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Pollutant Removal from Water by Polymer Nanocomposites as Adsorbents - A Review

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Abstract: Polymer nanocomposites have emerged as a pivotal solution to contemporary environmental challenges due to their remarkable ability to address issues such as greenhouse gas emissions reduction and wastewater contamination. The integration of innovative nanomaterials like nanoparticles, carbon nanotubes, nanofibers, and activated carbon into polymers has spurred the development of transformative nanotechnologies for wastewater treatment. These advancements offer substantial benefits in terms of pollutant removal, particularly heavy metals, dyes, and oils from wastewater. The utilization of polymer nanocomposites has facilitated rapid decontamination processes with high selectivity for a wide range of contaminants. This comprehensive review highlights the significant role of polymer nanocomposites in effectively removing metal ions, dyes, and microorganisms from polluted water sources. Through synergistic interactions between the polymer matrix and nanomaterials, these composites exhibit enhanced adsorption capacities and efficient pollutant sequestration, contributing to the mitigation of environmental pollution and safeguarding water resources for sustainable development.

Keywords: Contaminants, Nanomaterials, Polymer nanocomposites, Wastewater, Water purification.

I. INTRODUCTION

Water (H_2O) stands as the paramount substance essential for the sustenance of life on Earth. The acquisition of purified water emerges as a formidable challenge in the 21st century [1]. The fundamental necessity for all living organisms on the planet is access to uncontaminated water. Unfortunately, merely 1% of the water present on the Earth's surface qualifies as pure, with the overwhelming majority being either saline or tainted by various contaminants [2]. Addressing the critical need for a sustainable and secure water supply is imperative to ensure the continued existence and well-being of diverse forms of life inhabiting our planet [2, 3]. Water contamination arises primarily from various sources, including industrial, municipal, and agricultural activities [4]. The discharge of waste from factories contributes significantly to the pollution of water bodies. Municipal waste, comprising domestic sewage and other urban effluents, also plays a substantial role in water contamination [5, 6]. Additionally, agricultural runoff, containing pesticides, fertilizers, and other chemicals, contributes to the degradation of water quality [5]. The detrimental impact of water pollution is exacerbated by the presence of hazardous substances such as heavy metals and dyes in aquatic ecosystems [7, 8]. Heavy metals, such as lead, mercury, and cadmium, are known for their toxic effects on both human health and aquatic organisms [9]. Exposure to these contaminants can lead to severe health problems, including neurological disorders and organ damage. Furthermore, the presence of dyes in water poses a threat to both human well-being and the environment [10]. These substances not only compromise water quality but also affect the aquatic ecosystem by disrupting the balance of various species and their interactions [5, 10, 11]. The consequences of water contamination extend beyond immediate health concerns, as they have far-reaching implications for the environment [12, 13]. Aquatic organisms, including fish and other wildlife, suffer adverse effects from polluted water, disrupting ecosystems and biodiversity [14]. In addressing the sources of water contamination and mitigating the presence of harmful substances such as heavy metals and dyes are crucial steps to safeguard human health and preserve the integrity of aquatic ecosystems and the environment at large [12, 14, 15]. Implementing effective pollution control measures and promoting sustainable practices across industrial, municipal, and agricultural sectors are essential for ensuring the availability of clean water for both current and future generations [14-16].

The elimination of diverse pollutants, including dyes, pesticides, fertilizers, and toxic metals, poses a formidable challenge, prompting the development of various technologies dedicated to purifying water [16, 17]. In recent years, significant research efforts have been devoted to exploring the efficacy of different adsorbents in wastewater purification. Among the strategies employed for pollutant removal, the utilization of industrial byproducts, agricultural waste, and activated carbon derived from biomass stands out as an economically viable option [18], [19]. Activated carbon, sourced from such materials, has proven to be effective in mitigating water pollution while also being cost-efficient [20].

Moreover, the emergence of nanomaterials has introduced a paradigm shift in water purification methodologies. Nanomaterials exhibit distinctive physical and chemical properties owing to their nanoscale dimensions [21-23]. Leveraging these unique characteristics, nanomaterials are increasingly employed as nano adsorbents, contributing to the enhancement of water purification processes [23]. The integration of nanomaterial-based adsorption technologies holds promise for achieving more efficient and targeted removal of pollutants from water sources [21, 23]. Nanoparticles characterized by a high surface area exhibit significant potential for enhancing water purification processes. Nevertheless, their practical application is impeded by the inherent tendency for agglomeration [24, 25]. The mitigation of agglomeration proves pivotal in unlocking the full efficacy of these nanoparticles. A viable strategy to address this challenge involves the transformation of nanomaterials into nanocomposites [24, 25]. This review provides a comprehensive exploration of various nanocomposites, encompassing discussions on their distinct types, methods of preparation, and inherent properties. Notably, particular emphasis is placed on polymer nanocomposites, elucidating their noteworthy attributes and applications in the realm of water purification. The pursuit of an effective solution to agglomeration-related limitations underscores the potential of nanocomposites as promising tools in advancing water treatment technologies.

