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REVIEW

Microorganisms-assisted degradation of Acid Orange 7 dye: a review

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Abstract

The escalating global concern over water pollution, predominantly propelled by industrial activities, underscores the urgency for effective environmental remediation strategies. Of particular, concern is the discharge of synthetic colorants into water bodies, a prevailing issue notably pervasive in textile industries. Azo dyes, ubiquitous in various industrial sectors, including food and textile manufacturing, constitute a significant portion of dye-contaminated wastewater, thereby contributing to soil and water pollution, especially in emerging and economically challenged nations. The deleterious impact of azo dyes on human health and aquatic ecosystems heightens the urgency of addressing this environmental menace. In response to the imperative need for mitigating the adverse effects of azo dyes on the environment, human health, and natural water resources, a spectrum of physio-chemical technologies has been proposed for azo dye degradation. However, a noteworthy paradigm shift toward environmentally friendly approaches is increasingly imperative. This comprehensive review critically examines various strategies employed for the degradation of Acid Orange 7, a representative azo dye, encompassing physical, chemical, and biological interventions. In the realm of biological treatment, the focus is predominantly on microorganisms such as fungi, yeast, bacteria, and algae, which have emerged as promising agents due to their inherent eco-friendly nature. This article provides an in-depth exploration of microbial remediation strategies, highlighting recent advancements in degradation techniques and elucidating the intricate mechanisms underlying azo dye degradation by bacteria. This review aims not only to present a consolidated overview of existing technologies but also to underscore the importance of harnessing the potential of microorganisms in the treatment of azo-dye-containing wastewater. The comprehensive insights provided herein contribute to the evolving discourse on sustainable and environmentally benign approaches for mitigating the impact of azo dyes on global water resources.

Keywords Water pollution · Azo dyes · Acid Orange 7 · Wastewater · Physico-chemical · Microorganisms · Environmental remediation

Introduction

The ever-increasing threat of environmental pollution poses a monumental challenge to the delicate balance of ecosystems and the well-being of humanity (Shen et al. 2023; Saharan et al. 2023; Ke Wang 2023, Kim et al. 2013). Defined as any human activity causing the natural environment's deterioration or loss of quality, pollution has evolved from a historical concern into the paramount factor in environmental morbidity and mortality (Ukaogo et al. 2020; Radhika 2019; Kaur et al. 2023; Su et al. 2023). This

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review embarks on an exhaustive exploration of the intricate web of environmental pollution, with a special focus on the profound implications of azo dyes emanating from the textile industry. The urgency of this review is underscored by the critical need for sustainable and innovative strategies to address the global ramifications of textile dye-associated pollution.

Environmental pollution is a complex phenomenon, manifesting across various dimensions including air, water, and soil/land pollution (Zhang et al. 2023; Kumar et al. 2023). The release of hazardous substances into the environment, such as toxic metals, gaseous pollutants, particulate matter, and a myriad of anthropogenic activities like sewage, industrial effluents, agricultural runoff, and electronic waste disposal, collectively contributes to the overarching menace of pollution (Jiku et al. 2021; Imran et al. 2023; Kamalam et al. 2023). A concerning aspect is the ineffective textile dyeing techniques, resulting in the discharge of 15–50% of azo dyes into generated wastewater, thereby exacerbating water pollution. These pollutants, classified as primary and secondary, infiltrate the atmosphere through domestic, industrial, and transportation sources, marking the distinction between directly released primary pollutants (e.g., CO, CO_2, NO_2, SO_2) and secondary pollutants, which form in the atmosphere from primary pollutants (Lin et al. 2022a, b; Kaur et al. 2021; Abdullah et al. 2023).

Underground water sources face pollution risks from naturally occurring ores rich in toxic metals like copper, lead, iron, and silver, further amplifying the complexity of the pollution landscape (Yan et al. 2022). Soil pollution, arising from the migration of organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), pesticides, herbicides, and volatile organic compounds (VOCs), adds another layer to the intricate tapestry of environmental degradation (Ma et al. 2021; Singh et al. 2023; Gupta et al. 2023). Anthropogenic sources, including open-air trash disposal, waste burning, and inadequate landfills, significantly contribute to soil pollution, marking three primary causes of this environmental concern (Li et al. 2019).

The worldwide economy and environmental pollution share an inextricable link, with the textile industry playing a pivotal role in this interplay (Olisah et al. 2021; Ramanpreet Kaur et al. 2021). China's ascendancy as the largest manufacturer of dye stuffs since 1995, producing over 200 kt annually, underscores the global significance of the textile industry in the pollution paradigm (Rafi et al. 1990). The historical attraction of humanity to color, expressed through the use of natural substances for dyeing, has evolved into a complex scenario with the advent of agriculture, permanent communities, and the utilization of textiles.

