy (UV-Vis)	Analyzes adsorption properties and optical behavior.	Absorption peaks, band gap energy.	Akash and Rehman, 2020
	Nuclear Magnetic Resonance (NMR)	Examines molecular structure and chemical interactions.	Chemical shifts, bonding environments.	Levitt, 2008
	X-Ray Fluorescence (XRF)	Identifies and quantifies bulk elemental composition.	Elemental composition.	Jenkins, 1999

3. Adsorption mechanisms and performance

3.1. Mechanism of removal of existing pollutants by nanomaterials

Nanomaterials are widely used for the removal of pollutants from sugar distillery wastewater using various adsorption, catalytic degradation, ion exchange, and membrane-based filtration mechanisms. The interactions of nanomaterials range from unique physicochemical properties, such as large surface area, enhanced porosity, high surface reactivity, and the presence of active functional groups, to color compounds, COD, BOD, organic phenols, and heavy metals (Dhila, Bhapkar and Shekhar Bhame, 2025). Currently, pollutants are physically or chemically bound to the surface of nano adsorbents such as activated carbon, graphene oxide, and carbon nanotubes (R.Hari Krishna *et al.*, 2023). In photocatalytic degradation and redox reactions, metal oxide nanoparticles, such as TiO_2, ZnO, and Fe_3O_4 play a significant role in removing complex organic molecules and reducing toxicity levels (Li *et al.*, 2020). Also, magnetic nanoparticles make it easy to separate and retrieve the nanomaterials (Soylak, Ozalp, and Uzcan, 2021). Nanocomposites and hybrid materials often inherit multiple mechanisms where the combinations, in turn, are synergistic to increase the overall treatment performance (Ribeiro, Dias, and Zille, 2022). This multifunctionality makes nanomaterials a highly suitable and sustainable option for the treatment of distillery effluent wastewater at low dosages in Sindh, Pakistan.

Table 3. Physical characterization techniques for nanomaterials.

	Technique	Purpose	Key outputs	References
Physical characterization	Scanning Electron Microscopy (SEM)	Studies surface morphology, particle size, and distribution.	High-resolution surface images.	Goldstein *et al.*, 2003
	Transmission Electron Microscopy (TEM)	Probes internal structure, crystallinity, and nanoparticle size.	Atomic-scale images, lattice fringes.	Zuo and spence, 2017
	Atomic Force Microscopy (AFM)	Measures surface roughness, topography, and mechanical properties.	3D surface profiles, roughness values.	Voigtländer, 2019
	X-Ray Diffraction (XRD)	Determines crystalline structure, phase purity, and grain size.	Diffraction patterns, lattice constants.	Cullity and Stock, 2001
	Dynamic Light Scattering (DLS)	Measures hydrodynamic diameter and size distribution in suspensions.	Particle size distribution.	Stetefeld, McKenna and patel, 2016
	Brunauer-Emmett-Teller (BET) Analysis	Measures surface area, pore size, and pore volume of porous materials.	Specific surface area, pore distribution.	Brunauer, Emmett and Teller, 1938
	Zeta Potential Measurement	Evaluates surface charge and colloidal stability in aqueous solutions.	Zeta potential values.	Clogston and Patri, 2010
	Thermogravimetric Analysis (TGA)	Analyzes thermal stability and adsorbent decomposition behavior.	Weight loss vs. temperature.	Brown, 2004
	Surface Area Analyzer (SSA)	Measures specific surface area and pore structure.	BET surface area, pore volume, pore diameter.	Sing, 1982
	Contact Angle Measurement	Measures surface wettability and hydrophilicity / hydrophobicity.	Contact angle values.	Kwok and Neumann, 1999

Table 4. Thermal characterization techniques for nanomaterials.

	Technique	Purpose	Key outputs	References
Thermal characterization	Thermogravimetric analysis (TGA)	Evaluates thermal stability, decomposition behavior, and residual mass.	Weight loss vs. temperature.	Rami *et al.*, 2021
	Differential scanning calorimetry (DSC)	Measures heat flow associated with phase transitions (e.g., melting, crystallization).	Glass transition temperature, melting point.	Koshy, Subramanian, and Thomas 2017
	Differential thermal analysis (DTA)	Identifies endothermic or exothermic reactions during heating.	Temperature difference between sample and reference.	Mansfield, 2015
	Thermomechanical analysis (TMA)	Measures dimensional changes in response to temperature.	Thermal expansion coefficients.	James, 2017
	Dynamic mechanical analysis (DMA)	Studies viscoelastic properties of nanomaterials under thermal stress.	Storage modulus, loss modulus, damping factor.	Bashir, 2021

3.2. Nanomaterial adsorption mechanisms

Adsorption is an essential process in wastewater treatment because it contributes significantly to the purification of pollutants (Rashid *et al.*, 2021). Adsorption is a mass transfer process in which a substance from the liquid phase is transferred onto a solid surface (Alaqarbeh, 2021). When a solute solution and a highly porous solid material come into contact, certain solute molecules are pulled to the solid by intermolecular forces, which leads to the solute molecules adhering to the solid's surface or accumulating (Sadegh *et al.,* 2017). During adsorption, the attractive forces on the adsorbent surface outweigh those on the dissolved components of the liquid. The forces between the adsorbate and adsorbent can be physical or chemical (Bhavsar *et al.,* 2021). In the former, physisorption involves weak forces, such as hydrogen bonding, van der Waals forces, and electrostatic interactions. It can purify pollutants through physical interactions between substrates, called adsorbents, and contaminants, called adsorbates (Zang and Xing, 2011). Electrostatic and hydrophobic interactions govern pollutant removal, damaging water quality and ecosystems (Mandal *et al.*2024). According to Xiong *et al.* (2024), amine-functionalized soy protein/GO aerogels have high affinity for compounds derived from sugars. The adsorption process is mainly driven by electrostatic (charge) interactions between the protonated amine groups and anionic sugar moieties, in addition to extensive hydrogen bond formation at the protein–graphene oxide interface. Nunes *et al.* (2015) used activated carbon to study melanoidin removal and found that π-π interactions and hydrogen bonding were the main adsorption mechanisms involved. Chemisorption, that is, chemical adsorption, occurs as a result of electron transfer and chemical bonding (Agboola and Benson, 2021). Gonzalez-Valerio *et al.* (2024) demonstrated that melanoidin adsorption on silica gel functionalized with thiol moieties occurred predominantly via chemisorption. This study also showed that thiol groups on the adsorbent surface can form covalent bonds with melanoidin, specifically through interactions with pyrazinium compounds derived from the Maillard reaction. Multiple studies have demonstrated that functionalized adsorbents exhibit a robust and specific affinity for target organics.

Different adsorption mechanisms are illustrated in Fig. 4. To understand the adsorption mechanisms and boost the adsorption process, adsorption kinetics and isotherm models (Karimi, Tavakkoli Yaraki, and Karri, 2019). The adsorption isotherm is useful for representing the capacity of an adsorbent and describing the functional dependence of the capacity on the concentration of pollutants (Saleh, 2022). Adsorption kinetic studies demonstrated the rate of adsorption and identified the adsorption mechanism. There were three main steps in this process. The adsorbate is first transported to the outside of the adsorbent via surface coating (also known as "film diffusion"); second, the adsorbate diffuses into the adsorbent's pores (also known as "pore diffusion"); and third, the solute adsorbs on the interior surfaces enclosing the capillary and pore gaps. (Díaz, García and Ordóñez, 2024). The performance of the adsorption process depends on the nature of the adsorbent, its physical attributes, and the process parameters (Sen, 2023).

3.3. Factors affecting adsorption process efficiency

The factors affecting adsorbent performance are interconnected with the wastewater being treated (Satyam and Patra, 2024). The physical and chemical properties of the adsorbent, such as the adsorption number, nanoparticle size, surface area, functional groups, and mesoporous distribution, play significant roles (Badran *et al.*, 2023). Smaller nanoparticles have higher adsorption efficiency owing to their larger surface area (Wang and Shadman, 2012). Nanoparticles operationalized with attached oxidizing and reducing sugar molecules are more reactive and exhibit better adsorption capabilities (Wang *et al.*, 2025). Functionalizing adsorbent surfaces with different functional groups and composite materials provides charged and synergistic effects (Olawade *et al.* 2024). The number of accessible active sites for adsorption to take place increased with increasing adsorbent dosage, improving adsorption effectiveness. However, an increase beyond a certain point also results in the aggregation of nanoparticles and a reduction in the surface area and active sites, which diminishes the adsorption capacity (Singh *et al.* 2021). The chemical composition of nanoparticles also affects adsorption, influencing their surface characteristics and nature. The adsorption capacity increased with nanoparticles (Naseer, 2024).

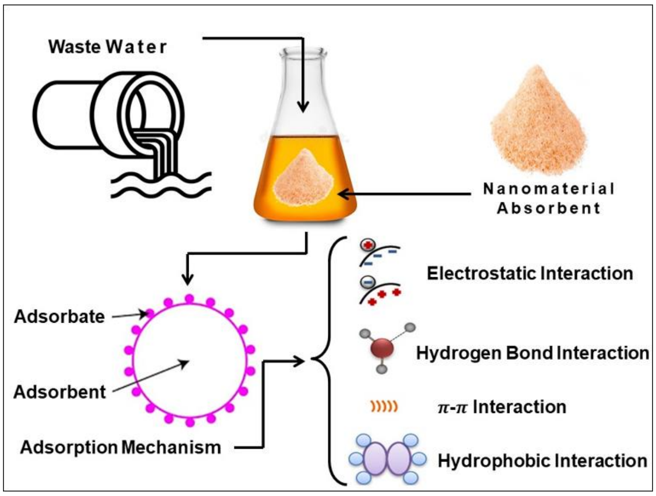

Fig. 4. Adsorption mechanism of nanomaterial adsorbents.

