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Review Article

Sustainable Degradation of Organic Pollutants Using Various Treatment Processes: A Review

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Abstract

Organic pollutants such as dyes or colorants are water-soluble compounds produced by various industries, including textiles, food, cosmetics, pharmaceuticals, printing inks, paints, leather, and plastics. Dyes are of particular concern because their stable aromatic structures make them toxic, mutagenic, and carcinogenic to living organisms. Therefore, environmental scientists have focused on developing various physical, chemical, and biological treatment processes to remove these contaminants from wastewater. The conventional techniques such as coagulation, flocculation, precipitation, photocatalytic degradation, ion exchange, and membrane filtration have been widely adopted. More recently, biomass-based waste materials such as bagasse, green algal biomass, and household vegetable and agricultural residues have been investigated as promising, low-cost, and sustainable adsorbents for dye removal. In addition, nanomaterials such as zinc oxide, titanium dioxide, silica powder, carbon nanotubes, and well-structured biocomposite materials have also shown great potential in wastewater treatment. The present review not only emphasizes a detailed study of essential treatment technologies but also highlights their merits and limitations in a structured manner, supported by comparative tables and illustrative figures.

Keywords: bioadsorbent; adsorption techniques; coagulation; flocculation; biological treatment processes; organic pollutants.

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Highlights:

- Sustainable Degradation of dyes Using Various Treatment Processes
- Degradation of Organic pollutants from textiles, food, cosmetics, pharmaceutical, etc.
- Removal of using various physical, chemical, and biological treatment processes.
- Conventional treatment techniques coagulation, flocculation, degradation, ion exchange, and membrane filtration

1. Introduction

Dy**e** is a colored substance that is soluble in water or in other solvents and form chemical bond to textiles, paper or leather and to impart color in this material [1]. Dyes are mostly divided in natural dyes and synthetic dyes. The most of the natural dyes are derived from natural resources like flowers, bark, plants, animals and minerals. also, it found, all the natural dyes are biodegradable and are having lower color range, and less durability. While all synthetic dyes are chemically produced from petrochemicals and coal tar derivatives which offer a wider color range and higher durability [2]. Synthetic dyes is a relatively recent discovery, and their large-scale production commenced in response to the growing demand for dyes [3]. In 1856, WH Perkins made a groundbreaking contribution by inventing a wide range of synthetic dyes, offering vibrant and colorfast shades for various applications [4]. While this invention resolved the limitations associated with natural dyes, new challenges emerged as industries using these synthetics started to discharge in open environment without doing waste dye treatment. Approximately 700,000 tons of various coloring agents, derived from around 100,000 commercially available dyes, are produced annually. However, it has frequently been observed that, in most cases, untreated dyes are discharged into rivers, ponds, or lakes. Globally, the textile sector accounts for the largest share of wastewater discharge (54%), followed by the pulp and paper industry (21%), paint and tannery industries (10%), and synthetic dye plants (7%) [5]. The remaining 8% comes from other industries, all of which contribute substantially to dye effluent generation through their respective processes. Figure 1 shows the demographic representation of different industrial contributions to dye effluents. The extensive utilization of dyestuffs in various textile processes leads to the generation of large volumes of dye-contaminated wastewater [6]. Since the textile industry consumes many types of dyes and chemicals, involving significant amounts of water in different unit operations, more than 75% of residual dye mixtures are discharged untreated into rivers, severely affecting aquatic organisms [7].

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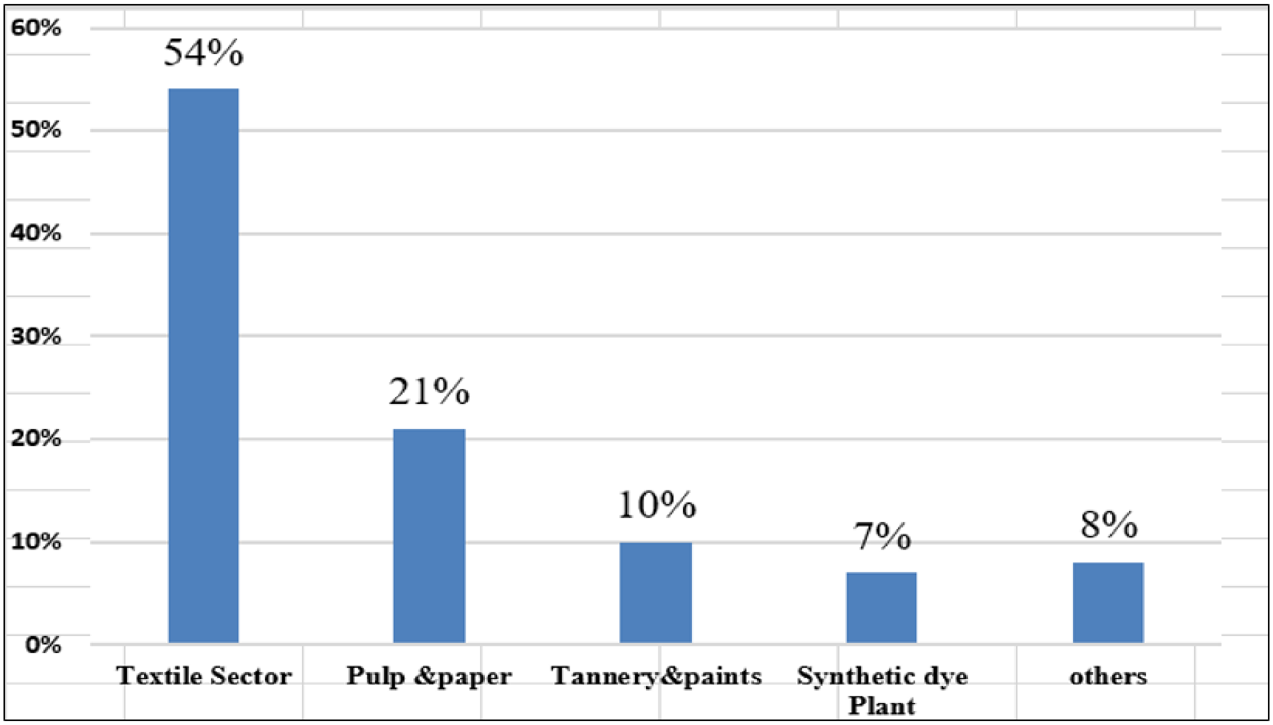

Fig.1 Demographic representation of Different Industrial Contribution of Dye Effluents

At present, various dye removal methods and techniques have been documented, demonstrating successful outcomes with relatively fewer drawbacks. However, although a variety of viable technologies exist, not all of them prove effective or practical due to inherent limitations. Here the Figure 2 presents a schematic representation of different types of dye effluents obtained from various industrial sources. The emphasis must be on eliminating contaminants from wastewater without producing additional hazardous by-products [8]. Synthetic dyes have become essential components, widely used to impart color to textiles, cosmetics, plastics, and printing materials [9]. This widespread application is primarily due to their inherent resistance to degradation, as their complex and stable molecular structures contain auxochromes (water-soluble bonding groups) and chromospheres (color-imparting groups) [10]. This structural complexity complicates the degradation of dyes through conventional treatment methods. To ensure that dyed materials retain their color and do not fade easily, even under extreme heat, exposure to oxidizing agents, or intense light, dyes are deliberately designed for high stability [11].