The modern textile industry, driven by a multitude of water-soluble dyes, introduces an array of environmental challenges. Dyes and pigments, integral to various sectors, are manufactured using organic solvents that chelate with metals, resulting in effluents containing acids, alkalis, salts, and nitro compounds (Gao et al. 2018; Sharma et al. 2020; Li et al. 2022a, b). The indispensable role of dyes in human life, evident in kitchenware, furniture, painted walls, and colored meals, necessitates a thorough examination of the environmental consequences of their production and usage.

The textile industry, a dynamic hub of innovation and creativity, relies on a diverse range of natural and synthetic fibers, including acrylic, wool, cotton, silk, polyester, and polyamide (Silva et al. 2021; Lin et al. 2022a, b). However, at various stages of the textile production process, the industry employs a vast array of harmful chemicals for finishing, smoothing, whitening, and sizing, further contributing to the environmental footprint (Gao et al. 2022; Kishor et al. 2021; Kaur et al. 2019; Sherwani et al. 2022). The discharge of textile dyes as untreated waste into marine ecosystems, including rivers, oceans, lakes, streams, and ponds, poses significant ecotoxicological risks with profound consequences for living organisms (Parmar et al. 2022; Meng et al. 2022).

The staggering removal of tons of azo dyes annually, driven by concerns related to cancer and mutation risks, forms a critical socioeconomic and environmental issue (Solovchenko et al. 2020; Bawazeer et al. 2022). It is against this backdrop of urgent and interconnected challenges that the need for a comprehensive review on the degradation of azo dyes arises.

The novelty of this review lies in its comprehensive exploration of the multifaceted dimensions of environmental pollution, focusing specifically on the impact of azo dyes from the textile industry. As pollution continues to escalate and pose a formidable threat to global ecosystems, the need for innovative and sustainable solutions is more pressing than ever. Traditional methods of wastewater treatment and pollution control are proving insufficient, necessitating a paradigm shift toward environmentally favorable technologies.

A critical examination of the techniques employed for the degradation of azo dyes becomes imperative in this context. This review serves as a repository of knowledge, dissecting treatment processes, physical and chemical interventions, and biological methods that hold promise in mitigating the adverse effects of azo dyes on the environment. The detailed exploration of factors influencing dye degradation, including pH, dye concentration, temperature, and structural attributes, contributes to a nuanced understanding essential for the formulation of effective remediation strategies.

The elucidation of the mechanisms orchestrating azo dye degradation by bacteria and white rot fungi adds a layer of sophistication to our understanding, paving the way for tailored and targeted interventions. Furthermore, the review ventures into other strategies utilized for azo dye degradation, providing a comprehensive overview of the evolving landscape in this critical field of study.

As the world grapples with the consequences of industrialization and globalization, the role of the textile industry in environmental pollution cannot be understated. This review, in its timeliness, seeks to bridge the existing knowledge gaps, offering insights into the current state of affairs and paving the way for future advancements in sustainable textile production and pollution control.

This review stands at the intersection of environmental science, chemistry, and engineering, presenting a holistic perspective on the challenges posed by azo dyes in the textile industry. Its significance lies not only in the critical examination of existing methodologies but also in the identification of emerging strategies that align with the principles of environmental sustainability. As we embark on this scientific journey, the urgency of addressing the environmental consequences of textile dyeing practices becomes palpable, highlighting the crucial role of this review in shaping the discourse on sustainable and eco-friendly solutions for the textile industry and beyond.

In the vast realm of synthetic dyes, the azo group stands as a distinctive and chemically significant entity, marked by the presence of the nitrogen-to-nitrogen double bond (-N = N-). This review embarks on an intricate exploration of azo dyes, delving into their chemical intricacies, industrial applications, and profound implications for environmental sustainability. A critical understanding of azo dyes is paramount, given their prevalence, vibrant coloring, and extensive use across diverse industries.

Azo dyes

Chemically characterized by the (-N = N-) azo chromophore group, azo dyes encapsulate a broad spectrum of compounds where one to three azo bonds unite phenyl and/or naphthyl rings. The versatility of these compounds is highlighted by the substitution possibilities with groups such as amino, chloro, nitro, and hydroxyl (Shindhal et al. 2021). Synthetic procedures, including hydrogenation and oxidation, yield varied azo compounds, with their vivid colors distinguishing them as a predominant class constituting nearly two-thirds of contemporary synthetic dyes (Bell et al. 2000; Chung 2016; Liu et al. 2022a, b; Ritika et al. 2018).