II. NANOCOMPOSITES

Nanocomposites are materials composed of multiple phases, with at least one phase exhibiting nano-sized dimensions (10-100 nm) [22]. These materials have gained prominence as alternatives to traditional engineering materials, addressing their limitations. Nanocomposites are considered pivotal materials for the 21st century [26, 27]. Their classification is based on the dispersed matrix and dispersed phase materials, providing a versatile range of applications in various fields [25] (Fig. 1).

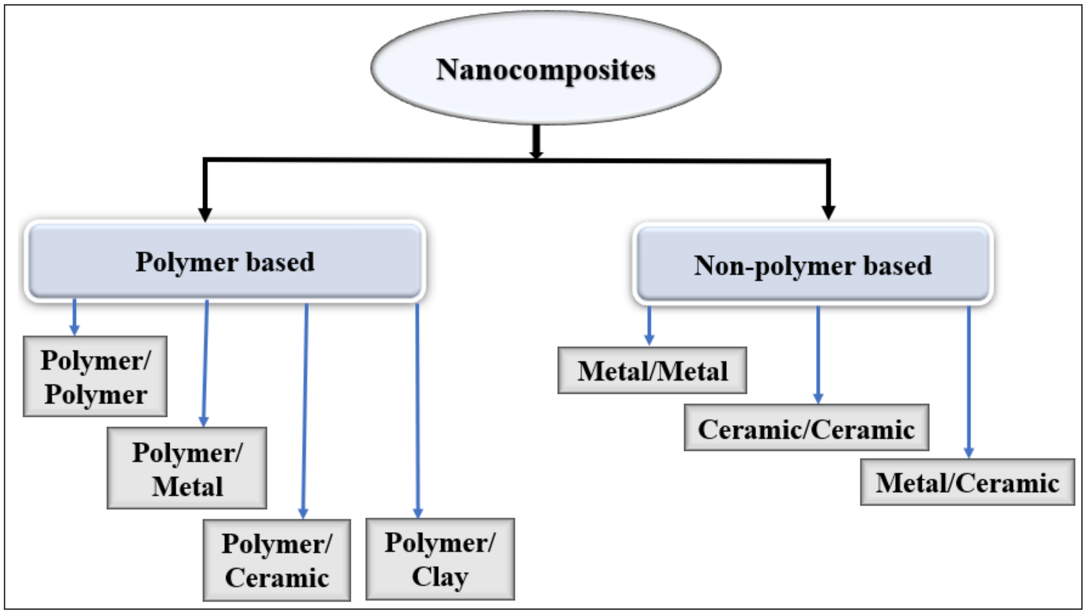

Fig. 1: Classification of Nanocomposites

Polymer-based nanocomposites (PNCs) are a significant focus in current scientific research and development. These nanocomposites offer advantageous properties like film-forming ability, dimensional variability, and activated functionalities [28, 29]. The increasing rate of publications in leading journals reflects the growing importance of these materials in scientific discourse [4], as depicted in Fig. 2. PNCs hold promise for various applications due to their unique properties and versatility in different fields.

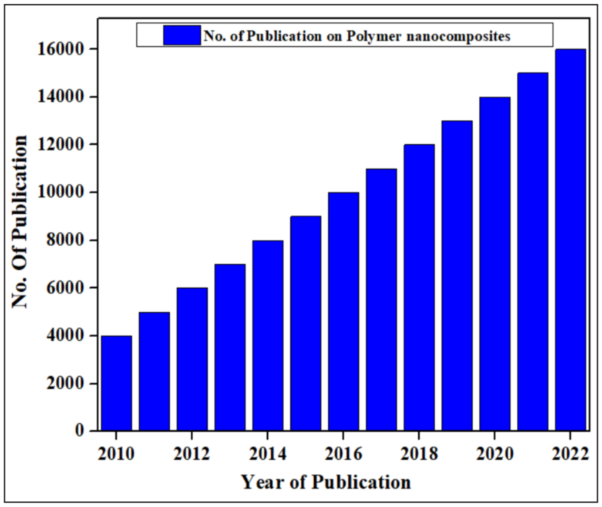

Fig. 2: Publication Trends in Polymer Nanocomposites

III. DIFFERENT METHODS TO SYNTHESIS NANOCOMPOSITES

Various methodologies have been employed in the synthesis of polymer nanocomposites. Table I, provides a concise overview and comparative analysis of diverse methods utilized in the preparation of these nanocomposites [2, 4]. It is imperative to highlight that the selection of an appropriate preparation technique is crucial for achieving a nanocomposite endowed with the desired properties [30]. The intricate nature of polymer nanocomposite design underscores the importance of a meticulous and informed approach in the selection of preparation methods to ensure the attainment of optimal material characteristics [31].