Another crucial factor that significantly influences the sorption capacity of wastewater is the pH (wang *et al.* 2005). Variations in pH affect the degree of ionization, speciation of pollutants, and charge on the adsorbent surface. Furthermore, a change in pH disrupts the adsorption process by dissolving the functional groups on the active sites of the adsorbent surface. Consequently, the equilibrium and kinetics of the adsorption process are altered (Ahmed *et al.*, 2020). Fan *et al.* (2022) studied the effect of pH on the uptake of melanoidin and observed that PMPC has a better adsorption efficiency for melanoidin in the pH range of 5–9.

The result is explained by the electrostatic interaction between the negatively charged melanoidin and the very positively charged PMPC. Interestingly, beyond the pH of PMPC, the surface charge of the adsorbent reverses to a negative charge, leading to decreased adsorption owing to the electrostatic repulsion between the similarly charged species.

In addition, factors such as contact time, mass transfer resistance, initial/final concentrations, and concentration steps can influence adsorption kinetics (Raji *et al.*, 2023). Longer adsorption times result in increased chemical conversion and faster adsorption (Mariana *et al.*, 2021). Saturation and aggregation also impede solute transportation and negatively impact the mass transfer resistance (Dou *et al.*, 2022). High solute concentration steps are unfavorable because they lead to the saturation of nanoparticle sites, hindering solute removal (Rapo and Tank, 2021). (Rafigh and Rahimpour Soleymani 2019) investigated the effect of the initial solute concentration of the melanoidin solution from 600 mg-1 to 1300 mg-1.

It was observed that as melanoidin concentrations increased up to 18.02 g−1, the GONs adsorption capability of GONs increased dramatically before declining substantially. This trend is explained by the rapid initial adsorption on the available sites, followed by saturation of the surface. Temperature is a significant variable that affects the adsorption capacity. This process is endothermic when the adsorption capacity increases with temperature. The decline in the adsorption capacity with increasing temperature implies that adsorption is an exothermic process (Budnyak *et al.*, 2020). Li *et al.* (2020) discussed the effect of temperature on RP-Si-CA adsorbents. The findings indicated that an increase in temperature increased the adsorption capacity of melanoidin, implying that the process was endothermic.

3.4. Removal efficiency of nanomaterial adsorbent in context of distillery wastewater

Ayub *et al.* (2014) reported the effective performance of activated carbon as an adsorbent. During 24 h of process time and at an optimum dosage of 10g/200 ml, the removal of COD, TDS, and DO at the levels of 93.33, 70.6, and 84.8 %, respectively, was observed. Sobande *et al.* (2024) studied the effect of orange peel carbon on melanoidin treatment using batch adsorption. They achieved 60.20 % removal at optimum conditions of 4 pH,2.5g/100ml adsorbent dosage, and one h retention time. Reyes *et al.* (2017) studied melanoidin removal through batch experiments using different forms of carbon, and found that carbon multi-walled nanotubes achieved the highest removal adsorption capacity of 5.3 mg/g. Wang *et al.* (2024) examined the performance of polyethylene glycol cross-linked modified chitosan/halloysite nanotube composite aerogel microspheres (PCAM@HNTs) for melanoidin degradation, and the removal rate was 98.53% at pH 7, 303K and 0.4mg/ml adsorbent dose. Kiran *et al.* (2015) investigated the treatment of distillery spent wash using mixed matrix membranes (MMMs) incorporating graphene oxide (GO) flakes into polyethersulfone (PES). Maximum color removal of 54% was achieved for the distillery spent wash effluent. Srivastava *et al.* (2021) examined the zero-valent iron nanoparticle treatment efficiency of distillery wastewater, which was synthesized and characterized as a green approach. They recorded maximum reductions in color, COD, BOD, and TSS were 99.07%, 84.25%, 89.23%, and 86.5%, respectively. Kazemi *et al.* (2015) investigated the catalytic efficiency of CuO and MnO in the treatment of distillery wastewater in a tubular reactor under hydrothermal conditions. They found the COD removal efficiencies of CuO and MnO_2 were 74.4% and 75.1%, respectively. They also achieved 98.2% color removal using MnO_2 at 400°C. Otieno *et al.* (2017) investigated the photo-decolorization of vinnase melanoidin using a composite nanomaterial adsorbent comprising zinc oxide (ZnO) immobilized on titanium dioxide supported by activated carbon (TiO_2-ZnO/AC) in a batch reactor. The study revealed that the hybrid material (TiO_2-ZnO/AC) achieved up to 86% decolorization. Wang *et al.*2022 studied the removal of melanoidin from sugarcane juice using a bagasse-based biochar composite with hydroxyapatite and obtained an excellent adsorption capacity of 313.33 mg/g. Navgire *et al.* (2012) have reported 70% of color removal from molasses solution using nanocrystalline composite material MoO_3-TiO_2 by photodegradation within 120 min time duration. Donyagard *et al.* (2017) examined melanoidin removal using a magnetic carbon nanocomposite as an adsorbent. They reported 90% removal in simulated aqueous solution and 80.76% in real wastewater at a concentration of 40 ppm. Onyango *et al.* (2011) investigated the sorption of melanoidin on surfactant-modified zeolites and reported an adsorption capacity of 1157.0 mg/g at a temperature of 45 °C. Tang *et al.* (2023), fabricated a hyperbranched polyethyleneimine-functionalized chitosan aerogel (HPCA) for melanoidin removal. HPCA demonstrated an efficient adsorption capacity of 868.36 mg/g.

4. Comparative analysis: Sindh v/s Global practices

Effluents from the distillery industry pose health risks owing to the lack of appropriate waste-treatment facilities. In recent years, the problem of pollution has highlighted the need for urgent research. Environmental literature on Pakistani distillery wastewater is scarce; therefore, research on foreign distillery industries should consider the proposed solutions. Some mills pretreat wastewater, but do not meet the required discharge standards. Other sectors use additional methods, such as aerated lagoons, to improve effluent quality for agricultural use. However, countries such as India, Thailand, Brazil, and South Africa have similar situations regarding distillery wastewater disposal. The governments of these nations have implemented strategic policies and have executed comprehensive industrial solutions to handle comparable challenges. Table 5 summarizes the comparative analyses.

5. Future research directions in nanomaterials for wastewater treatment in Sindh, Pakistan

A review of critical research gaps and opportunities for nanomaterial-based wastewater treatment in Pakistan to address resource-constrained and environmental degradation problems. Four key research priorities have emerged:

Table 5. Comparative analysis between Sindh and global practices for distillery wastewater remediation.

Aspect	Sindh (Pakistan)	Global practices
Primary treatment	- TSS is removed by sedimentation 30–50% (Khan *et al.*, 2003).	- Automated systems have TSS (70–90%) removal (EPA, 2020).
	- There is no automssation and neutralization (lime/alum) adjust the pH.	- Dosing with real time suggests a consistent pH control.
Anaerobic treatment	- 40–60% removal of COD: 1–2 hectares required per 1,000 m^3 (Rasool *et al.*, 2023).	- 80–90% removal of COD: less than 0.1 hectares required per 1000 m3 (Fito *et al.*, 2018).
	- Biogas yield in the region of 0.1–0.2 m^3/m^3 wastewater	- Biogas yield of 0.3–0.5 m^3/m^3 (with energy recovery).
Biological treatment	- 60–75% of COD removal: wastewater native microbial communities. (Ali *et al.*, 2024).	- 85–95% of COD removal: Engineered strains + hybrid systems (Ravikumar *et al.*, 2021).
		- 71.83% color removal (Chowdhary *et al.*,2020)
Constructed wetlands	- 70% of COD removal: Pilot studies (Rehman *et al.*, 2024).	- 85–95% of COD removal: Large-scale systems (Zurita & Vymazal, 2023).
	-Lack of Policy support and underutilization	- Cost-effective and localized method for distributed treatment.
Physico-chemical	- 85% of COD & 91% color removal: Electrocoagulation (Khokar *et al.*, 2023).	- > 90% of COD and color removal: Advanced oxidation (Khandegar & Saroh, 2014).
	- Expansive operational method (\$0.5–1/m^3).	-Economical operational method (\$0.3–0.8/m^3)
Membrane tech.	- Small scale biogas plants: < 50% COD with >\$200,000 capital expanses (Parveen & Khan, 2023).	- Industrial scale MBR/RO systems: 90–95% COD removal with 80% water recovery (Gupta *et al.*, 2008).
Energy recovery	- less than 10% energy recovery: Biogas rarely encapsulated (Jatoi *et al.*, 2018).	- More than 50% energy recovery: CHP systems with 0.45 to 0.55 m^3/Kg of Biogas production. (Wagh & Nemade, 2018).
Sludge management	- 30–50% dumped without treatment (Kaloi *et al.*, 2017).	- 90% waste is treated using pyrolysis and gasification methods (Dhote *et al.*, 2022).
Water reuse	- Less than 20% reused: majority being discharged as untreated (Noor *et al.*, 2023).	- 50–70% reused: mostly for irrigation or industrial use (Kharraz *et al.*, 2022).
Pollutant removal	- COD effluent range: 300 to 500 mg/L (250 mg/L set by the U.S. Environmental Protection Agency).(Nergis *et al.*, 2012)	- COD effluent range: <50 mg/L (Using Integrated MBR+RO systems) (Dialynas Diamadopoulos,2009)

5.1. Development of multifunctional nanocomposites and membranes

Engineered nanocomposites (e.g., TiO_2/graphene oxide hybrids or MOFs/polymer hybrids) in which adsorption and degradation by catalysis and membrane filtration effect are synergized remain to be investigated in future work. By utilizing such materials, dyes, heavy metals, etc. can be removed effectively (>90%) with regeneratability and reduced fouling. To enable industrial adoption, it must be scalable and analyzable by lifecycle.