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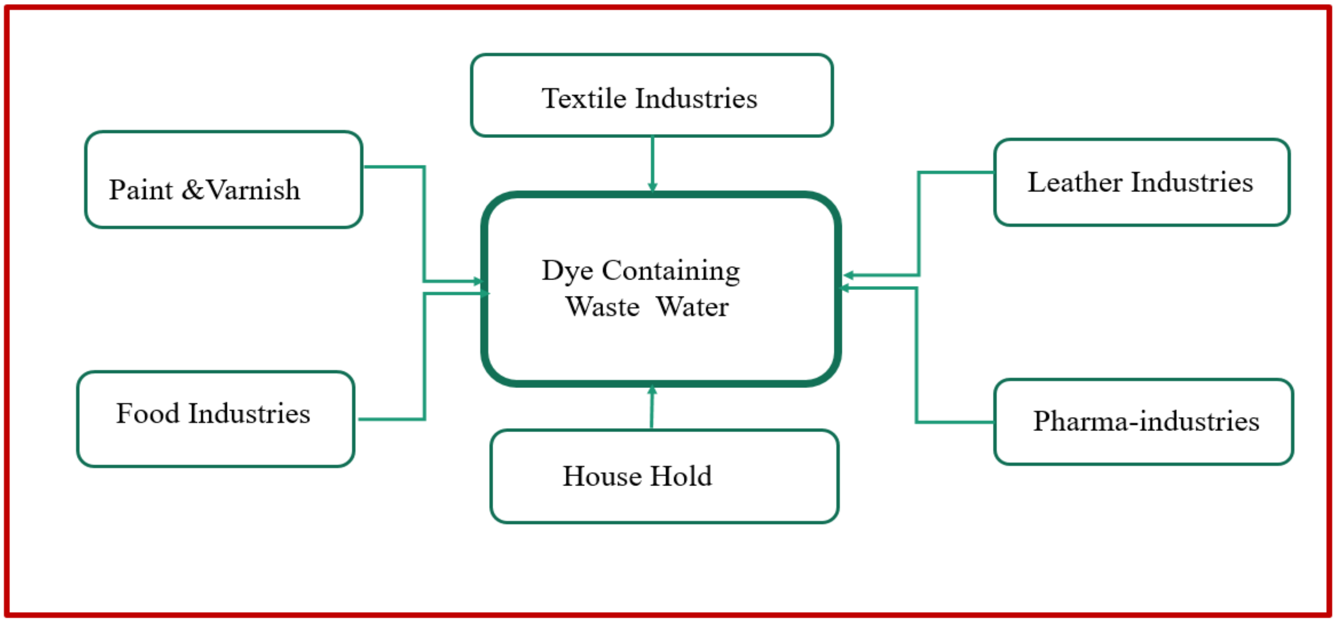

Fig.2. Diagram for representation of Different types of dye Effluents obtained from various resources

However, the dye effluents as industrial waste transforms clean water into contaminated water of river. This dye reduces the dissolved oxygen (DO) levels, which in turn increases the biological oxygen demand (BOD) and causes odor formation, thereby adversely affecting nearby aquatic ecosystems and human populations [12]. Since the most of village population or poor Communities live nearby the bank of rivers so there is risk to becoming sick from unknowingly consuming contaminated water [13]. The gradual degradation of the environment and harm human health issues causing skin problem breathe difficulty, nausea, or vomiting etc. [14]. These water contaminant issue gained attention over the past 30 years when health issue is coming in picture. Subsequently, efforts were made to gather information on dyes, their applications, and methods to remove them [15]. In previous year many papers are published, and as review observed comparative analysis of research publication trends on various water treatment technologies from 2015 to 2024. Figure 3 (a) shows the absolute number of published papers, indicating that adsorption remains the most researched technique, with publications steadily increasing from around 120 in 2015 to over 260 in 2024. Reverse osmosis and membrane filtration also show consistent growth, followed closely by coagulation & flocculation and a notable rise in ultra-/nano membranes, especially post-2020 [16]. Ion exchange maintains a moderate presence, while irradiation consistently has the least number of publications. Figure 3(b) shows the percentage share of publications per technology over time, revealing that although adsorption dominates in absolute numbers, its percentage share is gradually declining due to the rising contribution of other technologies [17]. Notably,

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ultra-/nano membranes show a significant upward trend in percentage share, reflecting growing research interest

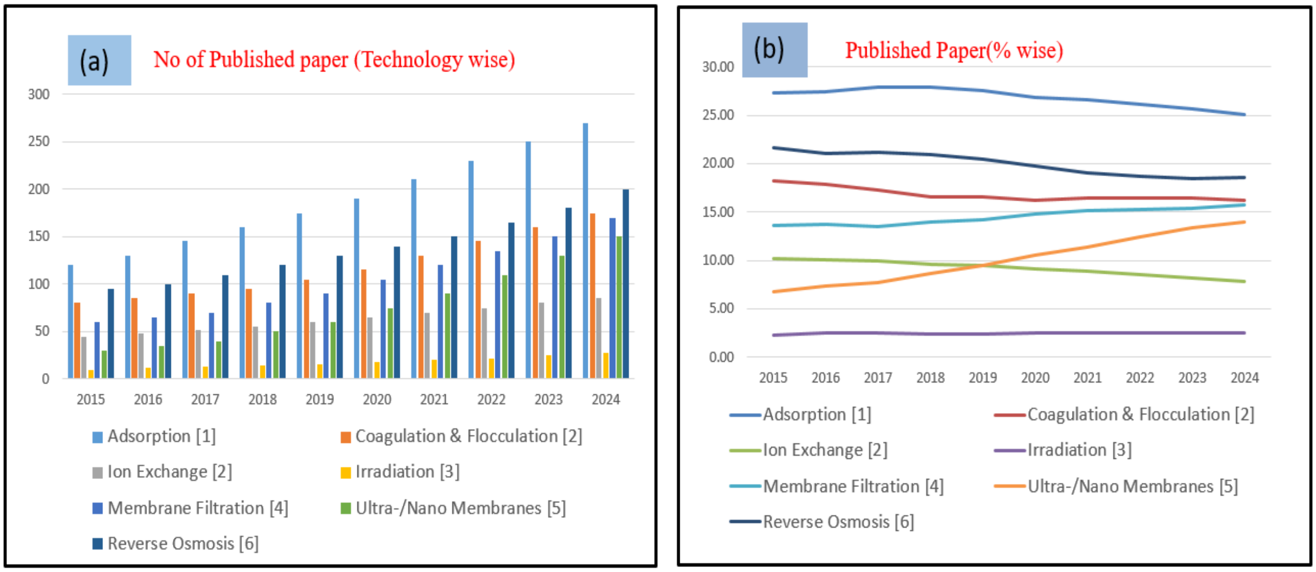

Fig. 3: (a) Number of published papers (technology wise) (b) The percentage share of publications based on dye removal.

Meanwhile, reverse osmosis**,** coagulation & flocculation, and ion exchange show a steady to slight decline in percentage contribution over the years [18]. The review aims to evaluate existing physical, chemical, and biological treatment methods such as coagulation, flocculation, precipitation, ion exchange, membrane filtration, and photocatalytic degradation [19]. In addition, it seeks to explore the potential of emerging low-cost and eco-friendly materials including biomass-based waste like bagasse, green algal biomass, and agricultural residues, as well as advanced materials like carbon nanotubes, zinc oxide, titanium dioxide, silica powder, and engineered biocomposites for improving the efficiency and sustainability of dye removal from wastewater [20].