The chemical structure of azo dyes is not merely an aesthetic consideration; it extends to functional aspects, particularly in metal complexation. The ortho positions adjacent to the azo group provide a coordination site for metal ions, with copper(II), cobalt(III), chromium(III), etc. emerging as prominent choices for commercial metal complexes (Ghosh et al. 2016; Suo et al. 2022). This intersection of chemical structure and metal coordination underscores the versatility and applicability of azo dyes in a myriad of industrial processes.

Azo dyes, celebrated for their vibrant hues, find extensive application across diverse industries, with the textile sector serving as a prominent canvas for their expression. They play a pivotal role in coloring textiles composed of protein fibers, cellulose, and synthetic counterparts like polyester and nylon. Beyond textiles, their influence extends to culinary, printing, leather, pharmaceutical, and cosmetic domains (Oon et al. 2017; Chaudhary et al. 2018; Liu et al. 2022a, b). Figure 1 encapsulates the pervasive role of azo dyes in textile production, illustrating the various wet processes involved, including dyeing, finishing, printing, and scouring. However, this multifaceted utility comes at a cost, as the contaminants released during these processes pose environmental and health risks if not adequately treated.

The intricate wet processes depicted in Fig. 1 unveil the complexity of textile production, emphasizing the potential contaminants released during dyeing, finishing, printing, and scouring. It serves as a visual testament to the profound impact of azo dyes on the environment and underscores the necessity for rigorous treatment before their release.

A deeper comprehension of azo dyes necessitates an exploration of their chemical structure, depicted in Fig. 2. The intricate arrangement of atoms in the azo chromophore embodies the essence of these compounds. Unraveling this structural complexity is pivotal for understanding their reactivity, interactions, and, importantly, their environmental fate.

Figure 2 elucidates the chemical architecture of an azo dye, providing a visual representation of the nitrogen-to-nitrogen double bond and the phenyl/naphthyl rings. This structural insight lays the foundation for a more nuanced exploration of their behaviors and transformations in various environments.

As we stand at the intersection of technological advancement and environmental consciousness, the significance of this review becomes evident. The widespread use of azo dyes in diverse industries demands a comprehensive evaluation of their chemical intricacies, industrial applications, and, crucially, their environmental impact. The urgency of this review is underscored by the evolving landscape of environmental regulations, consumer awareness, and the imperative for sustainable industrial practices. In an era where the ecological footprint of industrial processes is under unprecedented scrutiny, a review focusing on the chemical nuances of azo dyes and their environmental implications is both timely and imperative. This work seeks to unravel the complexities surrounding azo dyes, providing a valuable resource for researchers, industry professionals, and policymakers navigating the intricate intersection of chemistry, industry, and environmental stewardship.