5.2. Utilization of agricultural waste for sustainable nanomaterials

The sustainable feedstock used for low-cost nanocatalysts and biochar includes agricultural residues (e.g., rice husk silica and date palm–activated carbon). The protocol for pyrolysis/functionalization should be optimized based on research to enhance the pollutant affinity (e.g., Cr (VI)) and ecotoxicity of the byproducts. Recycling garbage sources aligns with SDG 12 (Responsible Consumption).

5.3. Solar-activated photocatalysis for decentralized systems

In Sindh, where the solar irradiation is approximately 2200 kWh/m^2/yr, photocatalytic nanomaterials (such as ZnO/SnS_2 heterojunctions) can generate water in an off-grid treatment regime with a sustainable load. Quantum efficiency under natural sunlight remains a critical challenge, and photocorrosion issues need to be resolved. Long-term performance in rural settings with high organic loads must be evaluated in pilot studies.

5.4. Integration of smart nano-sensors for real-time monitoring

Coupling Au/Ag or fluorescent nanoparticles into IOT-enabled sensors for monitoring COD, heavy metals, and pathogens could revolutionize integrated monitoring. Underfunded municipal facilities require low-cost production (e.g., paper-based tests) and choose research in difficult matrices to use these technologies.

Future research will need to resolve the databases of realistic risk assessments of the mechanisms of interaction of real-world nano-pollutants with environmental pollutants. Furthermore, international collaboration and interdisciplinary work in environmental science, chemical engineering, and materials chemistry are necessary for the development of scalable and cost-effective treatment technologies. This will enable Universities, Industries, and Governmental agencies to accelerate the deployment of these sustainable solutions in Pakistan through Pilot Programs and Funding Initiatives.

6. Potential socio-economic benefits of adopting nanomaterial-based treatment methods in Sindh, Pakistan

The integration of advanced materials in wastewater treatment offers significant cost advantages by effectively reducing contaminants to negligible levels in the initial applications. Because of their improved activity, selectivity, and reusability, the use of small amounts of these materials results in significant cost savings and low spatial requirements, making their wider adoption possible. These technologies provide affordable treatment options; ensure public safety; and provide jobs in the manufacturing, installation, and system operation industries. Enhanced wastewater treatment improves public health by reducing the occurrence of waterborne infections and improving the water quality. The application of advanced materials such as nanomaterials for efficient contaminant removal or transformation extends the socioeconomic benefits of water reuse and agricultural productivity. Over 6,000 full-time jobs can be created by treating and disposing of 10% of used agricultural water, demonstrating the substantial employment contribution of the water sector. Productivity gains, regardless of how little, can boost job prospects, particularly for low-income groups. Because cleaner water resources support jobs in a range of industries, including agriculture, fishing, and water and sanitation services, their economic value has increased. For every 1% increase in population access to improved water supply, agricultural productivity might increase by 0.7%. Social and economic structures are affected by geopolitical and economic interconnections driven by modern global dynamics.

7. Conclusions

Enhancing distillery wastewater treatment procedures using nanoparticles has become a viable way to address the intricate problems of resource management and water contamination. The primary benefits of nanomaterials are highlighted in this review, including their ability to increase the pollutant removal efficiency through adsorption. In addition, nanomaterials contribute to resource recovery and environmental sustainability, offering opportunities for their incorporation into broader water-management strategies. However, successful adoption of these technologies requires a balanced approach that considers environmental, economic, and regulatory factors. Increasing scientific understanding, encouraging teamwork, and supporting creative research will be essential for achieving the full potential of nanomaterials in distillery wastewater treatment and for assisting sustainable water management techniques for future generations.

Author Contributions

Mehwish Qaseem: Contributed to structuring the manuscript outline, conceptualizing the research theme, conducting an extensive literature review, and preparing the original draft.
Yasir Khan: Provided constant guidance during the study and reviewed the final manuscript.
M. Waseem Akhter: Worked with the comparative analysis of local versus global treatment methodologies and evaluated their performance.
Syed Zeeshan Abbas: Ensured journal-compliant formatting and offered insights into the importance of the topic in environmental policies.
Mehwish Altaf: Performed a literature review on the features of distillery wastewater and collected pertinent data from Sindh, Pakistan.
Shakeel Ahmed: Focusing on the nanomaterial adsorbents section, their properties, and mechanisms of adsorption in wastewater treatment.
Muhammad Saquib Ali: Supported the manuscript with linguistic consistency and citation management.

Conflict of Interest

There are no conflicts to disclose.

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Data Availability Statement

The data for this study are available within the article and can be obtained from the corresponding author upon request.

References

Aditya Kiran, S. *et al.* (2015) ‘Impact of graphene oxide embedded polyethersulfone membranes for the effective treatment of distillery effluent’, *Chemical Engineering Journal*, 286, pp. 528–537. doi: https://doi.org/10.1016/j.cej.2015.10.091

Afzal, M.S. *et al.* (2018) ‘Characterization of industrial effluents and groundwater of Hattar industrial estate, Haripur’, *Advances Agricultural Environment Sciences*, 1(2), pp. 70−77. doi: http://doi.org/10.30881/aaeoa.00013

Agboola, O.D. and Benson, N.U. (2021) ‘Physisorption and chemisorption mechanisms influencing micro (nano) plastics-organic chemical contaminants interactions’: a review, *Frontiers in Environmental Science*, 9, pp. 1-27. doi: https://doi.org/10.3389/fenvs.2021.678574

Ahmad, W. *et al.* (2020) ‘Utilization of tires waste-derived magnetic-activated carbon for the removal of hexavalent chromium from wastewater’, *Materials*, 14(1), pp. 34. doi: https://doi.org/10.3390/ma14010034

Ahmed, S. *et al.* (2020) ‘Experimental study and dynamic simulation of melanoidin adsorption from distillery effluent’, *Environmental Science and Pollution Research*, 27(9), pp. 9619–9636. doi: https://doi.org/10.1007/s11356-019-07441-8

Akash, M.S.H. and Rehman, K. (2019) ‘Ultraviolet-visible (Uv-vis) spectroscopy’, *Essentials of Pharmaceutical Analysis*, pp. 29–56. doi: https://doi.org/10.1007/978-981-15-1547-7_3

Akhtar, M. *et al.* (2024) ‘Use of Low-Cost adsorbent for Waste Water Treatment: Recent progress, new trend and future perspectives’, *Desalination and Water Treatment*, pp. 100914. doi: https://doi.org/10.1016/j.dwt.2024.100914

Akhtar, M.S. *et al.* (2024) ‘Innovative adsorbents for pollutant removal: exploring the latest research and applications’, *Molecules*, 29(18), p. 4317. doi: https://doi.org/10.3390/molecules29184317

Alaqarbeh, M. (2021) ‘Adsorption phenomena: definition, mechanisms, and adsorption types: Short review’, *RHAZES: Green and Applied Chemistry*,13, pp. 43–51. doi: https://doi.org/10.48419/IMIST.PRSM/rhazes-v13.28283

Alayan, H.M. *et al.* (2018) ‘The formation of hybrid carbon nanomaterial by chemical vapor deposition: an efficient adsorbent for enhanced removal of methylene blue from aqueous solution’, *Water Science and Technology*, 77(6), pp. 1714–1723. doi: https://doi.org/10.2166/wst.2018.057

Ali, Y., Pervez, H. and Khan, J. (2020) ‘Selection of the most feasible wastewater treatment technology in pakistan using multi-criteria decision-making (MCDM)’, *Water Conservation Science and Engineering*, 5(3-4), pp. 199–213. doi: https://doi.org/10.1007/s41101-020-00094-6

Ali, Z., Qambrani N.A., and Mahar, R.B. (2024) ‘Advanced blast algorithm for molecular identification, biodegradation and decolorization of synthetic melanoidins using fungal species isolated from soil and spent wash’, *International Journal of Innovations in Science and Technology*, 6(2), pp. 945–960. Available at: https://journal.50sea.com/index.php/IJIST/article/view/881

Almadani, M. (2023) ‘Adsorption process modeling to reduce COD by activated carbon for wastewater treatment’. Chemosphere, 339, p. 139691. doi: https://doi.org/10.1016/j.chemosphere.2023.139691

Amusat, S.O. *et al.* (2021) ‘Ball-milling synthesis of biochar and biochar–based nanocomposites and prospects for removal of emerging contaminants: A review’, *Journal of Water Process Engineering*, 41, pp. 101993. doi: https://doi.org/10.1016/j.jwpe.2021.101993

Anh, L. et al. (2014) ‘Utilization of turbidity as an indicator for biochemical and chemical oxygen demand’, *Journal of Water Process Engineering*, 4, pp. 137–142. doi: https://doi.org/10.1016/j.jwpe.2014.09.009

Anjum, M. *et al.* (2019) ‘Remediation of wastewater using various nano-materials’, *Arabian Journal of Chemistry*, 12(8), pp. 4897–4919. doi: https://doi.org/10.1016/j.arabjc.2016.10.004

Apollo, S. *et al.* (2019) ‘Influence of zeolite support on integrated biodegradation and photodegradation of molasses wastewater for organic load reduction and colour removal’, *Microorganisms for sustainability*, pp. 287–300. doi: https://doi.org/10.1007/978-981-32-9664-0_12

Arimi, M.M. *et al.* (2015) ‘Color removal of melanoidin-rich industrial effluent by natural manganese oxides’, *Separation and Purification Technology*, 150, pp. 286–291. doi: https://doi.org/10.1016/j.seppur.2015.07.013

Shedayi, A.A., *et al.* (2016) ‘Physico-chemical and bacteriological analysis of drinking water quality of Nomal, Gilgit-Baltistan, Pakistan’, Journal of Biodiversity and Environmental Sciences, 7(2), pp. 81–87. Available at: https://www.researchgate.net/publication/280851555_Physico-chemical_and_bacteriological_analysis_of_drinking_water_quality_of_Nomal_Gilgit-Baltistan_Pakistan (Accessed date: 7 January 2025).