The polymeric nanocomposites (PNCs) synthesized through in situ polymerization, incorporating inorganic constituents such as metals and metal oxide nano-particles, exhibit commendable adsorptive characteristics [7, 32]. Moreover, these PNCs demonstrate versatility by manifesting proficiency in diverse applications, serving as effective catalysts, sensors, reducing agents, and bactericides [33, 34]. The amalgamation of inorganic materials within the polymeric matrix not only enhances sorbent properties but also imparts multifunctionality to the resultant composites, thereby broadening their potential utility in various technological domains [35].

TABLE I

Methods	*Advantages*	*Disadvantages*
Solvent casting method	Expensify	Contaminants
Intercalation	Systematic arrangement	Scattering
Melt Mixing	Efficiency, adaptability, and cost-effectiveness	Conglomeration
Sol-Gel	Harmony and distinctive feature	Advanced Responsiveness
Direct Polymerization	Small-scale indentation, solution-phase processing, non-agglomerated matrix	Resource-Intensive
Electrosynthesis	Room-temperature synthesis	Surface reaction

IV. CHARACTERIZATION OF NANOCOMPOSITES

The characterization of Polymer Nanocomposites (PNCs) involves various scientific techniques to understand their thermal, microscopic, and spectroscopic properties. Thermal analysis techniques such as Thermogravimetric Analysis (TGA) [22], Differential Thermal Analysis (DTA), Differential Scanning Calorimetry (DSC), Thermomechanical Analysis (TMA), and Dynamic Mechanical Analysis (DMA) are commonly employed. These techniques help assess the thermal stability and processing behaviour of PNCs [22, 23, 28, 36]. Microscopic techniques, including Scanning Electron Microscopy (SEM) [37], Transmission Electron Microscopy (TEM) [31], and Atomic Force Microscopy (AFM), provide detailed images of the surface, revealing properties like homogeneity, roughness, and porosity. These images also offer insights into compatibility and lattice mismatch between components [38]. Scanning Probe Microscopy (SPM) and Scanning Tunnelling Microscopy (STM) are also crucial for characterizing PNCs.

Spectroscopic techniques such as Fourier-Transform Infrared Spectroscopy (FT–IR) and Raman spectroscopy aid in identifying chemical compositions and molecular structures within the PNCs. Additionally, X-ray diffraction techniques provide information about the crystalline structure. The presence of a polymer matrix in PNCs enhances the processibility of non-polymeric components and significantly improves the thermal stability of the polymer [3, 39, 40].

V. SOURCES OF WATER POLLUTION

Various industrial facilities such as factories, power plants, sewage systems, and oil wells contribute to water pollution by releasing significant amounts of pollutants [10-12]. These pollutants include toxic sludges, solvents, and other harmful materials. Industrial activities result in the annual discharge of millions of tons of these substances into water bodies, leading to contamination. This contamination poses a threat to aquatic ecosystems, human health, and overall water quality [12, 13]. The diverse sources of water pollution (Fig. 3) highlight the need for effective environmental management strategies to mitigate the adverse impacts of industrial activities on water resources [12, 37].

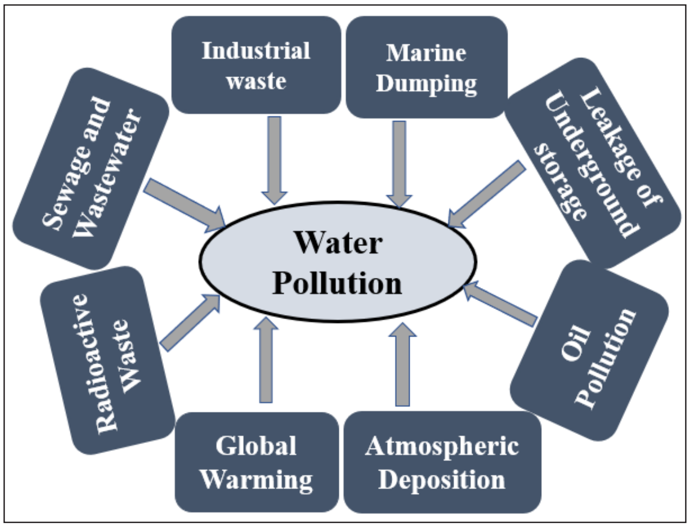

Fig. 3: Sources of Water Pollution

VI. TECHNIQUES WATER PURIFICATION

A comprehensive examination of various water purification methodologies has been recently undertaken, and the findings are systematically presented in Table II [17, 18]. The methodologies employed for water purification are primarily classified according to separation techniques, namely physical adsorption, chemical degradation, and biological treatment. Each method exhibits distinct advantages and disadvantages; however, no singular process possesses the capability to sufficiently purify water [21, 41]. Consequently, it is advisable to implement a combination of processes to ensure the attainment of requisite water quality standards. Research findings emphasize the imperative need for concerted efforts in integrating various techniques, such as adsorption-biological treatments, to augment the biodegradation of dye substances and mitigate sludge formation [41].