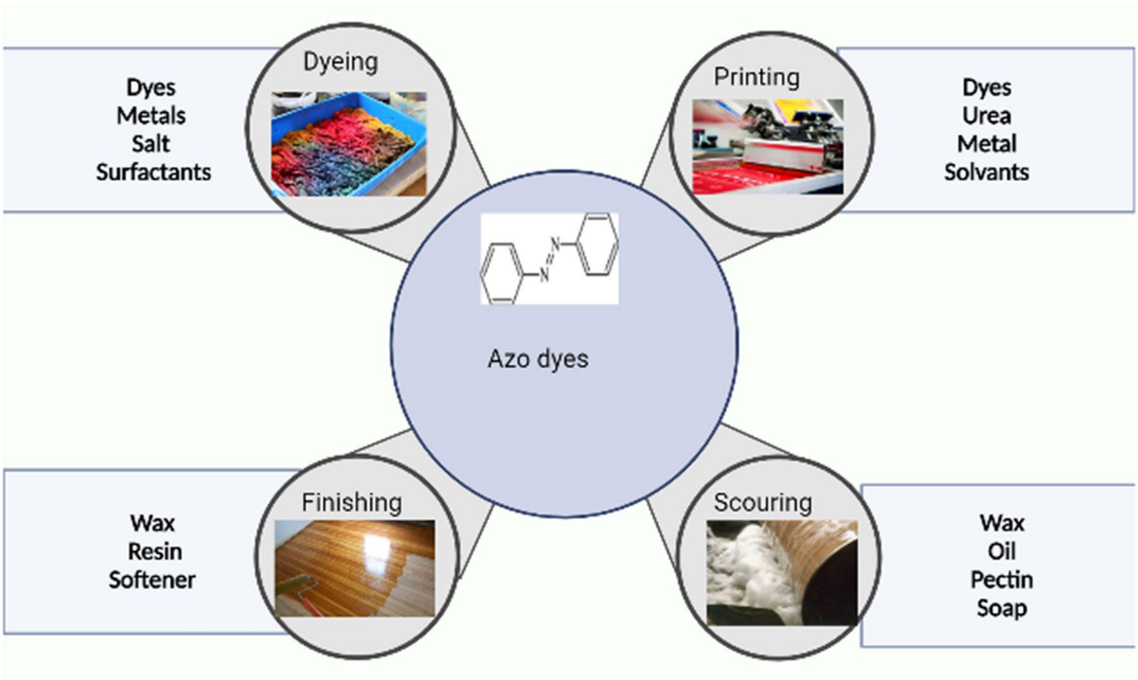

Fig. 1 Azo dyes in textile production

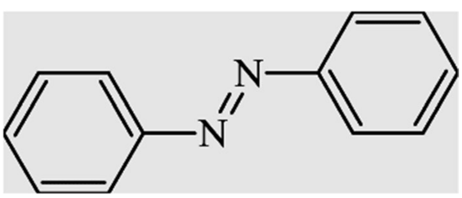

Fig. 2 Chemical structure of azo dye

Acid Orange 7

In the realm of synthetic colorants, Acid Orange 7 (AO7) stands out as a ubiquitous azo dye, boasting a distinctive orange hue employed in the vibrant coloring of leather, paper, and a spectrum of textile materials, including wool, silk, and nylon. Functioning as a direct printing agent, AO7's chromatic allure is deeply intertwined with its molecular architecture and the intricate interplay of auxochromes and chromophores (Anliker et al. 1980). Auxochromes, pivotal in the color expression of dyes, act as electron-donating or electron-withdrawing substituents. They not only produce but also amplify the color of chromophores, the atomic groups responsible for imparting color to dyes. In the case of AO7, notable auxochromes include hydroxyl (OH), amine (NH_3), and carboxyl (COOH), while key chromophores encompass azo (NN), sulfonate (SO_3H), nitro (NO_3), carbonyl (CO), and methine (CH). The environmental implications of AO7 are profound, especially when discharged untreated into water bodies. This unbridled release leads to a surge in water color and a consequential decline in water quality. Of particular concern is the anaerobic breakdown of AO7 by microorganisms within water bodies, culminating in the production of aromatic amines. These amines, recognized for their carcinogenic and mutagenic properties, pose a severe threat to both human health and the delicate balance of aquatic ecosystems.

The impact of high salinity levels, reaching 2.0% salinity, adds another layer of complexity to the AO7 conundrum. This elevated salinity adversely affects the viability of microbial cells, thereby diminishing the efficacy of AO7 removal and nutrient elimination. Addressing this challenge necessitates a strategic approach, balancing rapid adsorption and deliberate biodegradation processes. In the realm of AO7 removal strategies, a nuanced combination of rapid adsorption and deliberate, albeit slow, biodegradation processes emerges as a viable solution. The biodegradation of AO7 unfolds gradually within the anaerobic granular sludge (AGS) system, involving intricate processes such as desulfurization, deamination, decarboxylation, and hydroxylation. This stepwise mineralization of AO7 underscores the complexity of its breakdown pathways within a controlled biological environment. The imperative for dedicated research on the degradation mechanisms of AO7 becomes evident, driven by the urgent need to mitigate the environmental impact of this widespread azo dye. Understanding the intricacies of AO7 degradation pathways equips researchers and environmental stewards with valuable insights, paving the way for sustainable solutions to counteract its deleterious effects on aquatic ecosystems. In this pursuit, the scientific community plays a pivotal role in unraveling the mysteries of AO7 degradation, contributing to the broader goal of ensuring environmental health and sustainability.

A comprehensive classification of azo dyes

In the kaleidoscopic realm of synthetic dyes, azo dyes reign supreme, exhibiting a versatility that stems from their diverse origin, intricate structures, and targeted applications across various industries. This comprehensive classification, shaped by insights from Holkar et al. (2016) and Akpomie et al. (2020), delves into the nuanced categories of azo dyes, shedding light on their molecular intricacies and industrial significance. Azo dyes exhibit a rich diversity that extends beyond mere color. Structurally, these dyes can be categorized based on the number of azo bonds present. Mono-azo molecules, with a single N=N azo bond, dominate the palette, imparting color to a myriad of materials. Beyond this, the complexity unfolds with di-azo dyes, featuring two N=N bonds, and poly-azo counterparts, boasting three or more azo bonds. This structural diversity becomes a canvas for the vibrant hues that azo dyes contribute to the world of synthetic coloring (Benkhaya et al. 2020; Bharathi et al. 2022; Liu et al. 2022a, b).