1.1 Various Dyes and their Applications:

Synthetic dyes can be classified on the bases of their molecular structure, application or solubility. Soluble dyes include categories like acid, basic, direct, mordant, and reactive dyes, while insoluble dyes encompass azo, disperse, sulfur, and vat dyes [21]. Among these, azo dyes stand out as the most widely produced type, accounting for 70% of the total production and being extensively applicable worldwide [22].

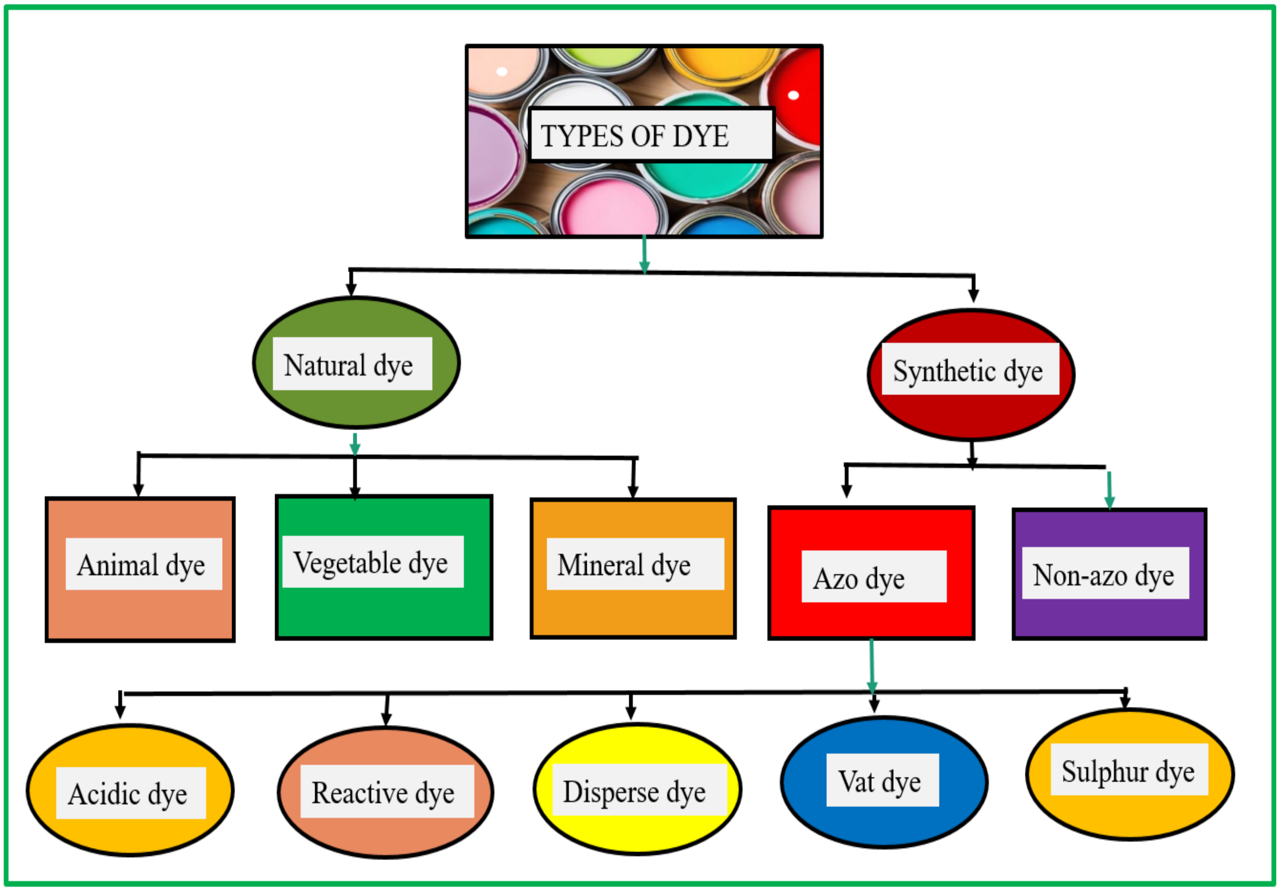

Fig.4 - Different types of dyes used in different application

Despite their structural diversity, all synthetic dyes share a common drawback due to their hazardous nature. Figure 4 shows the various types of dyes used in different utilization. So, it is necessary that untreated water should not discharge into the environment where they can contaminate water sources due to their toxicity [23]. Some name of important type dye like reactive dyes are water-soluble colorants that form covalent bonds with hydroxyl groups in cellulose or amino groups in proteins, giving them high wash fastness and bright shades. They are extensively applied to printing inks, silk, wool, cellulosic fibers, and cotton [24]. Solvent dyes, such as Solvent Red 26 and Solvent Blue 35, are non-polar and water-insoluble, which allows them to dissolve in organic solvents. This makes them particularly suitable for coloring lubricants, oils, waxes, plastics, and varnishes, where good solubility and transparency are required. Sulphur dyes, with Sulphur Black being the most common, are applied to rayon, silk, wood, leather, paper, and polyamide fibers [25]. These dyes are typically insoluble in water and must first be reduced in an alkaline solution of sodium sulfide to a soluble form, after which they penetrate the fiber and are re-oxidized to their original insoluble form, producing excellent wash durability. Vat dyes, such as Vat Blue 4 (indanthrene), also rely on a reduction–oxidation process: they

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are reduced to a soluble leuco form that penetrates fibers like cotton, cellulosic fibers, rayon, polyester–cotton blends, and wool, before being oxidized back to their insoluble state within the fabric. Azo dyes, characterized by their –N=N– azo linkage, are widely used due to their versatility and bright color range, including bluish-red shades. They are applied to cotton, rayon, polyester, cellulose, and acetate, and their chromophore–auxochrome system provides good strength [26].

2. Different Methods of Dye Removal

In beginning dye removal methods primarily consisted of primary treatment method such as equalization and sedimentation process are taken initially due to the absence of specific discharge limits of dye. But it is observed that these primary treatment methods are not sufficient to treat the water with in permissible limit and also not cost effective due to having more maintenance and operational cost and on the same time also generate secondary pollutants to [27] Currently, extensive research is being conducted to identify the ideal dye removal method that would allow for the recovery and reuse of dye wastewater [28]. In modern time or currently the water treatment of dye removal is divided in physical chemical, biological process. Although numerous dye removal technologies have been developed, only a select few are useful in industrial systems due to the limitations associated with most of these methods [29]. The schematic diagram for different types of dyes applied in different application have been shown in Fig 5.

2.1 Physical treatment of Dye:

The physical treatment techniques as coagulation, flocculation, and Ion exchange, and nano-filtration, Reverse osmosis membrane filtration are important water treatment technology that based on mechanical and mass transfer operations [30]. Out of the different approaches e.g physical. Chemical, and biological, but on initial level the physical methods for dye removal are the preferred because of their high efficacy [12]. Here the summary of various physical methods with their respective advantages and disadvantages [31-38], are given as Table 1 as follow.