Arshad, M. *et al.* (2019) ‘Ethanol production from molasses: Environmental and socioeconomic prospects in Pakistan: feasibility and economic analysis’, *Environmental Technology & Innovation*, 14, pp. 100317. doi: https://doi.org/10.1016/j.eti.2019.100317

Asghar, N. *et al.* (2024) ‘Advancement in nanomaterials for environmental pollutants remediation: a systematic review on bibliometrics analysis, material types, synthesis pathways, and related mechanisms’, *Journal of Nanobiotechnology*, 22(1), pp. doi: https://doi.org/10.1186/s12951-023-02151-3

Ashraf, H. *et al.* (2024) ‘A $CoFe_2O_4$/Nb2C-MXene-modified anode improved the performance characteristics of a microbial fuel cell in terms of bioelectricity generation and water treatment’, *Catalysts*, 14(12), pp. 862. doi: https://doi.org/10.3390/catal14120862

Avoyan, A. *et al.* (2000) ‘Fabrication and characterization of the Ag-based high-technology model nanocluster catalyst for ethylene epoxidation manufactured by electron beam lithography’, *Topics in Catalysis*, 10, pp. 107–113. doi: https://doi.org/10.1023/a:1019116117973

Awan, A.N. *et al.* (2012) ‘Industrial Waste Water Management in District Gujranwala of Pakistan- current status and future suggestions’, *Pakistan Journal of Agricultural Research*, 49(1), pp.79–85. Available at: https://api.pakjas.com.pk/downloadPaper/1980.pdf (Accessed date: 7 January 2025).

Badran, A.M. *et al.* (2023) ‘Advancements in adsorption techniques for sustainable water purification: a focus on lead removal’, *Separations*, 10(11), p. 565. doi: https://doi.org/10.3390/separations10110565

Bano, I. and Arshad, M. (2017) 'Impact of Biofuel’s Production on Ground Water', in Arshad, M. (ed.) *Perspectives on Water Usage for Biofuels Production*. Cham: Springer.

Bashir, M.A. (2021) ‘Use of dynamic mechanical analysis (DMA) for characterizing interfacial interactions in filled polymers’, *Solids*, 2(1), pp. 108–120. doi: https://doi.org/10.3390/solids2010006

Berg, C. (2004) ‘World fuel ethanol – analysis and outlook’, Sugar Trading Manual, pp. 1-32. doi: https://doi.org/10.1016/b978-1-85573-457-9.50012-3

Bhardwaj, S. *et al.* (2019) ‘Distillery spent wash (DSW) treatment methodologies and challenges with special reference to incineration: An overview’, *Environment Conservation Journal*, 20(3), pp. 135–144. doi: https://doi.org/10.36953/ecj.2019.20318

Bhavsar, N.D. *et al.* (2021) 'Nanomaterials for treatment of air pollutants', in *Handbook of nanomaterials for wastewater treatment*, pp. 313-339. doi: https://doi.org/10.1016/B978-0-12-821496-1.00023-4

Brown, M.E. (2004) 'Reaction kinetics from thermal analysis', in *Introduction to thermal analysis*. Springer, Dordrecht, pp. 181-214. doi: https://doi.org/10.1007/0-306-48404-8_10

Brunauer, S., Emmett, P.H. and Teller, E. (1938) ‘Adsorption of gases in multimolecular layers’, *Journal of the American Chemical Society*, 60, pp. 309-319. doi: http://dx.doi.org/10.1021/ja01269a023

Budnyak T.M. *et al.* (2020) ‘Chitosan deposited onto fumed silica surface as sustainable hybrid biosorbent for acid orange 8 dye capture: effect of temperature in adsorption equilibrium and kinetics’, *Journal of Physical Chemistry*,124(28) pp: 15312–15323. doi: https://doi.org/10.1021/acs.jpcc.0c04205

Cerri, B.C. *et al.* (2020) ‘Evaluation of new environmental friendly particulate soil fertilizers based on agroindustry wastes biopolymers and sugarcane vinasse’, *Waste Management*, 108, pp. 144–153. doi: https://doi.org/10.1016/j.wasman.2020.04.038

Chandra, R. *et al.* (2008) ‘Melanoidins as major colourant in sugarcane molasses-based distillery effluent and its degradation’, Bioresource Technology, 99(11), pp. 4648–4660. doi: https://doi.org/10.1016/j.biortech.2007.09.057

Chaudhari, P.K. *et al.* (2007) ‘Decolourization and removal of chemical oxygen demand (COD) with energy recovery: Treatment of biodigester effluent of a molasses-based alcohol distillery using inorganic coagulants’, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 296(1-3), pp. 238–247. doi: https://doi.org/10.1016/j.colsurfa.2006.10.005

Chella, S. *et al.* (2015) ‘Solvothermal synthesis of MnFe2O4-graphene composite—Investigation of its adsorption and antimicrobial properties’, Applied Surface Science, 327, pp. 27-36. doi: https://doi.org/10.1016/j.apsusc.2014.11.096

Chowdhary, P. *et al.* (2017) ‘Distillery wastewater: a major source of environmental pollution and its biological treatment for environmental safety’, *Green Technologies and Environmental Sustainability*, pp. 409–435. doi: https://doi.org/10.1007/978-3-319-50654-8_18

Chowdhary, P. *et al.* (2020) ‘Bacterial degradation of distillery wastewater pollutants and their metabolites characterization and its toxicity evaluation by using Caenorhabditis elegans as terrestrial test models’, *Chemosphere*, 261, p. 127689. doi: https://doi.org/10.1016/j.chemosphere.2020.127689

Chowdhary, P. *et al.* (2018) ‘Environmental pollution and health hazards from distillery wastewater and treatment approaches to combat the environmental threats: A review’. *Chemosphere*, 194, pp. 229–246. doi: https://doi.org/10.1016/j.chemosphere.2017.11.163

Clogston, J.D., and Patri, A.K. (2010) ‘Zeta potential measurement’, *Methods in Molecular Biology*, 697, pp. 63–70. doi: https://doi.org/10.1007/978-1-60327-198-1_6

Collivignarelli, M.C. *et al.* (2019) ‘Treatments for color removal from wastewater: State of the art’, *Journal of Environmental Management*, 236, pp. 727–745. doi: https://doi.org/10.1016/j.jenvman.2018.11.094

Cullity, B. and Stock, S. (2014) *Elements of X-ray diffraction*. 3rd edn. Harlow: Pearson. Available at: https://www.pearson.com/en-gb/subject-catalog/p/elements-of-x-ray-diffraction-pearson-new-international-edition/P200000004006/9781292040547 (Accessed date: 4 April 2025).

Dao, T. *et al.* (2011) ‘Control of food spoilage fungi by ethanol’, *Food Control*, 22(3-4), pp. 360–368. doi: https://doi.org/10.1016/j.foodcont.2010.09.019

De Gisi, S. *et al.* (2016) ‘Characteristics and adsorption capacities of low-cost sorbents for wastewater treatment: A review’, *Sustainable Materials and Technologies*, 9, pp. 10–40. doi: https://doi.org/10.1016/j.susmat.2016.06.002

Dhila, H.H. *et al.* (2025) ‘Metal oxide/biochar hybrid nanocomposites for adsorption and photocatalytic degradation of textile dye effluents: a review’, *Desalination and Water Treatment*, pp. 101004–101004. doi: https://doi.org/10.1016/j.dwt.2025.101004

Dhote, L. *et al.* (2022) ‘Evaluation of pyrolysis and gasification of distillery sludge and bio-compost mixed with coal’, *Fuel*, 319, p. 123750. doi: https://doi.org/10.1016/j.fuel.2022.123750

Dialynas, E. and Diamadopoulos, E. (2009) ‘Integration of a membrane bioreactor coupled with reverse osmosis for advanced treatment of municipal wastewater’, *Desalination*, 238(1-3), pp. 302–311. doi: https://doi.org/10.1016/j.desal.2008.01.046

Díaz, E. *et al.* (2024) ‘Adsorption of stable and labile emerging pollutants on activated carbon: degradation and mass transfer kinetic study’, *Applied Water Science*, 14(4), pp. 1-12 doi: https://doi.org/10.1007/s13201-023-02087-x

Dou, Z. *et al.* (2022) ‘Saturation dependence of mass transfer for solute transport through residual unsaturated porous media’, *International Journal of Heat and Mass Transfer*,188(7), p. 122595. doi: https://doi.org/10.1016/j.ijheatmasstransfer.2022.122595

Du, Q. *et al.* (2014) ‘Highly enhanced adsorption of congo red onto graphene oxide/chitosan fibers by wet-chemical etching off silica nanoparticles’, *Chemical Engineering Journal*, 245, pp. 99–106. doi: https://doi.org/10.1016/j.cej.2014.02.006

El-Dib, F.I. *et al.* (2016) ‘Remediation of distilleries wastewater using chitosan immobilized Bentonite and Bentonite based organoclays’, *International Journal of Biological Macromolecules*, 86, pp. 750-755. doi: https://doi.org/10.1016/j.ijbiomac.2016.01.108

Fan, B.H. *et al.* (2022) ‘Effective melanoidin adsorption of polyethyleneimine- functionalised molasses-based porous carbon: Adsorption beha viours and microscopic mechanisms’, *Separation and Purification Technology*, 310, p. 123016. doi: https://doi.org/10.1016/j.seppur.2022.123016

Donyagard, F. *et al.* (2017) ‘Application of magnetic carbon nanocomposites to remove melanoidin from aqueous media: kinetic and isotherm studies’, *Research on Chemical Intermediates*, 43(8), pp. 4639–4655. doi: https://doi.org/10.1007/s11164-017-2902-y

Ferrari, A.C. and Basko, D.M. (2013) ‘Raman spectroscopy as a versatile tool for studying the properties of graphene’, *Nature Nanotechnology*, 8(4), pp. 235–246. doi: https://doi.org/10.1038/nnano.2013.46

Fito, J. *et al.* (2018) ‘Anaerobic treatment of blended sugar industry and ethanol distillery wastewater through biphasic high rate reactor’, *Journal of Environmental Science and Health*, Part A, 53(7), pp. 676–685. doi: https://doi.org/10.1080/10934529.2018.1438826

FitzGibbon, F. *et al.* (1998) ‘The effect of phenolic acids and molasses spent wash concentration on distillery wastewater remediation by fungi’, *Process Biochemistry*, 33(8), pp. 799–803. Available at: https://pure.ulster.ac.uk/en/publications/the-effect-of-phenolic-acids-and-molasses-spent-wash-concentratio-3 (Accessed date: 3 April 2025).