The treatment of wastewater involves three fundamental techniques: physical, biological, and chemical processes (Fig. 4) [41, 42]. Each technique plays a specific role in purifying wastewater.

However, despite their effectiveness, many of these methods face limitations when dealing with large volumes of polluted water. Here's a brief explanation of each method with their application:

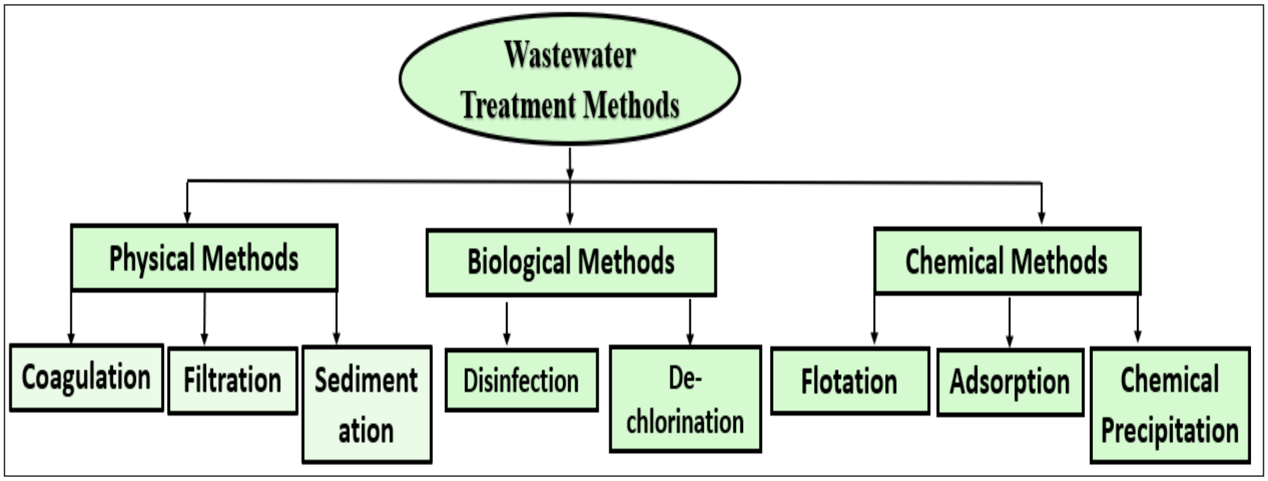

Fig. 4: Wastewater Treatment Methods

A. Physical Methods

(i) Coagulation

(a) *Definition:* Coagulation is the process where small particles in a liquid come together to form larger particles, aided by gentle agitation or mixing [43].

(b) *Purpose:* Facilitates sedimentation and distinct separation of larger particles from the liquid medium.

(c) *Application:* Widely used in wastewater treatment processes for effective particle removal.

(ii) Filtration

(a) *Definition:* Filtration is a separation process where a fluid is passed through a porous medium or filter to separate particles based on size [10].

(b) *Purpose:* Allows smaller particles to pass through while retaining larger ones, commonly used in water purification and air filtration.

(c) *Application:* Applied in various scientific and industrial settings for achieving desired purity or clarity.

(iii) Sedimentation

(a) *Definition:* Sedimentation involves the gravitational settling of dense particles suspended in a heterogeneous mixture [23].

(b) *Purpose:* Used for removing grit, particulate matter, biological floc, and chemical precipitates in wastewater treatment.

(c) *Application:* Fundamental unit operation in primary and activated sludge settling basins.

B. Biological Methods

(i) Disinfection

(a) *Definition:* Microbial control process aiming to destroy or inhibit the growth of microbes using physical, chemical, or biological methods [19].

(b) *Purpose:* Renders microbes inactive by disrupting or destroying crucial structures or functions within them.

(c) *Application:* Essential step in wastewater treatment to ensure microbial safety.

(ii) Dichlorination

(a) *Definition:* Process of removing chlorine from wastewater before reuse or release into water bodies [44].

(b) *Purpose:* Uses activated carbon or specific chemicals to eliminate chlorine, preventing environmental impact.

(c) *Application:* Important for water quality management and environmental protection.

C. Chemical Methods

(i) Chemical Precipitation

(a) *Definition:* Certain chemicals react with heavy metals to form solid particles, which can be removed through settling or filtering [2].

(b) *Purpose:* Effective removal of heavy metals from water, improving water quality.