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Table1. Different Physical Dye Removal Methods

Method	Description	Advantages	Disadvantages
1. Adsorption	Adsorption is mass transfer operation Involves using adsorbents made from highly capable to trap dye molecules on their active surface [31]	It is an excellent for removing a variety of dyes, and adsorbents can be reused or regenerated.	It can be expensive.
2. Coagulation and Flocculation	In this process some coagulant and flocculent are used to settle down the aggregate the molecule of dye .and after this operation filtration is applied to remove dye molecule and water [32]	It is Cost-effective and suitable for dispersant, sulfur, and vat dye effluents.	Generates significant concentrated sludge.
3. Ion Exchange	This treatment method where ionic contaminate like dye molecule are removed from water [33]	It is re-generable and effective for dye removal, producing high-quality water.	Limited effectiveness for certain dyes.
4. Irradiation	Uses radiation to eliminate molecule of dye from wastewater.	Effective at the laboratory scale, but requires substantial dissolved oxygen.	Irradiation is Expensive, not suitable for dye removal, prone to fouling, and results in concentrated sludge [34].

5. Membrane Filtration	It is a thin size membrane is applied to separate dye and water molecule [35]	Membrane Filtration is considered best for water recovery and reuse.	Initial investment can be costly, and membranes are prone to fouling.
6. Ultra And Nano Membrane Process	wastewater of dye effluent is passed through a thin size membrane [36]	It is Capable of removing any dye type.	Ultra And Nano Membrane Process is also High cost and, high energy consumption, and needs backwashing.[37]
7. Reverse Osmosis	Reverse Osmosis Utilizes pressure to pass water through an extremely thin membrane, allowing osmosis to remove contaminants and produce pure water.[38]	Widely applied for water recycling, effective in de-coloring and desalting various dyes, yielding pure water.	Costly and necessitates high pressure

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While the schematic diagram may represent as:

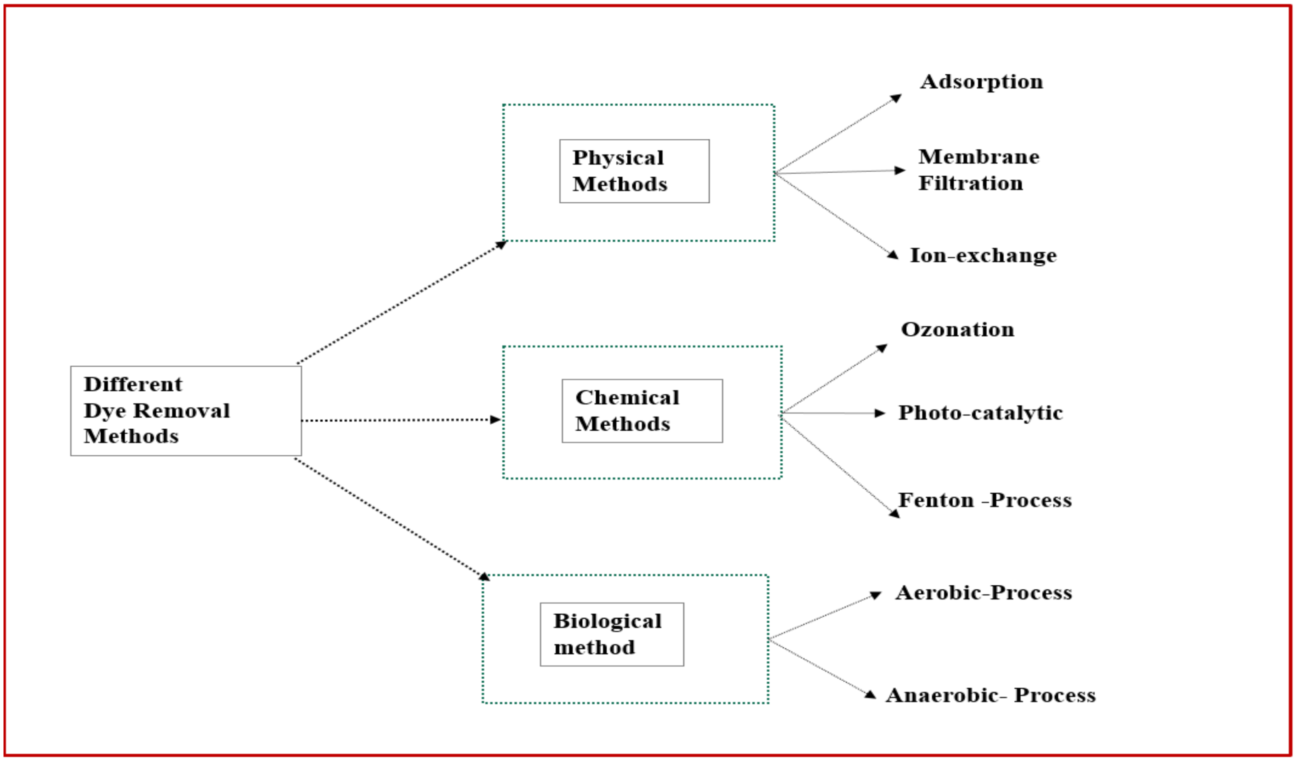

Fig.5 Schematic diagram of different dye removal process

2.2 Chemical Methods for dye removal:

The chemical approach involves the utilization of chemical principles to extract dyes from waste for employing various separation techniques. These methods encompass oxidation processes, electrochemical destruction, photochemical or ultraviolet rays' treatment and Fenton, ion exchange and ozone treatment process may also use, they all are, highlighting their respective descriptions, advantages, and disadvantages as presented in reference [39-47] in Table 2 as follow.

Table 2: Chemical Treatment Method along with Its Advantages & Disadvantages

Method	Description	Advantages	Disadvantages
Advanced Oxidation Process	(AOPs) refer to a set of chemical treatment methods that generate highly reactive species, particularly hydroxyl radicals (•OH), to degrade and mineralize organic pollutants, including dyes, in wastewater. AOP processes are highly effective for breaking down complex dye molecules that are resistant to conventional treatment methods.[39]	Effective for toxic materials. Suitable for unusual conditions.	Advanced Oxidation Process is Expensive. Inflexible. Produces undesirable by-products. PH-dependent. High electricity cost. Less effective at high flow rates.[40]
Electrochemical Destruction	Electro-chemical methods are attractive for dye removal due to their high efficiency, ability to operate without chemical additives, and potential for complete mineralization of dyes without secondary sludge formation. However, Electro-chemical methods their energy consumption and electrode material	Electrochemical Destruction does not consume. No sludge buildup. Suitable for soluble and insoluble dyes.[41]	A greater production of potentially hazardous substances. High cost of electricity. less successful at high flow rates

	degradation are challenges to be optimized. [42]		
Fenton reaction	Fenton reaction is considered reaction between hydrogen peroxide (H_2O_2) and ferrous iron (Fe^{2+}) in the presence of acidic conditions (typically using sulfuric acid, H_2SO_4) [43]	It is suitable for both soluble and insoluble dyes, effectively eliminating harmful pollutants This method is typically well-suited for wastewater with a high solid content.[44]	This process is ineffective for eliminating disperse and vat dyes and tends to produce a substantial amount of iron sludge. Furthermore, it is noted for its delayed reaction and operates most efficiently under acidic conditions (low pH).[45]
Ozonation	Utilizes ozone from oxygen to eliminate dye particles.	Effective for color removal and disinfection. Not generate chemical residuals.	High equipment and energy costs. It May not remove all dyes.
Photochemical Reaction	Photochemical reactions can involve the breaking or formation of chemical bonds, resulting in the creation of new substances or the alteration of existing molecules.[46]	It is Effective for color and organic matter removal.it Can treat a wide range of dyes.[47]	Hydrogen peroxide cost. Sludge generation