Fu, F. and Wang, Q. (2011) ‘Removal of heavy metal ions from wastewaters: A review’, *Journal of Environmental Management*, 92(3), pp. 407–418. doi: https://doi.org/10.1016/j.jenvman.2010.11.011

Fuess, L.T., and Garcia, M.L. (2014) ‘Implications of stillage land disposal: A critical review on the impacts of fertigation’, *Journal of Environmental Management*, 145, pp. 210–229. doi: https://doi.org/10.1016/j.jenvman.2014.07.003

Goldstein, J.I., *et al.* (2003) 'Scanning electron microscopy and x-ray microanalysis'. 3rd edn, Boston, MA: Springer US. doi: https://doi.org/10.1007/978-1-4615-0215-9

Gonsioroski, A., Mourikes, V.E. and Flaws, J.A. (2020) 'Endocrine disruptors in water and their effects on the reproductive system', *International Journal of Molecular Sciences*, 21(6), p. 1929. doi: https://doi.org/10.3390/ijms21061929

Gonzalez-Valerio, C. *et al.* (2024) 'Color compounds removal from tequila vinasses using silica gel adsorbents functionalized with thiol moieties: equilibrium and kinetics studies', *Molecules*, 29(24), p. 5910. doi: https://doi.org/10.3390/molecules29245910

Gupta, R. *et al.* (2008) 'Submerged membrane bioreactor using fly ash filters: Trials with distillery wastewater', *Water Science and Technology*, 58(6), pp. 1281–1284. doi: https://doi.org/10.2166/wst.2008.352

Hanjra, M.A. *et al.* (2012) 'Wastewater irrigation and environmental health: Implications for water governance and public policy', *International Journal of Hygiene and Environmental Health*, 215(3), pp. 255–269. doi: https://doi.org/10.1016/j.ijheh.2011.10.003

Ijaz, I. *et al.* (2020) 'Detail review on chemical, physical and green synthesis, classification, characterizations and applications of nanoparticles', *Green Chemistry Letters and Reviews*, 13(3), pp. 223–245. doi: https://doi.org/10.1080/17518253.2020.1802517

Ikram, D.M., Bari, A. and Haider, J. (2023) 'Photocatalytic dye degradation using green polymer-based nanostructures'. Bristol: IOP Publishing. doi: https://doi.org/10.1088/978-0-7503-5517-9

James, J. (2017) 'Thermomechanical analysis and its applications', *Thermal and Rheological Measurement Techniques for Nanomaterials Characterization*, pp. 159–171. doi: https://doi.org/10.1016/b978-0-323-46139-9.00007-4

Jamshed, A. *et al.* (2023) 'A quick review on the applications of nanomaterials as adsorbents' *MOJ ecology & environmental sciences*, 8(3), pp. 86–89. doi: https://doi.org/10.15406/mojes.2023.08.00278

Jatoi, A.S. *et al.* (2018) 'Utilization of distillery effluent as substrate for power generation with optimized parametric conditions using microbial fuel cell', *Eurasian Journal of Analytical Chemistry*, 13(5), pp. 2-8. doi: https://doi.org/10.29333/ejac/94974

Jenkins, R. (1999) *X-Ray Fluorescence Spectrometry*. 2nd edn. New York: Wiley. doi: https://doi.org/10.1002/9781118521014

Kaloi, G.M. *et al.* (2017) 'Effect of sugar industry spentwash (diluted) on the characteristics of soil and sugarcane (Saccharum officinarum L.) growth in the subtropical environment of Sindh, Pakistan', *Environmental Monitoring and Assessment*, 189(3), pp. 127. doi: https://doi.org/10.1007/s10661-017-5861-2

Karimi, S. *et al.* (2019) 'A comprehensive review of the adsorption mechanisms and factors influencing the adsorption process from the perspective of bioethanol dehydration', *Renewable and Sustainable Energy Reviews*, 107, pp. 535–553. doi: https://doi.org/10.1016/j.rser.2019.03.025

Karnwal, A. and Malik, T. (2024) 'Nano-revolution in heavy metal removal: engineered nanomaterials for cleaner water', *Frontiers in Environmental Science*, 12, p. 1393694. doi: https://doi.org/10.3389/fenvs.2024.1393694

Kaushik, A. *et al.* (2018) 'Fractionation of sugarcane molasses distillery wastewater and evaluation of antioxidant and antimicrobial characteristics', *Industrial Crops and Products*, 118, pp. 73–80. doi: https://doi.org/10.1016/j.indcrop.2018.03.040

Kaushik, A., *et al.* (2005) 'Impact of long and short term irrigation of a sodic soil with distillery effluent in combination with bioamendments', *Bioresource Technology*, 96(17), pp. 1860–1866. doi: https://doi.org/10.1016/j.biortech.2005.01.031

Kazemi, N. *et al.* (2014) 'High-strength distillery wastewater treatment using catalytic sub- and supercritical water'. *The Journal of Supercritical Fluids*, 97, pp. 74–80. doi: https://doi.org/10.1016/j.supflu.2014.10.025

Khalid, S. *et al.* (2018) 'A review of environmental contamination and health risk assessment of wastewater use for crop irrigation with a focus on low and high-income countries', *International Journal of Environmental Research and Public Health*, 15(5), p. 895. doi: https://doi.org/10.3390/ijerph15050895

Khan, M. *et al.* (2003) 'Characterization and treatment of industrial effluent from sugar industry', *Journal of the Chemical Society of Pakistan*, 25(3), pp. 242-247. Available at: https://www.researchgate.net/publication/288739816 (Accessed: 4 April 2025).

Khan, M.A.H. *et al.* (2021) 'Investigation of biofuel as a potential renewable energy source', *Atmosphere,* 12(10), p. 1289. doi: https://doi.org/10.3390/atmos12101289

Khan, M.M. *et al.* (2022) 'Towards sustainable application of wastewater in agriculture: a review on reusability and risk assessment'. *Agronomy*, 12(6), p. 1397. doi: https://doi.org/10.3390/agronomy12061397

Khan, M.T. *et al.* (2019) 'Sugarcane biofuels and bioenergy production in Pakistan: current scenario, potential, and future avenues', *Sugarcane Biofuels,* pp. 175–202. doi: https://doi.org/10.1007/978-3-030-18597-8_9

Khan, M.A. (2007) *Biofuels trade and sustainable development: the case of Pakistan*. London: International Institute for Environment and Development. Available at: https://www.iied.org/g02286 (Accessed: 4 April 2025).

Khandegar, V. and Saroh, A.K. (2014) 'Treatment of distillery spentwash by electrocoagulation', *Journal of Clean Energy Technologies*, 2(3), pp. 244–247. doi: https://doi.org/10.7763/jocet.2014.v2.133

Kharayat, Y. (2012) 'Distillery wastewater: bioremediation approaches', *Journal of Integrative Environmental Sciences*, 9(2), pp. 69–91. doi: https://doi.org/10.1080/1943815x.2012.688056

Kharraz, J.A. *et al.* (2022) 'Membrane distillation bioreactor (MDBR) for wastewater treatment, water reuse, and resource recovery: A review', *Journal of Water Process Engineering*, 47, p. 102687. doi: https://doi.org/10.1016/j.jwpe.2022.102687

Khokhar, W.A. *et al.* (2023) 'Treatment of anaerobically digested distillery spent wash using electrocoagulation with al-ss-al electrode configuration', *Water, Air, & Soil Pollution,* 234(125), pp. 1-12. doi: https://doi.org/10.1007/s11270-023-06091-4

Koshy, O., Subramanian, L., and Thomas, S. (2017) 'Differential Scanning Calorimetry in Nanoscience and Nanotechnology', Elsevier eBooks, pp. 109–122. doi: https://doi.org/10.1016/b978-0-323-46139-9.00005-0

Kumar, H. (2014) 'Influence of wastewater pH on turbidity', *International Journal of Environmental Research and Development,* 4(2), pp. 105–114. Available at: https://www.ripublication.com/ijerd_spl/ijerdv4n2spl_02.pdf (Accessed date: 8 January 2025).

Kumar, P.S., Pavithra, K.G. and Naushad, Mu. (2019) 'Characterization techniques for nanomaterials', *Nanomaterials for Solar Cell Applications*, pp. 97–124. doi: https://doi.org/10.1016/b978-0-12-813337-8.00004-7

Kwok, D.Y. and Neumann, A.W. (1999) 'Contact angle measurement and contact angle interpretation', *Advances in Colloid and Interface Science*, 81, pp. 167-249. doi: http://dx.doi.org/10.1016/S0001-8686(98)00087-6

Lachenmeier, D.W. (2008) 'Safety evaluation of topical applications of ethanol on the skin and inside the oral cavity', *Journal of Occupational Medicine and Toxicology*, 3(1), p. 26. doi: https://doi.org/10.1186/1745-6673-3-26

Lako, A., and Çomo, E. (2024) 'Sustainable water management: an integrated approach to solving the problems of wastewater treatment', *Qubahan Academic Journal*, 4(1), pp. 91–100. doi: https://doi.org/10.58429/qaj.v4n1a267

Levitt, M.H. (2013) *Spin Dynamics: Basics of Nuclear Magnetic Resonance*. 2nd edn. Chichester: John Wiley & Sons. Available at: https://www.wiley.com/en-us/Spin+Dynamics%3A+Basics+of+Nuclear+Magnetic+Resonance%2C+2nd+Edition-p-9780470511176 (Accessed: 4 April 2025).