(c) *Application:* Involves chemicals such as Alum, Ferric Chloride, Ferric Sulphate, Ferrous Sulphate, and lime.

(ii) Flotation

(a) *Definition:* Flotation uses air bubbles to make solid or liquid particles float, facilitating their removal from a liquid [9].

(b) *Purpose:* Efficient separation of particles from liquid through floating mechanisms.

(c) *Application:* Commonly used in wastewater treatment for particle removal.

(iii) Adsorption

(a) *Definition:* Adsorption is the process where a metal ion moves from the liquid to adhere to a material's surface through physical or chemical interaction [12, 37].

(b) *Purpose:* Removes metal ions from liquid, improving water quality.

(c) *Application:* Utilized in various chemical processes for water treatment.

TABLE II

Methods	*Advantages*	*Disadvantages*
Adsorption	Efficient method for eliminating a broad spectrum of colors. Adsorbent can be regenerated. Low cost.	Incapable of effectively competing with dispersion and reactive dyes, a nondestructive approach is utilized.
Coagulation	Simple and cost-effective.	Less and complex process, proper functioning is critical.
Chemical Precipitation	Complete precipitation of metal ions.	Financial constraints make it difficult to use dispersion dyes effectively.
Flotation	Easy and effective method.	Low elimination efficiency, complex process.
Microbial Treatment	Ecofriendly.	Process is slow, standardization is difficult.

VII. ADSORPTION

Adsorption is the process that moves from a gas or liquid phase to form a molecular layer on the surface of solid or liquid. Depending on the nature of the forces, the adsorption is of two types:

(i) Physical or Physisorption: Physisorption, also known as physical adsorption, is a surface phenomenon characterized by the non-specific and reversible adhesion of molecules or atoms to a substrate [41, 45]. This type of adsorption primarily arises from weak van der Waals

forces, including London dispersion forces, dipole-dipole interactions, and induced dipole forces. For example, H_2 and N_2 gases adsorption on coconut charcoal.

(ii) *Chemical or Chemisorption:* Chemical or chemisorption is a process in surface chemistry wherein molecules are adsorbed onto a solid surface through chemical bonds formation between the adsorbate molecules and the atoms or ions on the surface [46]. This phenomenon typically involves a transfer of electrons between the adsorbate and the surface atoms, resulting in the creation of new chemical species at the interface [28]. Chemisorption differs from physical adsorption in that it involves stronger bonds and usually leads to a more stable adsorbate-substrate complex. For example, formation of iron nitride on the surface when iron is heated in N_2 gas at 623K.

VIII. Polymer Nanocomposite as Adsorbents

Adsorption is a favorable and economically viable process due to its low cost and high efficiency. Various carbonaceous materials have been utilized as adsorbents for diverse adsorption processes, showcasing exceptional performance across different applications [35]. However, there is a global demand for the development of highly selective adsorbents targeting the removal of toxic metals and organic contaminants.

Polymer nanocomposite adsorbents have recently emerged as promising materials for wastewater treatment, offering robust mechanical strength, excellent hydraulic performance, high stability, and tunable surface chemistry [24, 35]. The success of contaminant elimination using these materials is contingent upon factors such as pore structure, physicochemical characteristics of the adsorbent material, surface functionality, and encapsulated moieties [35, 47]. Nano adsorbents, with their substantial surface area and facile accessibility to sorption sites, exhibit outstanding adsorption efficiency and rapid process kinetics.

Both material design and adsorption kinetics have been systematically investigated, leading to a comprehensive understanding of their interplay [35]. The remarkable adsorption performance, coupled with the cost-effectiveness and widespread availability of nano adsorbents, has garnered significant attention. In the subsequent sub-section, we delve into a systematic review of the utilization of polymer nanocomposites as adsorbents for the removal of dye contaminants, elucidating their efficacy in addressing environmental challenges.

Polymer Nanocomposites as Efficient Adsorbents for the Removal of Dyes

Over the past three decades, there has been considerable scientific inquiry into the movement and dispersal of dyes in water, driven by the awareness of their deleterious effects on human health, plant life, animals, and aquatic ecosystems [35, 47, 48]. The discharge of dyes into water sources has been identified as a significant contributor to the deterioration of water quality [35]. Industries involved in the production of dyes for textiles, cosmetics, rubber, paper, leather, food products, and plastics have been major culprits, releasing substantial quantities of synthetic dyes and generating large volumes of colored wastewater [49, 50]. The characteristics of these colored effluents, including high oxygen demand, variable pH, persistence, and resistance to various oxidizing agents, pose challenges for their effective treatment [51, 52]. The complex molecular structures of dyes and their resistance to degradation make the decolorization and demineralization of wastewater effluents a formidable task [53]. Approximately 30% of dyes used in textile industries are discharged during the dyeing process, with 2-25% directly entering ecological components. The adverse impact of dyes on aquatic life extends beyond mere coloration, hindering sunlight penetration due to the dye-induced reduction in water transparency [54, 55]. Compounded by the high half-life of many dyes, their persistence in the environment is exacerbated in the absence of appropriate treatment processes [35]. The intricate synthetic nature of dyes further complicates their removal, as they exhibit resistance to a range of chemicals, oxidizing agents, and heat, rendering them biologically non-degradable.