2.3. Biological Methods for Dye Removal & Their Efficiency:

Biological methods include aerobic and anaerobic processes to use dye effluents before their discharge into the environment. The conventional approach is predominantly favored due to its efficacy ranging from 85% to 98% [48]. Among these techniques, adsorption stands out as the most effective method for degrading a wide spectrum of dyes, either individually or as mixtures. Typically, the adsorption and enzyme degradation methods can be employed iteratively until the adsorbent reaches its saturation point [49]. The only drawback to this approach is the potentially higher cost associated with certain adsorbents, which can be mitigated by exploring cost-effective raw materials to create alternative adsorbents. Given the effectiveness of both enzyme degradation and adsorption techniques in dye removal, there is a compelling case for investigating the integration of these methods into a unified, comprehensive technology for future dye removal applications. On the same way a comparative analysis among Enzyme vs. Microbial vs. Algal Approaches is also presented as Table 3 [50-62]:

Table 3: Comparative Analysis: Enzyme vs. Microbial *vs.* Algal Approaches

Parameter	**Enzyme-Based Approach**	**Microbial Approach**	**Algal Approach**	**Ref.**
Mechanism	Direct oxidation or breakdown of dyes via enzymes	Biodegradation or bio sorption using bacteria/fungi	Bio sorption + biodegradation using algae	[50]
Common Agents/Species	Laccase, peroxidase, manganese peroxidase	*Pseudomonas*, *Bacillus*, *Phanerochaete*, *Aspergillus*	*Chlorella vulgaris*, *Spirulina*,	[51]
Typical Removal Efficiency	70–95%	50–90%	40–80%	[52]
Reaction Time	Minutes to hours	Hours to days	Several days	[53]
Operational Conditions	Optimal pH, temperature, enzyme stability needed	Tolerates moderate variation in pH and temp	Requires light, CO_2, and stable pH	[54]

Sludge Generation	Minimal	Moderate	Low	[55]
Advantages	Fast, highly specific, no microbial growth required	Inexpensive, adaptable to multiple dyes	Eco-friendly, biomass reuse possible	[56]
Limitations	High enzyme cost, sensitive to inhibitors	Sensitive to toxicity, slow degradation for complex dyes	Slower rate, needs sunlight and CO_2, lower tolerance to toxicity	[57]
Byproduct Toxicity	Often non-toxic	Possibly toxic intermediates	Usually, non-toxic	[58]
Scalability	Challenging (due to cost of enzymes)	Highly scalable in bioreactors	Scalable in ponds or photo bioreactors	[59]
Environmental Impact	Low (enzyme residues are biodegradable)	Low–moderate (depends on sludge disposal)	Very low (uses renewable light and CO_2)	[60]
Energy Demand	Low–Medium (if immobilized or reused)	Low	Low	[61]
Reuse/Recovery	Possible via immobilization	Difficult	Biomass can be harvested and reused	[62]

3-Application of Advanced Dye Removal Technology:

Several methods that have been thoroughly tested, but treatment though adsorption is one of the best techniques for dye removal due to having excellent capacity to eliminate different type of dye [63]. It is widely recognized that conventional methods are inefficient in completely eliminating synthetic dyes from dye wastewater, making adsorption one of the most suitable approaches for dye removal

[64]. Dye effluents treated using the adsorption method have consistently yielded higher water quality compared to other dye removal techniques [65]. The one drawback associated with this method applicable to be the high cost of adsorbents. However, the discovery of cost-effective yet equally efficient adsorbents has transformed this approach into an economically viable dye removal method on a global scale. Adsorption is a mass transfer process in which adsorbate accumulate at the surface of adsorbents. Adsorption process is driven by various forces, including physical interactions, electrostatic forces, and chemical bonding, leading to the concentration of solutes onto the solid surface [66]. The existing advance technology for removal of dye may explain as following:

3.1. Mechanism of Natural Adsorbent:

Adsorption is a process in which substances are captured or accumulated at the interface of two phases, typically a solid surface and a fluid as liquid or gaseous solution obtain from environment [67]. This phenomenon effectively reduces the concentration of dissolved dye particle present in dye containing waste solution the word "adsorbate" means the material that is adsorbed. While the material used for adsorption is the adsorbent Adsorption can be carried out through physical& chemical adsorption is the more commonly used method in adsorption, although chemisorption is employed in specific cases [68]. In Physico-sorption, various forces, including hydrogen bonds, and polar bonds, Adsorption is an extremely successful dye removal approach due to its low dependence on a specialized treatment system and relatively simple application. Van der Waals forces are weak, non-specific interactions that occur between all atoms or molecules, including London dispersion, Debye, and Keesom forces. These forces play a key role in physisorption, especially in dye adsorption on non-polar surfaces like activated carbon or untreated biomass [69]. They enable reversible dye attachment without strong chemical bonding. While π–π interactions, on the other hand, involve non-covalent stacking between aromatic rings in both dyes and adsorbents. These are stronger and more specific, enhancing dye removal when adsorbents like biochar have graphitic or aromatic structures, making them particularly effective for aromatic dyes like methylene blue and Congo red. Additionally, no pre-treatment is necessary to initiate the adsorption process. Sometimes, adsorption is used conventional methods to decolorize dye effluents, the effectiveness of the adsorption is enhanced when suitable adsorbent is used, ensuring efficient dye removal [70]. Another desirable feature of adsorption is that it does not produce additional hazardous materials at the end of operation. The figure 6 shows the various adsorbents, while essential overview of Adsorption Kinetics, Reactor Design, and Toxicological Assessment is given as follow in Table 4.

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Table.4: Overview of Adsorption Kinetics, Reactor Design, and Toxicological Assessment

Aspect	Model/Type	Key Features / Assumptions	Application / Relevance
Kinetic Models	Langmuir isotherm	Monolayer adsorption on homogeneous surface; finite number of identical sites.	Used to determine maximum adsorption capacity and favorability of process.
Kinetic Models	Freundlich isotherm	Empirical model; adsorption on heterogeneous surfaces; multilayer possible.	Suitable for systems with diverse active sites; good for low concentration ranges.
Kinetic Models	Pseudo-first-order (PFO)	Adsorption rate proportional to unoccupied sites; often fits early-time data.	Describes physical adsorption or initial stage kinetics.
Kinetic Models	Pseudo-second-order (PSO)	Adsorption rate depends on square of unoccupied sites; chemisorption mechanism.	Commonly used for dye and heavy metal adsorption with better overall fit.
Reactor Design	Batch reactors	Simple setup, closed system; easy to control pH, dosage, temperature.	Laboratory studies, small-scale wastewater treatment, kinetic/isotherm analysis.