The expansive utility of azo dyes becomes apparent as we explore their application across various sectors. Industries such as cosmetics, textiles, leather, paints, and printing harness the vivid properties of azo dyes extensively, weaving them into the fabric of everyday life. This broad classification underscores the ubiquitous nature of azo dyes, emphasizing their pivotal role in the coloration of diverse materials (Varjani et al. 2020). Within the azo dye spectrum, acid colors emerge as one of the most diverse groups, predominantly characterized by their anionic nature. Applied extensively to color wool and cloth, acid dyes form a bond with the cationic functional group ($NH4^+$) of fibers. Found both in nature and synthetically produced, acid dyes encompass the azoic (red), anthraquinone (blue), and triarylmethane variants, illustrating the extensive chromatic range within this category. Reactive dyes carve a unique niche by forming covalent bonds with the "–OH," "–NH," or "–SH" groups of materials like cotton, wool, silk, or nylon. Aptly named, these reactive colors showcase a chromophore responsiveness, aligning with the substrate fiber. However, a caveat arises, as 40% to 50% of reactive dyes persist in hydrolyzing in the aqueous phase, contributing to colored water effluent. A subset of acid and reactive dyes takes on a distinctive character by incorporating metal complexes. These metal-complex dyes, although not explicitly distinguished in the Color Index, wield significant influence. Their application extends across diverse industries, bringing forth a nuanced interplay of color and metallic elements. Direct dyes showcase a high affinity for cellulose fibers, drawn together by Van der Waals forces. Meanwhile, basic dyes, characterized by their cationic nature, lend their vibrant hues to artificial fabrics such as polyester, silk, and wool. The adherence of basic dyes necessitates the use of dye mordants, contributing to their extensive use in histological research for tissue and cell staining.

Disperse dyes, predominantly azo or anthraquinone-based, exhibit low water solubility, making them ideal for specific applications. Vat dyes, initially insoluble, undergo reduction and become water-soluble with sodium dithionite treatment. Sulfur dyes, sharing similarities with vat dyes, undergo reduction and oxidation processes during textile dyeing, contributing to their unique coloration properties. Within the vast tapestry of azo dyes, solvent dyes take center stage in coloring substrates like plastic, wax, varnish, ink, and fat. Solubilized in these mediums, solvent dyes impart color to materials that remain otherwise insoluble.

Figure 3 encapsulates the essence of azo dye classification, offering a visual representation of mono-azo, di-azo, and poly-azo bonds. This molecular tapestry captures the structural intricacies that define the chromatic richness of azo dyes. The classification of azo dyes transcends color, delving into the very essence of molecular structures and industrial applications. This expansive categorization, spanning mono to poly-azo bonds and diverse application strategies, unravels the intricate tapestry of azo dyes, portraying them as indispensable contributors to the vivid palette of synthetic coloring agents.

Impact and toxicity of textile dyes

The vibrant and diverse world of textile dyes conceals a darker reality as their unbridled release into the environment wreaks havoc on ecosystems and poses a looming threat to both aquatic life and human well-being. This section delves into the multifaceted impacts and inherent toxicity of textile dyes, shedding light on the intricate web of consequences that ensue from their unregulated disposal. Textile wastewater, laden with azo dyes, emerges as a potent environmental pollutant, staining water bodies with vivid hues and threatening aquatic life. Zebrafish, a sensitive indicator of water quality, bears the brunt of this pollution. Research findings by Ahlström et al. (2005) reveal a spectrum of maladies inflicted upon zebrafish embryos exposed to varying concentrations of Azo dye. From hatching issues to genetic abnormalities, including heart enlargement, decreased heart rate, placental enlargement, and spinal distortions, the impact is profound. At higher concentrations of 100 mM, the lethal

Fig. 3 Different types of dyes and their application

repercussions underscore the urgency of addressing azo dye contamination in aquatic ecosystems.

The insidious infiltration of Azo dyes into the soil disrupts the delicate balance of nitrogen and carbon cycles (Rehman et al. 2018). Regulatory measures, exemplified by the European Commission's restrictions on specific dyes, underscore the gravity of the issue. The prohibition of certain dyes in textiles above 30 ppm concentration and the restriction of leather and textile items containing hazardous amines, especially those in direct skin contact, aim to mitigate the environmental and health risks associated with Azo dyes (Wesenberg et al. 2003; Sood et al. 2015a, b; Tang et al. 2022).