Among the various methods employed for treating wastewater, crucial techniques include ion exchange, reverse osmosis, precipitation, and adsorption. Of these, adsorption stands out as the most versatile and widely used approach for dye removal [25, 35, 47]. Recent attention has shifted towards natural polymeric materials as adsorbents, owing to their non-toxic and biodegradable properties. Polymer nanocomposites, characterized by their availability, low cost, excellent granulometric properties, high surface area, and chemical/thermal stability, have gained prominence for commercial purposes, particularly in dye removal from wastewater [26, 35, 56]. Functionalized polymer nanocomposites, with their enhanced chemical and physical features, ease of separation, and diverse reactive groups, have garnered significant interest. The ongoing advancements in adsorbent synthesis and functionalization aim to produce adsorbents with improved performance and tailored characteristics. This functionalization enhances the responsiveness of adsorbents to binding with larger dye molecules. Ultimately, functionalized adsorbent materials are customized for specific applications, such as the adsorption of organic pollutants, metal ions, and dyes.

IX. Adsorption Mechanism

The main goal of the photocatalysis process is to transform harmful organic pollutants into easily manageable byproducts, specifically carbon dioxide (CO_2) and water (H_2O) [57]. Initially, sunlight is absorbed at a wavelength corresponding to the semiconductor's bandgap, resulting in the creation of a hole in the semiconductor due to the energy transfer, moving electrons from the valence band to the conduction band [58]. In the presence of oxygen in the solution, an electron in the conduction band is captured, leading to the generation of superoxide ($O^{\bullet -}$). Moreover, holes formed during the process interact with water molecules, producing hydroxyl radicals ($OH^{\bullet}$). Protons neutralize the superoxide ($O_2^{\bullet -}$) species, and the subsequent dismutation of oxygen yields temporary hydrogen peroxide, which is then broken down through oxygen reduction.

In the depicted mechanism (Fig. 5), the organic dye represented by R undergoes oxidation by hydroxyl radicals (•OH), transforming into simpler molecules. The photo holes ($h^+_{(VB)}$) play a direct role in oxidizing the organic dye during this process.

$$\text{Polymer nanocomposites} + \text{Sunlight} \longrightarrow e^-_{(CB)} + h^+_{(VB)}$$

$$e^-_{(CB)} + O_2 \longrightarrow O_2^{\bullet -}$$

$$h^+_{(VB)} + H_2O\ (H^+ + {}^-OH) \longrightarrow H^+ + OH^{\bullet}$$

$$O_2^{\bullet -} + H^+ \longrightarrow {}^{\bullet}HO_2$$

$$2\,{}^{\bullet}HO_2 \longrightarrow H_2O_2 + O_2$$

$$H_2O_2 + e^- \longrightarrow OH^{\bullet} + OH^-$$

$$R\ (\text{dye}) + OH^{\bullet} \longrightarrow R^{\bullet} + H_2O$$

$$R + h^+_{(VB)} \longrightarrow R^{+\bullet} \longrightarrow \text{Removal product}$$