Li, K. *et al.* (2020) 'Metal oxide (ZnO and TiO_2) and Fe-based metal–organic-framework nanoparticles on 3d-printed fractal polymer surfaces for photocatalytic degradation of organic pollutants', *ACS Applied Nano Materials*, 3(3), pp. 2830–2845. doi: https://doi.org/10.1021/acsanm.0c00096

Li, W. *et al.* (2020) 'Rosin-based polymer@silica core–shell adsorbent: Preparation, characterization, and application to melanoidin adsorption', *LWT,* 132, pp. 109937–109937. doi: https://doi.org/10.1016/j.lwt.2020.109937

Liu, W. *et al.* (2014) 'Adsorption of Cu(II) and Cd(II) on titanate nanomaterials synthesized via hydrothermal method under different NaOH concentrations: Role of sodium content'. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 452, pp. 138–147. doi: https://doi.org/10.1016/j.colsurfa.2014.03.093

Luo, J. *et al.* (2021) 'Review of advances in engineering nanomaterial adsorbents for metal removal and recovery from water: synthesis and microstructure impacts', *ACS ES&T Engineering*, 1(4), pp. 623–661. doi: https://doi.org/10.1021/acsestengg.0c00174

Mahessar, A.A. *et al.* (2020) 'Impact of the effluents of Hyderabad city, Tando Muhammad Khan, and Matli on Phuleli Canal water', *Engineering, Technology & Applied Science Research*, 10(1), pp. 5281–5287. doi: https://doi.org/10.48084/etasr.3269

Mahmoudabadi, Z.S. *et al*. (2022) 'Optimizing treatment of alcohol vinasse using a combination of advanced oxidation with porous α-Fe_2O_3 nanoparticles and coagulation-flocculation', *Ecotoxicology and Environmental Safety*, 234, p. 113354. doi: https://doi.org/10.1016/j.ecoenv.2022.113354

Malik, S.N. *et al.* (2018) 'Ozone pretreatment of biomethanated distillery wastewater in a semi batch reactor: mapping pretreatment efficiency in terms of COD, color, toxicity and biohydrogen generation', *Biofuels*, 11(7), pp. 801–809. doi: https://doi.org/10.1080/17597269.2017.1416521

Mandal, A. *et al.* (2024) 'Research progress of persistent organic pollutants in water: classification, sources, potential risks, and treatment approaches', *Water Practice & Technology*, 19(3), pp. 937-959. doi: https://doi.org/10.2166/wpt.2024.031

Manikandan, S. *et al.* (2022) 'A critical review of advanced nanotechnology and hybrid membrane-based water recycling, reuse, and wastewater treatment processes, *Chemosphere*, 289, p. 132867. doi: https://doi.org/10.1016/j.chemosphere.2021.132867

Mansfield, E. (2015) 'Recent advances in thermal analysis of nanoparticles', in *Modelling, characterization, and production of nanomaterials*. Sawston: Woodhead Publishing, pp. 167-178. doi: https://doi.org/10.1016/b978-1-78242-228-0.00006-5

Mariana, M. *et al.* (2021) 'Development of biosorbent derived from the endocarp waste of gayo coffee for lead removal in liquid wastewater—effects of chemical activators', *Sustainability*, 13(6), p. 3050. doi: https://doi.org/10.3390/su13063050

Martí, E., Riera, J.L. and Sabater, F. (2009) 'Effects of wastewater treatment plants on stream nutrient dynamics under water scarcity conditions', *The Handbook of Environmental Chemistry*, pp. 173–195. doi: https://doi.org/10.1007/698_2009_33

Masjedi, A., *et al*. (2020) 'Magnetic nanoparticles surface-modified with tridentate ligands for removal of heavy metal ions from water', *Materials Chemistry and Physics*, 249, p. 122917. doi: https://doi.org/10.1016/j.matchemphys.2020.122917

Mehmood, C.T., *et al*. (2013) 'Combined biological and advanced oxidation treatment processes for cod and color removal of sewage water', *International Journal of Environmental Science and Development*, 4(2), pp. 88–93. doi: https://doi.org/10.7763/ijesd.2013.v4.311

Mikucka, W. and Zielińska, M. (2020) 'Distillery stillage: characteristics, treatment, and valorization', *Applied Biochemistry and Biotechnology*, 192(3), pp. 770–793. doi: https://doi.org/10.1007/s12010-020-03343-5

Mir, S. *et al.* (2020) 'Waste water treatment-bed of coal fly ash for dyes and pigments industry'. Available at: https://www.researchgate.net/publication/344979239_Waste_Water_Treatment-Bed_Of_Coal_Fly_Ash_For_Dyes_And_Pigments_Industry (Accessed: 4 April 2025).

Miranda, M.P. *et al.* (1996) 'Color elimination from molasses wastewater by Aspergillus niger', *Bioresource Technology*, 57(3), pp. 229-235. doi: https://doi.org/10.1016/s0960-8524(96)00048-x

Mohana, S., *et al*. (2009) 'Distillery spent wash: treatment technologies and potential applications', *Journal of Hazardous Materials*, 163(1), pp. 12–25. doi: https://doi.org/10.1016/j.jhazmat.2008.06.079

Momeni, M.M. *et al.* (2018) 'Using Chitosan/CHPATC as coagulant to remove color and turbidity of industrial wastewater: Optimization through RSM design', *Journal of Environmental Management*, 211, pp. 347–355. doi: https://doi.org/10.1016/j.jenvman.2018.01.031

Mubarik, S. *et al.* (2021) 'Synthetic approach to rice waste-derived carbon-based nanomaterials and their applications', *Nanomanufacturing*, 1(3), pp. 109–159. doi: https://doi.org/10.3390/nanomanufacturing1030010

Muller, C. *et al.* (2022) 'A review of the practical application of micro-aeration and oxygenation for hydrogen sulfide management in anaerobic digesters', *Process Safety and Environmental Protection*, 165, pp. 126–137. doi: https://doi.org/10.1016/j.psep.2022.07.009

Muzammil, S. *et al.* (2023) 'A review on toxicity of nanomaterials in agriculture: Current scenario and future prospects', *Science progress*, 106(4), pp. 1-19. doi: https://doi.org/10.1177/00368504231221672

Nadeem, N. *et al.* (2021) 'Coal fly ash-based copper ferrite nanocomposites as potential heterogeneous photocatalysts for wastewater remediation', *Applied Surface Science*, 565, p. 150542. doi: https://doi.org/10.1016/j.apsusc.2021.150542

Naseem, T. and Durrani, T. (2021) 'The role of some important metal oxide nanoparticles for wastewater and antibacterial applications: A review', *Environmental Chemistry and Ecotoxicology*, 3, pp. 59–75. doi: https://doi.org/10.1016/j.enceco.2020.12.001

Naseer, A. (2024) 'Role of nanocomposites and nano adsorbents for heavy metals removal and dyes. An overview', *Desalination and Water Treatment*, 320, pp: 100662. https://doi.org/10.1016/j.dwt.2024.100662

Nataraj, S.K. *et al.* (2006) 'Distillery wastewater treatment by the membrane-based nanofiltration and reverse osmosis processes', *Water Research*, 40(12), pp. 2349–2356. doi: https://doi.org/10.1016/j.watres.2006.04.022

Navgire, M. *et al.* (2012) 'Photodegradation of molasses by a MoO_3-TiO_2 nanocrystalline composite material', *Chinese Journal of Catalysis*, 33(2-3), pp. 261–266. doi: https://doi.org/10.1016/S1872-2067(10)60298-7

Nergis, Y. *et al.* (2012) 'Impact of industrial and sewage effluents on karachi coastal water and sediment quality', *Middle-East Journal of Scientific Research*, 11(10), pp. 1443–1454. doi: https://doi.org/10.5829/idosi.mejsr.2012.11.10.63209

Noor, R. *et al.* (2023) 'A comprehensive review on water pollution, South Asia Region: Pakistan', *Urban Climate*, 48, p. 101413. doi: https://doi.org/10.1016/j.uclim.2023.101413

Nunes, L. *et al.* (2015) 'Melanoidin removal mechanism in an aqueous adsorption system', *Physical Chemistry: An Indian Journal*, 7(1), pp. 99-107. Available at: https://www.ingentaconnect.com/content/ben/pfna/2015/00000007/00000001/art00009 (Accessed: 11 April 2025).