The nexus between textile dyes and human health is fraught with peril, primarily driven by the presence of carcinogens like benzidine and other aromatic chemicals produced during microbial metabolism (Nikulina et al. 1995). Water-soluble colors, including Azo dyes, become conduits for human exposure through ingestion or direct contact. The repercussions are severe, encompassing physiological afflictions such as intermittent fever, hypertension, kidney damage, and cramping. The insidious integration of these toxins into water bodies and aquatic species through the food chain amplifies the urgency of addressing this health and environmental crisis (Asad et al. 2007).

Azo dyes, characterized by their chemical stability and synthetic nature, pose a formidable challenge to conventional wastewater treatment processes. Their slow breakdown and resistance to microbiological attacks perpetuate their persistence in the environment, emphasizing the need for innovative strategies to tackle their recalcitrance (Vinitnantharat et al. 2008). In underdeveloped nations, the use of untreated industrial effluents for agricultural irrigation presents a stark agricultural conundrum. The repercussions are felt as crop germination rates plummet, and soil quality deteriorates. This alarming trend underscores the urgency of implementing treatment plans to safeguard both agriculture and the overarching ecosystem, ensuring sustainability for future generations (Sojobi et al., 2022; Manickam et al., 2021; Lamba et al. 2015; Sood et al. 2015a, b).

The imperative for sustainable practices echoes loudly in the face of escalating environmental degradation caused by textile dye contaminants. Addressing the toxicity and carcinogenicity of these substances requires concerted efforts, innovative treatment methodologies, and stringent regulations. As textile dyes continue to infiltrate the intricate tapestry of ecosystems, the call for sustainable practices and holistic solutions becomes more urgent than ever (Mudhoo et al. 2020).

The impact and toxicity of textile dyes extend far beyond the realms of aesthetics, unraveling a narrative of environmental peril, human health risks, and agricultural vulnerabilities. Mitigating these threats demands a collective commitment to sustainable practices, innovative technologies, and unwavering regulatory measures to safeguard the delicate balance of our ecosystems.

The captivating array of colors that enrich our fabrics belies a concealed threat, as textile dyes, when not meticulously managed, can unleash a myriad of health hazards. Khan et al. (2014) underscore the potential impact on the immune system, unveiling a phenomenon known as respiratory sharpening. The consequences range from mild irritations, such as tingling, watering eyes, and sniffling, to more severe asthmatic symptoms, including wheezing and hacking. Beyond the immediate discomfort, the long-term ramifications are ominous, with the potential to escalate to heightened immune reactivity upon subsequent exposure.

The sinister alliance between azo dyes and various cancers further intensifies the health risks. Azo dye consumption has been linked to elevated risks of bladder cancer, splenic sarcomas, and hepatocarcinoma, painting a dire picture of the potential consequences for human health (Mishra et al. 2014). Skin ailments, allergies, and DNA damage add another layer to this complex narrative, with the latter paving the way for the insidious growth of cancerous tumors. Methyl Yellow dye, once used illicitly to color butter, serves as a chilling example of the latent dangers, inducing liver cancer in rats after mere months of exposure. Similarly, Amaranth, implicated in DNA damage in mouse colon epithelial cells, serves as a poignant reminder of the genotoxic potential of certain dyes (Ali et al. 2020).

Figure 4 demonstrates the comprehensive spectrum of effects that azo dyes can impose on human health, underscoring the urgency of addressing these health hazards. The list includes tartrazine, associated with angioedema, nasal congestion, itchy skin, and hives, as well as the potential to bind to albumin, induce neurotoxicity, and impair mental abilities (Zanoni et al. 2013). The hepatocarcinogenicity of printer dye 4-aminobenzene, also known as aniline yellow, further accentuates the range of adverse health outcomes linked to dye exposure (Chung 2016). Sudan III, commonly used in coloring non-polar materials, adds to the ominous tally, with documented links to cancer (Puvaneswari et al. 2006).