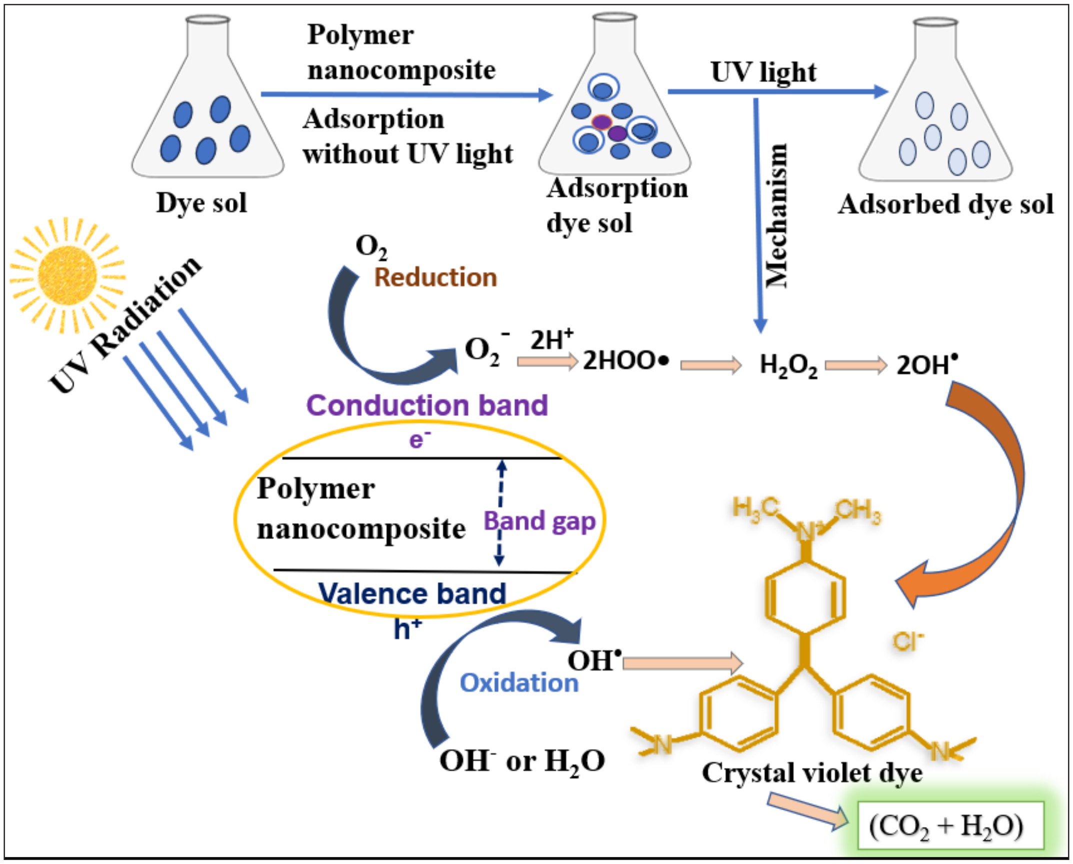

Fig. 5: Illustrative Diagram Depicting the Degradation of Dye using Polymer Nanocomposites

X. POLYMER NANOCOMPOSITES IN WATER PURIFICATION PROCESSES

Various types of Polymer Nanocomposites (PNCs) are presently under investigation for their potential application in water purification [25, 35]. The utilization of PNCs in diverse applications is driven by their distinctive properties, setting them apart from their conventional counterparts [25]. The unique characteristics of PNCs make them particularly suitable for water purification technologies. Fig. 6 illustrates the diverse PNCs employed in water purification applications, highlighting their specific contributions to the enhancement of water treatment processes. This exploration of PNCs in water purification signifies a promising avenue for addressing water quality challenges through advanced materials and innovative technologies [25, 26].

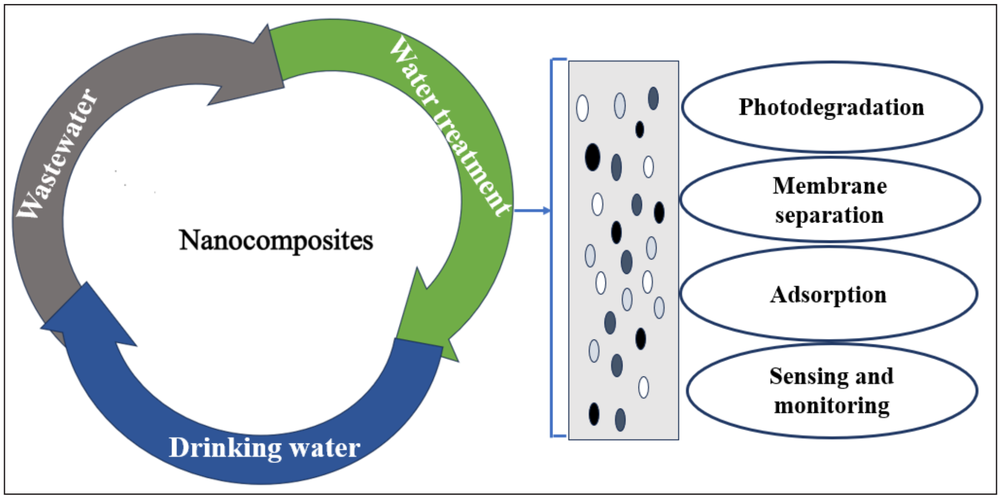

Fig. 6: The Significance of Nanocomposites in Enhancing Water Purification Processes

XI. EQUILIBRIUM STUDIES

A. Adsorption Isotherm

Adsorption, elucidated through isotherms, is a complex physicochemical process wherein temperature exerts a profound influence [59, 60]. Various isotherms serve as invaluable tools to characterize and describe the diverse techniques employed in adsorption phenomena [59]. The selection of a specific isotherm is contingent upon the nature of the adsorbent-adsorbate system under consideration. Among the notable isotherms utilized in this context are:

Freundlich Theory: The Freundlich Theory, proposed by chemist Herbert Freundlich in 1909, elucidates the adsorption behaviour of solutes onto solid surfaces, providing a foundational framework for understanding heterogeneous surface interactions [49, 61]. This theory specifically addresses the non-ideal adsorption behaviour of solutes onto heterogeneous surfaces. The Freundlich equation can be expressed as equation 1:

$$\log \frac{X}{m} = \frac{k \times p}{n} \tag{1}$$

Where, x represents amount of gas adsorbed on the m gram of adsorbent.