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Reactor Design	Continuous reactors (fixed-bed, fluidized-bed, CSTR)	Steady influent/effluent; scalable; requires hydrodynamic and regeneration considerations.	Industrial applications; fixed-bed widely used for large-scale adsorption processes.
Toxicological Assessments	Identification of by-products	Analytical tools (LC-MS, GC-MS, FTIR, and NMR) to detect degraded intermediates.	Ensures no harmful or persistent by-products remain post-treatment.
Toxicological Assessments	Bioassays	Tests on algae, Daphnia, fish embryos, or cell cultures for acute/chronic toxicity.	Evaluates real environmental and health impact of effluent.
Toxicological Assessments	Risk assessment	Compare concentrations to permissible limits (PNEC, WHO, EPA standards).	Confirms treated water is safe for discharge or reuse.

3.1.1. Different Adsorbents Used for Dye Removal:

All Adsorbents are porous materials capable to trap adsorbate on its surface. Adsorbents can be made from a variety of raw materials, not limited to solid substances, and can even include such as enzymes.

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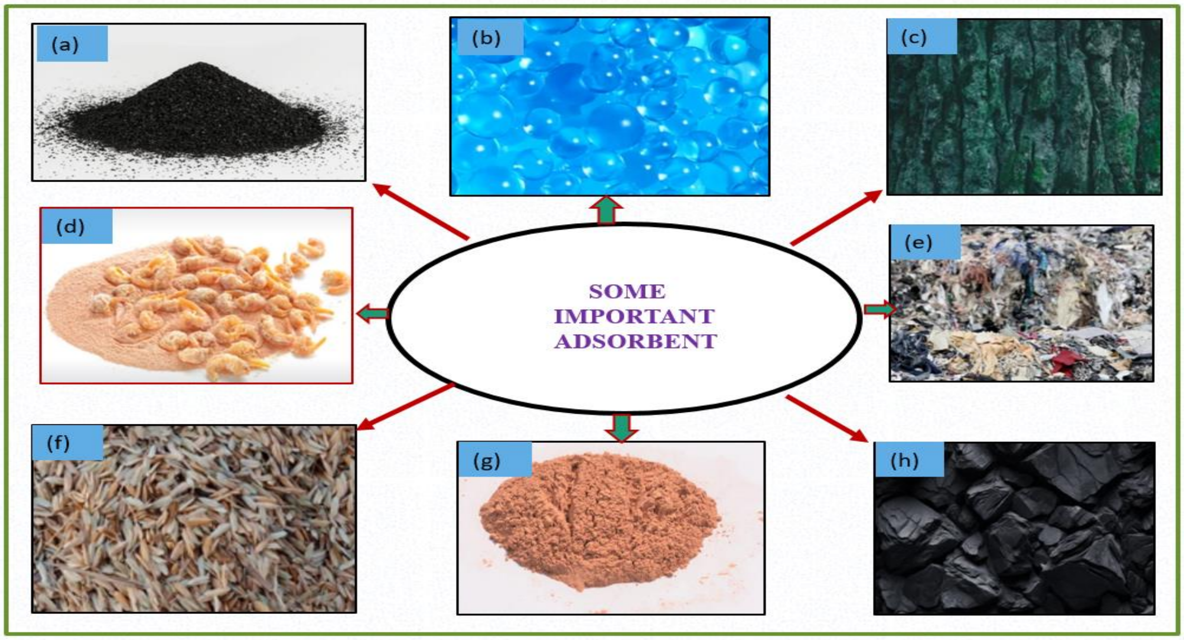

Fig.6. Various adsorbent (a) Activated Carbon (b) Silica Gel (c) Plant Bark (d) Chitosan (e) cotton Waste (f) Rice Husk (g) Saw Dust (h) Natural Coal

The cost of the adsorbent is a common concern associated with the adsorption technique. To address this issue, researchers have identified and developed cost-effective adsorbents, gathering research from various sources to prove the existence of inexpensive yet effective adsorbents [71].The key characteristics of a good adsorbent include its good adsorbed capacity to trap solute molecule, high surface area (higher porosity results in greater surface area and higher adsorption capacity), short adsorption time (rapid equilibrium reaching), and versatility to remove molecule of different size (ability to function under varying dye concentrations), pH levels, and temperatures.

3.1.2 Factors Influencing Adsorption:

The rate of adsorption is influenced by following several key parameters related to the adsorption process. Any changes in these five parameters can impact the adsorption rate. To achieve the desirable removal rate, it's essential to establish optimal adsorption conditions the outlines the five most significant parameters presented as:

Adsorbent Dosage: It measures the quantity of adsorbent containing active site to adsorbate which depend on dye concentration and pH of dye solution [65].

Contact Time: It measures the duration of contact between the adsorbate and adsorbent .as the contact period between active site and adsorbate is increased, the chances of adsorption is enhanced [72].

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Dye Concentration: it also effects adsorption process of available binding sites and adsorbents surface. Whenever dye concentration is increased then the number of available active site are reducing cause reduction the efficiency of dye removal [65].

pH: It indicates the solution's acidity or alkalinity. Adsorption rates can be affected by pH, which governs the electrostatic charges between charged dye molecules.

Temperature: Adsorption is significantly influenced by the solution's temperature processes based on the dye effluent's features. For endothermic reaction high temperature is suited for adsorption of dye while for exothermic reaction low temperature is suited for adsorption of dye [73].

3.2. Photocatalytic Processes:

Photo oxidation utilizes light, typically in the form of ultraviolet or sunlight, and a catalyst to produce highly reactive species, such as hydroxyl radicals (OH), which break down and mineralize organic pollutants, including dyes [74]. When the catalyst is exposed to UV light, it becomes excited, generating electron-hole pairs.

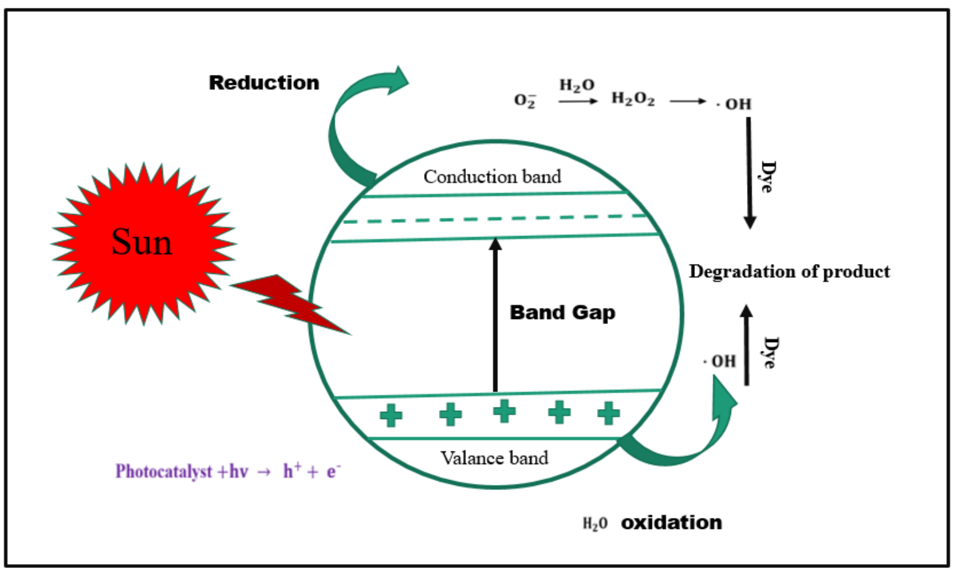

Fig. 7. Schematic view of Mechanism of Photocatalytic Dye Degradation

These electron-hole pairs react with water and oxygen to produce reactive oxygen species, primarily hydroxyl radicals. These radicals then attack and degrade the dye molecules, breaking into smaller and less injurious compounds [75]. Photo oxidation is effective against a wide range of organic dyes. As example removal of method methylene blue is removed by Photochemical decomposing with a Combined System of for the purpose of to improve color removal even more in this procedure, polyvinyl alcohol was used to immobilize titanium dioxide [76]. The starting concentration of dye of 20 mg/L, the UV light intensity of 4 W, the liquid volumetric flow rate of 2 mL/min, and the wavelength

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of 254 nm were found to be the ideal process parameters. Contact time is less than 20 hours were needed for the maximum dye removal reaction time. 90% Maximum Efficiency, [77]. The principle of Mechanism of Photocatalytic Dye Degradation has been shown in Figure 7 as follow.