Nure, J.F. *et al.* (2017) 'COD and colour removal from molasses spent wash using activated carbon produced from bagasse fly ash of Matahara sugar factory, Oromiya region, Ethiopia', *Water SA*, 43(3), pp. 470-479. doi: https://doi.org/10.4314/wsa.v43i3.12

Olawade, D.B. *et al.* (2024) 'Metal and metal oxide nanomaterials for heavy metal remediation: novel approaches for selective, regenerative, and scalable water treatment', *Frontiers in Nanotechnology*, 6, 1466196. doi: https://doi.org/10.3389/fnano.2024.1466196

Onyango, M. *et al.* (2011) 'Sorption of melanoidin onto surfactant modified zeolite', *Chemical Industry and Chemical Engineering Quarterly*, 17(4), pp. 385–395. doi: https://doi.org/10.2298/ciceq1101250250

Otieno, B.O. *et al.* (2017) 'Photodecolorization of melanoidins in vinasse with illuminated TiO2-ZnO/activated carbon composite' *Journal of Environmental Science and Health*, *Part A*, 52(7), pp. 616–623. doi: https://doi.org/10.1080/10934529.2017.1294963

Panhwar, S. *et al.* (2019) 'Methane production by anaerobic digestion of spent wash in continuous stirred tank reactor', *Mehran University Research Journal of Engineering and Technology*, 38(3), pp. 791–798. doi: https://doi.org/10.22581/muet1982.1903.21

Pant, D. and Adholeya, A. (2007) 'Biological approaches for treatment of distillery wastewater: A review', *Bioresource Technology*, 98(12), pp. 2321–2334. doi: https://doi.org/10.1016/j.biortech.2006.09.027

Parveen, F. and Sher Jamal Khan (2023) 'Wastewater treatment in Pakistan: issues, challenges and solutions', *Global Issues in Water Policy*, 30, pp. 323–349. doi: https://doi.org/10.1007/978-3-031-36131-9_12

Pathak, C. *et al.* (2014) 'Bioaccumulation of heavy metals in Spinacea oleracea grown in distillery effluent irrigated soil', *Journal of Applied and Natural Science*, 6(2), pp. 797–803. doi: https://doi.org/10.31018/jans.v6i2.539

Patricio, E., López, J. and Thirumuruganandham, S.P. (2023) 'Experimental studies on TiO_2 NT with metal dopants through co-precipitation, sol-gel, hydrothermal scheme and corresponding computational molecular evaluations', *Materials*, 16(8), p. 3076. doi: https://doi.org/10.3390/ma16083076

Pellenz, L. *et al.* (2023) 'A comprehensive guide for characterization of adsorbent materials', *Separation and Purification Technology*, 305, p. 122435. doi: https://doi.org/10.1016/j.seppur.2022.122435

Qureshi, A.L. *et al.* (2015) 'Impact of releasing wastewater of sugar industries into drainage system of LBOD, Sindh, Pakistan', *International Journal of Environmental Science and Development*, 6(5), pp. 381–386. doi: https://doi.org/10.7763/ijesd.2015.v6.622

Hari Krishna, R. *et al.* (2023) 'Carbon nanotubes and graphene-based materials for adsorptive removal of metal ions – A review on surface functionalization and related adsorption mechanism', *Applied Surface Science Advances*, 16, pp. 100431–100431. doi: https://doi.org/10.1016/j.apsadv.2023.100431

Rafatullah, M. *et al.* (2010) 'Adsorption of methylene blue on low-cost adsorbents: a review', *Journal of Hazardous Materials*, 177(1-3), pp. 70–80. doi: https://doi.org/10.1016/j.jhazmat.2009.12.047

Rafigh S.M. and Rahimpour Soleymani A. (2019) 'Melanoidin removal from molasses wastewater using graphene oxide nanosheets', *Separation Science and Technology*, 55(13), pp. 2281–2293. doi: https://doi.org/10.1080/01496395.2019.1626424

Raji, Z. *et al.* (2023) 'Adsorption of heavy metals: mechanisms, kinetics, and applications of various adsorbents in wastewater remediation—a review', *Waste*, 1(3), pp. 775–805. doi: https://doi.org/10.3390/waste1030046

Rami, J.M. *et al.* (2021) 'Thermogravimetric analysis (TGA) of some synthesized metal oxide nanoparticles', *Materials Today: Proceedings,* 43(1), pp. 655-659. doi: https://doi.org/10.1016/j.matpr.2020.12.554

Rápó, E. and Tonk, S. (2021) 'Factors affecting synthetic dye adsorption; desorption studies: a review of results from the last five years (2017–2021)'. *Molecules*, 26(17), p. 5419. doi: https://doi.org/10.3390/molecules26175419

Rashid, F. (1996) 'Role of economic policies in protecting the environment: the experience of Pakistan', *The Pakistan Development Review*, 35(4), pp. 483-506. Available at: https://ideas.repec.org/a/pid/journl/v35y1996i4p483-506.html (Accessed: 3 April 2025).

Rashid, M. and Altaf, Z. (2008) 'Potential and environmental concerns of ethanol production from sugarcane molasses in Pakistan', *Nature Precedings*. Available at: https://www.nature.com/articles/npre.2008.1499.1.pdf (Accessed: 12 April 2025).

Rashid, R. *et al.* (2021) 'A state-of-the-art review on wastewater treatment techniques: the effectiveness of adsorption method', *Environmental Science and Pollution Research*, 28(8), pp. 9050–9066. doi: https://doi.org/10.1007/s11356-021-12395-x

Rasool, T. (2023) 'Performance evaluation of gravity-driven bioreactor (GDB) for simultaneous treatment of black liquor and domestic wastewater', *Environmental Science and Pollution Research*, 31(5), pp. 7043–7057. doi: https://doi.org/10.1007/s11356-023-31576-4

Ratna, S. *et al.* (2021) 'Current trends for distillery wastewater management and its emerging applications for sustainable environment', *Journal of Environmental Management*, 290, p. 112544. doi: https://doi.org/10.1016/j.jenvman.2021.112544

Ravikumar, Y. *et al.* (2021) 'Recent advances in Microalgae-based distillery wastewater treatment', *Environmental Technology & Innovation*, 24, p. 101839. doi: https://doi.org/10.1016/j.eti.2021.101839

Reyes-Reyes, C. *et al.* (2017) 'Immobilizing different carbon sources in alginate beads for melanoidins removal from yeast effluents', *Journal of Chemical Environmental and Biological Engineering*, 1(1), p. 14. doi: https://doi.org/10.11648/j.jcebe.20170101.13

Ribeiro, A.I. *et al.* (2022) 'Synergistic effects between metal nanoparticles and commercial antimicrobial agents: a review', *ACS Applied Nano Materials*, 5(3), pp. 3030–3064. doi: https://doi.org/10.1021/acsanm.1c03891

Robak, K. and Balcerek, M. (2018) 'Review of second-generation bioethanol production from residual biomass', *Food Technology and Biotechnology*, 56(2), pp. 174-187. doi: https://doi.org/10.17113/ftb.56.02.18.5428

Rutz, D. and Janssen, R. (2007) *Biofuel technology handbook*. 1st edn. Munich: WIP Renewable Energies. Available at: https://www.osti.gov/etdeweb/biblio/21214116 (Accessed: 4 April 2025).

Sadegh, H. *et al.* (2017) 'The role of nanomaterials as effective adsorbents and their applications in wastewater treatment', *Journal of Nanostructure in Chemistry*, 7(1), pp. 1–14. doi: https://doi.org/10.1007/s40097-017-0219-4

Saleem, H. and Zaidi, S.J. (2020) 'Developments in the application of nanomaterials for water treatment and their impact on the environment', *Nanomaterials*, 10(9), p. 1764. doi: https://doi.org/10.3390/nano10091764

Saleh, T.A. (2021) 'Protocols for synthesis of nanomaterials, polymers, and green materials as adsorbents for water treatment technologies', *Environmental Technology & Innovation*, 24, p.101821. doi: https://doi.org/10.1016/j.eti.2021.101821

Saleh, T.A. (2022) 'Isotherm models of adsorption processes on adsorbents and nanoadsorbents', in *Interface science and technology*. Amsterdam: Elsevier, pp. 99-126. Available at: https://www.sciencedirect.com/science/article/abs/pii/B9780128498767000099 (Accessed: 4 April 2025).

Salem, S.S. (2023) 'A mini review on green nanotechnology and its development in biological effects', *Archives of Microbiology*, 205(4). doi: https://doi.org/10.1007/s00203-023-03467-2

Sankaran, K. *et al.* (2014). DEPHY project: 'Distillery wastewater treatment through anaerobic digestion and phycoremediation—A green industrial approach', *Renewable and Sustainable Energy Reviews*, 37, pp. 634–643. doi: https://doi.org/10.1016/j.rser.2014.05.062

Sarwar, O. *et al.*, (2024) 'Synthesis, utilization, and recycling of graphene oxide-based nanohybrid biopolymeric hydrogels for purification of dye wastewater', *AQUA - Water Infrastructure Ecosystems and Society,* 73(6), pp. 1228–1256. doi: https://doi.org/10.2166/aqua.2024.033

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

Satyawali, Y. and Balakrishnan, M. (2008) 'Wastewater treatment in molasses-based alcohol distilleries for COD and color removal: A review', *Journal of Environmental Management*, 86(3), pp. 481–497. doi: https://doi.org/10.1016/j.jenvman.2006.12.024

Ratna, S. *et al.* (2021) 'Current trends for distillery wastewater management and its emerging applications for sustainable environment', *Journal of Environmental Management*, 290, p. 112544. doi: https://doi.org/10.1016/j.jenvman.2021.112544

Shahzad, T. *et al.* (2025) 'A review on cutting-edge three-dimensional graphene-based composite materials: redefining wastewater remediation for a cleaner and sustainable world', *Journal of Composites Science*, 9(1), p.18. doi: https://doi.org/10.3390/jcs9010018

Shinde, P.A. *et al.* (2020). 'Distillery spent wash: An emerging chemical pool for next generation sustainable distilleries', *Journal of Water Process Engineering*, 36, p.101353. doi: https://doi.org/10.1016/j.jwpe.2020.101353

Siles, J.A. *et al.* (2011) 'Integrated ozonation and biomethanization treatments of vinasse derived from ethanol manufacturing', *Journal* *of Hazardous Materials*, 188(1-3), pp. 247–253. doi: https://doi.org/10.1016/j.jhazmat.2011.01.096

Sing, K.S.W. (1982) 'Reporting physisorption data for gas/solid systems with special reference to the determination of surface area and porosity (Provisional)', *Pure and Applied Chemistry*, 54(11), pp. 2201–2218. doi: https://doi.org/10.1351/pac198254112201

Singh, S. *et al.* (2021) 'Mechanism and kinetics of adsorption and removal of heavy metals from wastewater using nanomaterials', *Environmental Chemistry Letters*, doi: https://doi.org/10.1007/s10311-021-01196

Smith, B. (2018) *Infrared Spectral Interpretation*. Boca Raton: CRC Press. doi: https://doi.org/10.1201/9780203750841

Sobande, M.A. (2024) 'Remediation of colour from distillery wastewater using orange peels as adsorbent', *LAUTECH Journal of Engineering and Technology*,18(3), pp. 130–143. Available at: https://laujet.com/index.php/laujet/article/view/711 (Accessed 16 April 2025).