K and n are adsorption constants.

P is pressure.

Drawbacks: This adsorption is failed because it could not explain multilayered adsorption process at high pressure.

Langmuir Theory: The Langmuir theory describes the adsorption of molecules onto a surface, proposing a monolayer coverage with a finite number of adsorption sites, assuming no lateral interaction between adsorbed molecules [50, 51]. The Langmuir equation can be expressed as equation 2:

$$\frac{1}{q_e} = \frac{1}{q_m\, b\, C_e} + \frac{1}{q_m} \tag{2}$$

Where, q_m represents the maximum adsorption capacity of the adsorbent per unit mass.

b is a constant related to the energy of adsorption.

C_e is the equilibrium concentration of the adsorbate in the solution.

q_e represents the quantity of adsorbate adsorbed per unit mass of the adsorbent at equilibrium.

B. Kinetic Study

The investigation of kinetics in water purification processes holds paramount significance as it enables the identification of optimal conditions for efficient adsorption of pollutants [55, 62]. Kinetics elucidate the rate at which solutes are absorbed, directly influencing the duration of residence for the sorbate at the solid-solution interface [63-65]. This study yields valuable insights into the mechanisms underlying adsorption, shedding light on factors such as mass transport, ionization, and chemical interactions that potentially optimize the rate [64].

Efforts have been dedicated to formulating a comprehensive framework that describes the kinetics of pollutant adsorption onto solid adsorbents in liquid-solid phase sorption systems [63, 66]. These kinetic studies address the complexity of sorption kinetics, which may manifest in both simple and intricate forms. Numerous kinetic models have been proposed in the scientific literature, contributing to the ongoing endeavor to comprehend and characterize the intricate processes associated with the adsorption of pollutants on solid surfaces.

C. Thermodynamic Study

The investigation of thermodynamic parameters is imperative for comprehending the impact of temperature on the adsorption dynamics of pollutants onto an adsorbent material. Several key thermodynamic parameters associated with the adsorption process include variations in standard free energy (ΔG^0), enthalpy (ΔH^0), and entropy (ΔS^0) [67-69]. These parameters serve as crucial indicators and are derived from experimental observations conducted at diverse temperatures. The standard free energy change (ΔG^0) plays a pivotal role in assessing the spontaneity of the adsorption process [70]. A negative value of ΔG^0 suggests that the adsorption is a spontaneous and energetically favorable phenomenon. Conversely, a positive ΔH^0 value characterizes the adsorption process as endothermic, indicating an absorption of heat during the adsorption event. Furthermore, the entropy change (ΔS^0) is another significant thermodynamic parameter [71-73]. A positive ΔS0 value signifies an increase in randomness or disorder at the solid/liquid interface. This enhancement in randomness reflects a more disordered state of the adsorbate molecules during the adsorption process.

XII. Future prospect

Nanomaterials exhibit distinctive size-dependent properties that afford opportunities for the advancement of innovative high-tech materials essential for efficient water and wastewater treatment methodologies. These materials encompass membranes, adsorption substrates, nano catalysts, functionalized surfaces, coatings, and reagents. However, the propensity for agglomeration and instability in nanoparticles has prompted a shift in preference towards nanocomposites, particularly polymer nanocomposites.

Despite the burgeoning utilization of adsorbents for water treatment, significant gaps persist, necessitating focused attention. Our investigations have scrutinized various adsorbents, evaluating their stabilities, costs, and efficacy in eliminating pollutants from water sources. Nonetheless, numerous challenges and limitations persist, compelling the development and optimization of next-generation adsorbents tailored for water purification, with a dual emphasis on efficiency and contribution to global economic prosperity.

XIII. Conclusion

In the current context marked by a scarcity of water resources, the imperative for effective water purification is paramount. To address this exigency, the development of novel technologies characterized by both high efficiency and low investment becomes indispensable. Nanocomposites, owing to their exceptional efficacy in decontaminating water from dyes along with their noteworthy regeneration capabilities and cost-effectiveness, have emerged as pivotal materials in the pursuit of water purification. While numerous methods exist for water purification, the process of adsorption has demonstrated heightened efficiency and effectiveness. Nevertheless, a comprehensive understanding of various aspects related to adsorbents necessitates detailed investigation. This exploration is crucial for optimizing the utilization of adsorption-based water purification methods and advancing the overall efficacy of water treatment technologies.

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