The deleterious impact of textile dye pollution necessitates urgent remediation strategies. Physico-chemical treatments, including electrocoagulation, coagulation–flocculation,

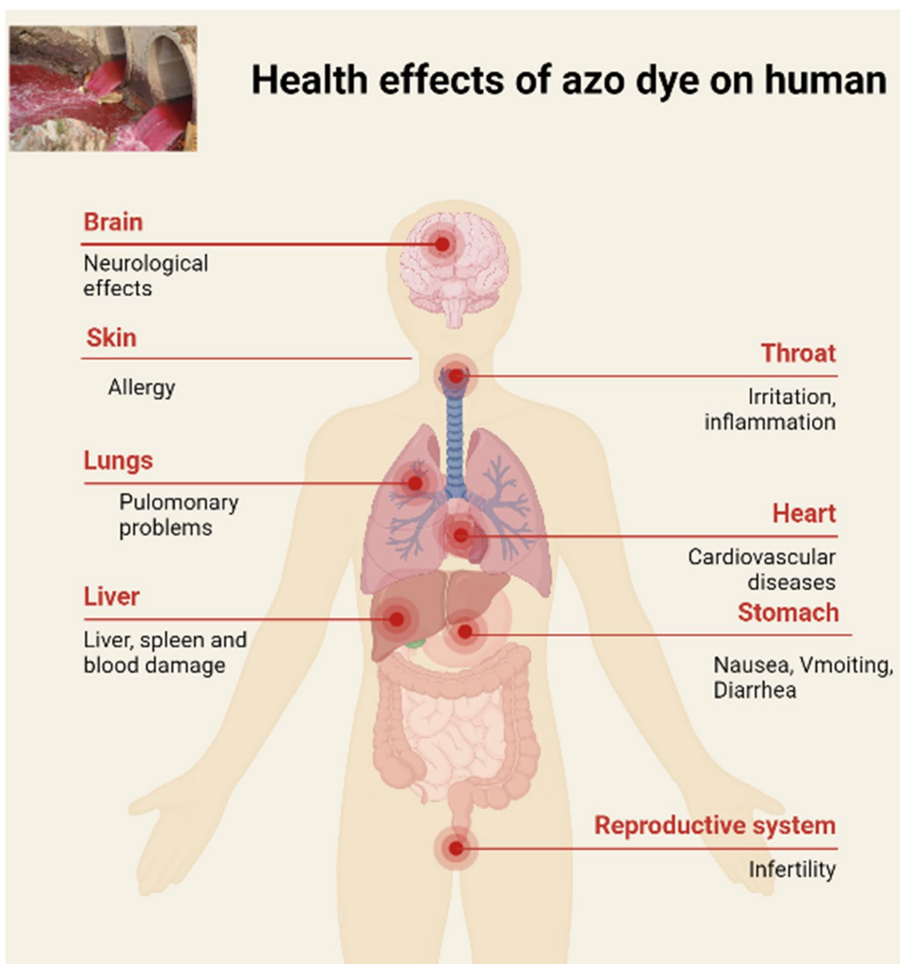

Fig. 4 Effects of azo dyes on human health

and adsorption, have been employed to address the issue. However, these methods bear significant drawbacks, ranging from high costs and substantial sludge production to the generation of harmful substances, such as aromatic amines, which pose disposal challenges (Bayramonglu et al., 2007; Wang 1990; Ghaly et al. 2014). Figure 4 encapsulates the complex effects of azo dyes on human health, urging the exploration of alternative and more sustainable solutions.

The quest for affordable and effective solutions to tackle textile wastewater pollution has spurred a paradigm shift toward bioremediation. This biological method emerges as a promising avenue, boasting advantages of lower costs, increased sustainability, and enhanced safety when compared to chemical and physical reclamation methods. Bioremediation, a process that leverages the natural capabilities of microorganisms to break down pollutants, offers a more eco-friendly approach to addressing the menace of dye pollution (Bayramonglu et al., 2007).

The significance of biodegrading azo dyes extends beyond immediate remediation. It provides a sustainable and eco-friendly avenue for addressing the chronic issue of dye pollution, offering insights into the mechanisms that drive the breakdown of these persistent compounds. This understanding becomes a catalyst for developing more efficient and effective bioremediation methods, ensuring a holistic and sustainable approach to environmental stewardship. In a world increasingly focused on sustainable production, bacterial bioremediation emerges as a crucial player in the endeavor to balance industrial progress with ecological responsibility. As we navigate the complexities of textile dye pollution, the importance of embracing innovative and eco-conscious solutions becomes more apparent, steering us toward a future where environmental health and industrial activity coexist harmoniously.

Techniques for azo dye degradation

As we grapple with the intricate challenge of azo dye degradation, the selection of an appropriate treatment technology becomes a pivotal decision. It is a multidimensional choice, intricately tied to the presence of additional inorganic and organic elements, their toxicity, and the mandated environmental discharge levels (Li et al. 2022a, b; Zhang et al. 2019). The daunting task is further exacerbated by the remarkable water solubility of azo dyes, making their removal through conventional techniques a formidable challenge (Varjani et al. 2021).