Sohail Ayub (2014) 'Treatment of distilleries and breweries spent wash wastewater', *International Journal of Research in Engineering and Technology*, 3(2), pp. 204–214. doi: https://doi.org/10.15623/ijret.2014.0302035

Soomro, M. *et al.* (2011) 'Drinking water quality challenges in Pakistan'. Available at: https://www.pecongress.org.pk/images/upload/books/Drinking%20Water%20Quality%20Challanges%20in%20Pakistan%20(6).pdf (Accessed: 18 April 2025).

Soylak, M. *et al.* (2021) 'Magnetic nanomaterials for the removal, separation and preconcentration of organic and inorganic pollutants at trace levels and their practical applications: A review', *Trends in Environmental Analytical Chemistry*, 29, p. e00109. doi: https://doi.org/10.1016/j.teac.2020.e00109

Srivastava, K. *et al.* (2021) 'Remediation of distillery waste water using zero valent iron nanoparticles', *Current Research in Green and Sustainable Chemistry*, 4, p. 100072. doi: https://doi.org/10.1016/j.crgsc.2021.100072

Stetefeld, J., McKenna, S.A. and Patel, T.R. (2016) 'Dynamic light scattering: a practical guide and applications in biomedical sciences', *Biophysical Reviews*, 8(4), pp. 409–427. doi: https://doi.org/10.1007/s12551-016-0218-6

Stevie, F.A. and Donley, C.L. (2020) 'Introduction to x-ray photoelectron spectroscopy', *Journal of Vacuum Science & Technology A*, 38(6), p. 063204. doi: https://doi.org/10.1116/6.0000412

Sultan, A. *et al.* (2024) 'Distillery spent wash enhances sugarcane (Saccharum officinarum L.) growth', *Pakistan Journal of Weed Science Research*, 30(1), pp. 37-43. doi: https://dx.doi.org/10.17582/journal.PJWSR/2024/30.1.37.43

Tabesh, S., Davar, F. and Loghman-Estarki, M.R. (2018) 'Preparation of γ-Al2O3 nanoparticles using modified sol-gel method and its use for the adsorption of lead and cadmium ions', *Journal of Alloys and Compounds*, 730, pp. 441–449. doi: https://doi.org/10.1016/j.jallcom.2017.09.246

Tang, J.-Y., *et al.* (2023) 'Hyperbranched polyethyleneimine-functionalised chitosan aerogel for highly efficient removal of melanoidins from wastewater', *Journal of Hazardous Materials*, 447, p. 130731. doi: https://doi.org/10.1016/j.jhazmat.2023.130731

Tariq, A., Yahaya, N. and Sajid, M. (2024) 'Low cost adsorbents derived from vegetables and fruits: Synthesis, properties, and applications in removal of heavy metals from water', *Desalination and Water Treatment*, 320, p. 100626. doi: https://doi.org/10.1016/j.dwt.2024.100626

Tariq, M. *et al.* (2022) 'Dye wastewater treatment using wheat straw biochar in Gadoon industrial areas of Swabi, Pakistan', *Water Conservation Science and Engineering*, 7(3), pp. 315–326. doi: https://doi.org/10.1007/s41101-022-00144-1

Tafese Bezuneh, T. and Kebede, E.M. (2015) 'Physicochemical characterization of distillery effluent from one of the distilleries found in Addis Ababa, Ethiopia', *Journal of Environment and Earth Science*, 5(11), pp. 41-46. Available at: https://www.iiste.org/Journals/index.php/JEES/article/view/23285 (Accessed: 4 April 2025).

Tripathi, S. *et al.* (2021) 'Biodegradation of organo-metallic pollutants in distillery wastewater employing a bioaugmentation process', *Environmental Technology & Innovation*, 23, p. 101774. doi: https://doi.org/10.1016/j.eti.2021.101774

Turker, M. (2004) 'Effect of production parameters on the structure and morphology of Ag nanopowders produced by inert gas condensation', *Materials Science and Engineering A*, 367(1-2), pp. 74–81. doi: https://doi.org/10.1016/j.msea.2003.10.290

Tushar, K. S. (2023) 'Agricultural solid wastes based adsorbent materials in the remediation of heavy metal ions from water and wastewater by adsorption: a review', *Molecules*, 28(14), pp. 5575–5575. doi: https://doi.org/10.3390/molecules28145575

Ullah, S. *et al.* (2019) 'Bioinspired synthesis of nanoparticles and their biomedical potential: the Pakistan experience', *Proceedings of the Pakistan Academy of Sciences*, 56(3), pp. 37-47. Available at: https://www.ppaspk.org/index.php/PPAS-B/article/view/107 (Accessed: 4 April 2025).

Umar, E. *et al.* (2023) 'A state of art review of the metal oxide-based nanomaterials effect on photocatalytic degradation of malachite green dyes and a bibliometric analysis', *Global Challenges*, 7(6), pp. 1-18. doi: https://doi.org/10.1002/gch2.202300001

Rehman, T. U. *et al.* (2024) 'Mitigation of sugar industry wastewater pollution: efficiency of lab-scale horizontal subsurface flow wetlands. *Processes*, 12(7), p. 1400. doi: https://doi.org/10.3390/pr12071400

Urbano, F., *et al.* (2014) 'Sugar cane vinasse in water bodies: Impact assessed by liver histopathology in tilapia', *Ecotoxicology and Environmental Safety*, 110, pp. 239–245. doi: https://doi.org/10.1016/j.ecoenv.2014.09.010

Verma, M. *et al.* (2017) 'Adsorptive removal of Pb (II) ions from aqueous solution using CuO nanoparticles synthesized by sputtering method', *Journal of Molecular Liquids*, 225, pp. 936–944. doi: https://doi.org/10.1016/j.molliq.2016.04.045

Voigtländer, B. (2015) *Scanning Probe Microscopy: Atomic Force Microscopy and Scanning Tunneling Microscopy*. Berlin: Springer. doi: https://doi.org/10.1007/978-3-662-45240-0

Wagh, M.P. and Nemade, P.D. (2018) 'Biogas generation from distillery spent wash by using an OPUR western biotechnology process: a case study', *Desalination and Water Treatment*, 118, pp. 241–248. doi: https://doi.org/10.5004/dwt.2018.22404

Wang, X. *et al.* (2022) 'Effective adsorption of colorants from sugarcane juice by bagasse-based biochar-hydroxyapatite composite', *Foods*, 11(14), p. 2171. doi: https://doi.org/10.3390/foods11142171

Wang, H. and Shadman, F. (2012) 'Effect of particle size on the adsorption and desorption properties of oxide nanoparticles', *AIChE Journal*, 59(5), pp. 1502–1510. doi: https://doi.org/10.1002/aic.13936

Wang, S. *et al.* (2005) 'The physical and surface chemical characteristics of activated carbons and the adsorption of methylene blue from wastewater', *Journal of Colloid and Interface Science*, 284, pp. 440-446. doi: http://doi.org/10.1016/j.jcis.2004.10.050

Wang, X. *et al.* (2025) 'Mechanisms of nano zero-valent iron in enhancing dibenzofuran degradation by a Rhodococcus sp.: Trade-offs between ATP production and protection against reactive oxygen species', *Journal of Hazardous Materials*, 481(1), p. 1131013. doi: https://doi.org/10.1016/j.jhazmat.2024.136502

Wang, Z. *et al.* (2024) 'Polyethylene glycol crosslinked modified chitosan/halloysite nanotube composite aerogel microspheres for efficient adsorption of melanoidin', *International Journal of Biological Macromolecules*, 266, pp. 131013. doi: https://doi.org/10.1016/j.ijbiomac.2024.131013

Wu, P. *et al.* (2009) 'Inductively coupled plasma optical emission spectrometry in the vacuum ultraviolet region', *Applied Spectroscopy Reviews*, 44(6), pp. 507–533. doi: https://doi.org/10.1080/05704920903069398

Xiong, Y.S *et al.* (2024) 'Amine-functionalized soy protein/graphene oxide aerogel for efficient removal of multiple sugar-derived contaminants (SDCs): Full life cycle exploration and interaction simulation', *Chemical Engineering Journal*, 499, p. 156479. doi: https://doi.org/10.1016/j.cej.2024.156479

Younas, F. *et al.* (2021) 'Current and emerging adsorbent technologies for wastewater treatment: trends, limitations, and environmental implications', *Water*, 13(2), p. 215. doi: https://doi.org/10.3390/w13020215

Zhang, C. and Xing, X.-H. (2011) 'Enzyme bioreactors', in Moo-Young, M. (ed.) *Comprehensive biotechnology*. 3rd edn. Oxford: Pergamon, pp. 479-488. doi: https://doi.org/10.1016/

Zhang, L. *et al.* (2023) ‘Hydrogen sulfide control in sewer systems: A critical review of recent progress’, *Water Research*, 240, p. 120046. doi: https://doi.org/10.1016/j.watres.2023.120046

Zhou, H. and Smith, D.W. (2002) ‘Advanced technologies in water and wastewater treatment’, *Journal of Environmental Engineering and Science*,1(4), pp. 247–264. doi: https://doi.org/10.1139/s02-020

Zielińska, M., Bułkowska, K. and Mikucka, W. (2021) ‘Valorization of distillery stillage for bioenergy production: a review’, *Energies*, 14(21), p. 7235. doi: https://doi.org/10.3390/en14217235

Zuo, J.-M. and Spence, J.C.H. (2016) *Advanced transmission electron microscopy: Imaging and diffraction in nanoscience*. 1st edn. New York, NY: Springer. doi: https://doi.org/10.1007/978-1-4939-6607-3

Zurita, F. and Vymazal, J. (2023) ‘Oportunities and challenges of using constructed wetlands for the treatment of high-strength distillery effluents: A review’, *Ecological Engineering*, 196, p. 107097. doi: https://doi.org/10.1016/j.ecoleng.2023.107097