3.3-Ozonation:

Ozonation process use ozone (O3), a powerful oxidizing agent, to treat waste water. Ozone is bubbled through the water, and it reacts with organic pollutants, including dyes, leading to their degradation [78]. Ozone reacts with the double bonds and aromatic rings present in dye molecules. Photo oxidation reaction involves the transfer of oxygen atoms, leading to the cleavage of chemical bonds within the dye molecules [79]. Ozonation breaks down the dye into simpler, less harmful compounds. Ozonation is effective against a wide variety of dyes, including those resistant to biological treatments [80]. It's also useful in decolorizing and dropping the COD of industrial wastewater. It's a potent and fast-acting oxidizing agent, capable of degrading a wide range of pollutants. The ozonation method was carried out in a batch reactor. The best conditions for processing were a pH of 9, a 6-hour reaction duration, and a 35°C constant temperature [81]. The research findings revealed that a reaction time of one fourth of an hour, a dye concentration of 50 mg/dm^3, an ozone dosage of 300 mg/dm^3, and an acidic pH were the optimal conditions for dye removal. Specifically, Acid Red 183 could be eliminated with a remarkable efficiency of up to 97% through ozonation method. In order to optimize the conventional ozonation method employed for removing dyes, a composite design featuring a central core was implemented [82].

3.4. Photocatalytic degradation of dyes using LED-based light sources:

Photo-catalytic degradation of dyes using LED-based light sources which is based on the activation of semiconductor photo catalysts (like TiO_2 or ZnO) by LED light of suitable wavelength, generating electron-hole pairs. These charge carriers produce reactive oxygen species such as hydroxyl (•OH) and superoxide radicals (•O_2^-), which attack and break down dye molecules into harmless end products like CO_2, H_2O, and inorganic ions. LEDs offer several advantages over traditional UV lamps, including lower energy consumption, wavelength tenability, longer lifespan, and minimal heat generation [83]. This makes LED-driven photo catalysis an efficient, eco-friendly, and emerging technology for wastewater treatment, as demonstrated in recent studies [84] As in the mechanism of dye degradation using LED-activated photo catalysis begins with the absorption of photons by a semiconductor photo catalyst, where LED light of suitable wavelength excites electrons from the valence band (VB**)** to the conduction band (CB**)**, generating electron-hole pairs .These charge carriers drive redox reactions: electrons reduce oxygen molecules on the catalyst surface to form superoxide radicals (•O_2^-), while holes oxidize water or hydroxide ions to produce hydroxyl radicals (•OH) [85]. These reactive oxygen species then attack the dye molecules, breaking their complex chromophoric structures into smaller intermediates and finally mineralizing them into CO_2, H_2O, and inorganic ions, making the process efficient for treating dye-contaminated wastewater [86].

3.5. Ultraviolet (UV) Irradiation:

This method uses ultraviolet light, typically in the UV-C range (200-280 nm), to disinfect and degrade organic compounds, including dyes, by disrupting their chemical structure UV light at certain wavelengths directly interacts with the chemical bonds in the dye molecules, breaking them [77]. This leads to the degradation of the dye into smaller fragments, which are often less colored and toxic. UV irradiation is effective against various dyes, especially those that absorb UV light within the appropriate wavelength range [77]. It's commonly used for disinfection and is useful for breaking down dyes into less harmful substances. It's a chemical-free process, leaves no harmful residues, and is effective in inactivating microorganisms present in the water, making it a dual-purpose method for wastewater treatment. The experimental the poly sulfonate ultra filtration membrane was subject to minor alterations through the application of acrylic acid. In this study, optimal operating conditions include an irradiation time exceeding 30 minutes and a pressure of approximately 4 bars [87]. Lower molecular weight dyes are more likely to be completely removed by this process., Acid Green 20, Acid Blue 92, and can be effectively eliminated by UV irradiation with a remarkable maximum efficiency of 99.9%,[88]. The experiment involving pulsed discharge plasma for water treatment demonstrated that the discharge operated in the spark-streamer mixed mode yielded the highest rate of dye removal. To achieve optimal results, the following parameters are recommended, a wavelength of more than 300 nm, an acidic pH (ideally around 3.5), dye concentration of 0.01 g/L, and a reaction time longer than 100 minutes. Of particular note, Ultraviolet (UV) Irradiation can successfully remove Methyl Orange, Rhoda mine B, and Chicago Sky Blue, with a maximum efficiency of 95%.[89].

3.6. Combined Application of Different Adsorbent for Dye Removal:

Recent studies indicate that the combined application of adsorbent increase the effectiveness of dye removal. The studies suggest that blending traditional physical adsorbents with biocatalysts, specifically biological adsorbents, can yield remarkable outcomes in dye removal. There is also the proposition that activated carbon, known for its highly efficient dye adsorption properties, could potentially achieve even greater results when combined with equally effective enzymes [90].

Furthermore, combining adsorbents may prove effective not only in removing dyes but also in tackling multiple hazardous substances simultaneously. If these combined adsorbents synergize effectively, their efficiency in dye removal could surpass current records. Additionally, the use of combined adsorbents tends to expedite the dye removal process [91]. Moreover, it is believed that this combined application of different adsorbent could lead to improvements such as prolonged retention times and reduced overall costs, mainly due to the reuse capability of such type of combined adsorbents [92]. In contrast, to develop adsorbents are typically single-use, resulting in significantly higher production costs.

4. Future Prospects of Dye Removal Methods

4.1. Physical methods: there are different methods such as adsorption, membrane filtration, and sedimentation are expected to remain central to dye removal due to their operational simplicity and broad applicability [93]. Adsorption, in particular, is widely favoured because of its cost-effectiveness and versatility. The future direction of adsorption-based treatment lies in the development of low-cost, renewable adsorbents such as biochar, activated carbon from agricultural waste, magnetic composites, and nanostructured materials [94]. These innovations aim to improve adsorption capacity, reduce material cost, and facilitate regeneration for multiple cycles. Moreover, the potential for scaling up physical methods makes them suitable for small- to medium-scale industries, particularly in decentralized settings [93]. However, limitations such as adsorbent saturation, disposal issues, and regeneration cost still persist. Future research must address these challenges by improving adsorbent recovery and reusability, particularly in magnetic and photocatalytic systems [94].

4.2. Chemical methods:

The future prospect of chemical methods such as coagulation–flocculation, ozonation, and advanced oxidation processes (AOPs) are also promising for dye removal due to their ability to degrade complex dye molecules into less harmful by-products [95]. Future advancements in this area are expected to focus on greener and more sustainable practices, including the use of eco-friendly coagulants, nanocatalysts, and visible-light-driven photo catalysis using light-emitting diodes (LEDs) [96]. These innovations can enhance the degradation efficiency while reducing energy costs and chemical residues. Despite these advantages, chemical methods face economic and practical constraints, particularly in terms of high energy consumption, chemical usage, and operational complexity [97]. Nevertheless, improvements in catalyst recovery systems, low-cost oxidants, and integration with renewable energy sources could significantly enhance the cost-effectiveness and scalability of chemical treatments in the near future [98].

4.3. Biological methods:

While the future of biological method offers an environmentally sustainable and economically attractive approach to dye removal, particularly for low-concentration and biodegradable dyes [99]. These methods employ dye-degrading bacteria, fungi, algae, and enzymes, which can break down dyes into non-toxic metabolites [100]. The major benefits of biological methods include low energy input, minimal chemical requirements, and ease of integration with natural systems like wetlands and bioreactors. Looking ahead, future developments may include genetically engineered microorganisms, enzyme immobilization, and microbial consortia tailored for specific dye types and wastewater characteristics [101]. However, biological methods are still limited by slow degradation rates, sensitivity to environmental changes, and lower efficiency for non-biodegradable dyes. Hybrid approaches, where biological processes are combined with physical or chemical pre-treatment steps, are likely to emerge as a viable solution to overcome these limitations and enhance overall efficiency and applicability [102].

4.4 Emerging Technologies for Next-Generation Dye Treatment

Next-generation dye wastewater treatment is advancing beyond traditional physical, chemical, and biological processes, integrating smart materials, digital tools, and nanotechnology to improve efficiency, selectivity, and sustainability [103]. One promising approach is the use of machine learning (ML) for process optimization. ML algorithms can analyze large datasets from treatment processes to predict optimal operating conditions—such as pH, temperature, adsorbent dosage, and contact time—for maximum dye removal efficiency [104]. Techniques like artificial neural networks (ANNs), support vector machines (SVM), and genetic algorithms are being used to model complex, nonlinear adsorption or degradation systems, thus minimizing experimental costs and accelerating process design. Smart adsorbents are another breakthrough [105]. These materials, often stimuli-responsive (e.g., pH- or temperature-sensitive), can selectively adsorb dyes and regenerate under specific triggers. For example, thermo responsive hydrogels or magnetic biochar composites can be easily separated and reused, making dye removal more sustainable [106]. Their tunable surface properties and selective binding capabilities offer significant advantages in complex textile effluents. Bio-nanomaterials—a convergence of biotechnology and nanotechnology—offer high surface area, functional group diversity, and catalytic potential [107]. Enzyme-immobilized nanoparticles, metal–organic frameworks (MOFs), and nano-biochar from agricultural waste are gaining attention for catalytic degradation and adsorption of synthetic dyes. These materials can act as nanozymes, mimicking enzymatic activity to break down resistant dye molecules under mild conditions. The Hybrid systems, combining photo catalysis, bio sorption, and AOPs with smart materials, are also gaining attraction [108]. These systems allow for synergistic effects such as simultaneous dye degradation and heavy metal removal offering comprehensive wastewater purification. Eco-friendly dye treatment methods like bio adsorption and solar-driven photocatalysis reduce energy use, minimize waste, and lower carbon emissions compared to conventional chemical processes.

4.5 Case study:

Sustainability in wastewater treatment focuses on resource recovery, including the reuse of water, energy generation, and nutrient recovery, while minimizing the overall environmental burden. The concept of the carbon footprint plays a vital role by quantifying greenhouse gas (GHG) emissions from different stages of treatment, such as aeration, sludge handling, and chemical dosing, thereby guiding industries toward the adoption of low-emission and energy-efficient technologies [109]. In parallel, machine learning (ML) brings significant advantages through predictive analytics, process optimization, and real-time monitoring, enabling industries to improve operational efficiency, reduce costs, and minimize ecological impacts. In practice, these innovations are being increasingly integrated into industrial wastewater systems. For instance, in the textile hub of Tirupur, India, dyeing units have adopted zero-liquid-discharge (ZLD) plants that recycle nearly 90% of wastewater, reducing freshwater consumption and chemical load. Similarly, in the Netherlands, the Heineken brewery employed anaerobic digestion of wastewater to lower fossil fuel use, cutting carbon dioxide emissions by approximately 40%. In the USA, petrochemical plants have applied ML-based models to predict pollutant fluctuations such as COD and TSS, optimize coagulant dosing, and dynamically control aeration, resulting in around 20% energy savings and improved regulatory compliance [110]. Together, these cases illustrate how sustainability, carbon footprint management, and machine learning can be practically combined to create efficient, low-carbon, and adaptive wastewater

5. Conclusion:

From an economic and practical standpoint, the photocatalytic process has emerged as a highly promising approach for treating low to moderate-strength dye wastewater, particularly in scenarios where significant color and toxicity reduction is required. Although the initial costs associated with photo catalyst materials and reactor systems can be high, the long-term benefit including low chemical consumption**,** solar energy utilizati**on**, and minimal secondary pollution—position photo catalysis as a

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competitive and sustainable option for advanced dye treatment technologies. Its practical application is increasingly evident in real effluent systems, especially when deployed as a pre- or post-treatment step in hybrid configurations, where it works synergistically with adsorption **or** biological methods to enhance overall treatment efficiency. Looking ahead, the future of photocatalytic dye removal lies in material science innovations, such as the development of 2D nanostructures**,** hetero junction photo catalysts, and photo electro catalytic systems, which offer improved degradation rates, selectivity, and reusability under visible light. In parallel, the use of combined adsorbents—composites derived from natural or modified materials—has shown great potential in improving dye removal performance, often surpassing the capabilities of single-component adsorbents. These materials are typically derived from readily available and low-cost raw sources, making them particularly attractive for large-scale industrial applications. Their economic feasibility and ease of preparation support their integration into existing wastewater treatment frameworks. Future research should focus on optimizing their surface properties**,** functional group interactions, and regeneration capabilities to handle the diverse and complex nature of industrial dye effluents.

List of Abbreviations:

- ANN: artificial neural networks
- AOP: advanced oxidation processes
- BOD: biological oxygen demand
- CB: conduction band
- COD: Chemical Oxygen demand
- CR: Congo Red
- DO: dissolved oxygen
- GHG: greenhouse gas
- LED: light-emitting diodes
- MB: Methylene Blue
- ML: machine learning
- MOF: metal–organic frameworks
- OH: hydroxyl radicals
- PFO: Pseudo-first-order
- SVM: support vector machines

- TSS: total suspended solid
- UV: Ultraviolet
- VB: valence band
- ZLD: zero-liquid-discharge

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Conceptualization, methodology, software: **DBP, AK**.; Validation, formal analysis, **AK.**; Investigation, resources, data curation, writing—original draft preparation, writing—review and editing, visualization, supervision, project administration: **GLD and DBP.** All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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