Figure 5 serves as a visual testament to the myriad factors that intricately interplay when determining the most suitable technology for textile dye degradation. The decision-making process involves a delicate balance, considering not only the nature of the dye but also the broader environmental implications. This intricate dance between elements underscores the need for a nuanced approach to azo dye treatment.

The vast landscape of dye wastewater treatment unfolds through three primary categories: chemical, physical, and biological treatment. This triad forms the backbone of the industrial arsenal against dye pollution, with a spectrum

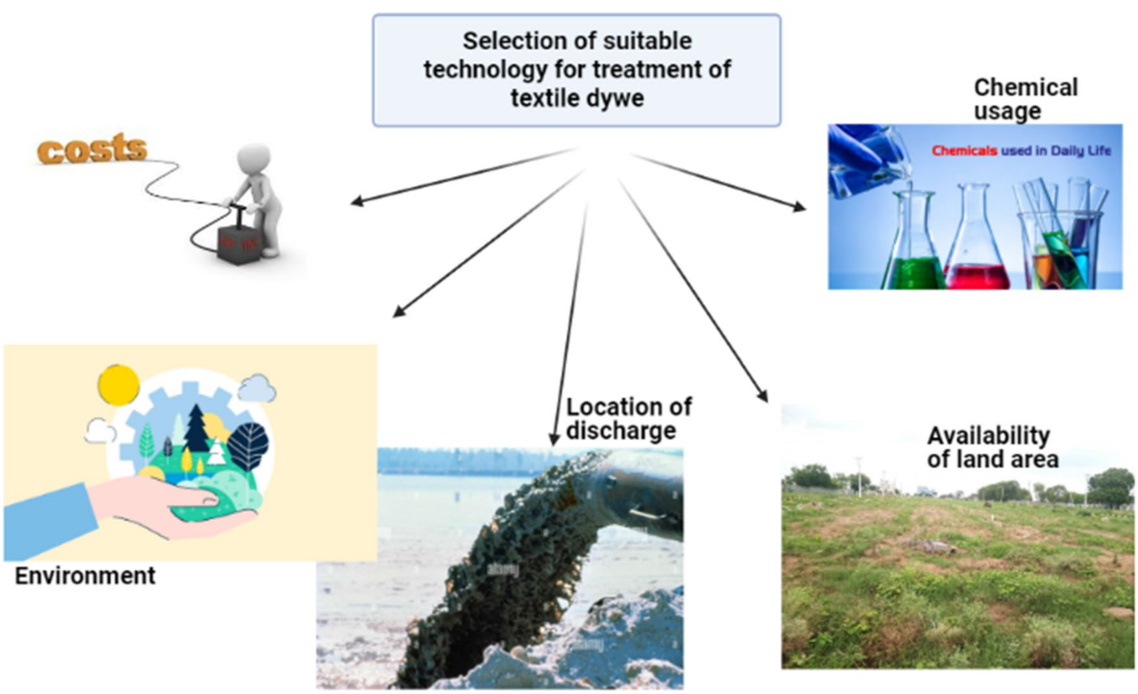

Fig. 5 Factors that affect the selection of suitable technology for the treatment of textile dye

of treatments employed at various stages of the effluent management process. The journey begins with preliminary treatment, encompassing equalization and neutralization, laying the foundation for subsequent interventions (Atul et al. 2012). Sedimentation, screening, chemical coagulation, flocculation, and floating constitute the initial steps, orchestrating the removal of impurities and preparing the effluent for further refinement. The secondary treatment phase comes into play, introducing methods such as physical–chemical separation and biological oxidation to target organic molecules and elevate the treatment efficiency (Mandal et al. 2020). It is a delicate choreography, a symphony of processes working in harmony to transform the polluted effluent into a more benign form. The crescendo of this treatment symphony is the tertiary treatment, a pivotal phase that significantly enhances the overall efficacy of effluent treatment. As illustrated in Fig. 6, this stage acts as a refining touch, addressing residual contaminants and ensuring that the effluent released into the environment meets stringent standards (Mandal et al. 2020). The array of treatment processes for azo dye degradation showcased in Fig. 6 underscores the diverse strategies employed, each tailored to the unique demands of the effluent at hand.

The journey through the intricacies of azo dye degradation treatment is a testament to the ongoing efforts to harmonize industrial progress with environmental responsibility. The selection of treatment technologies is not merely a technical decision; it is a conscientious choice that echoes through the delicate ecosystems impacted by dye pollution. As we navigate the complexities of dye wastewater treatment, the imperative remains to seek sustainable and effective solutions that safeguard our environment for future generations.

Efficient wastewater treatment is a multistage process, crucial for mitigating the environmental impact of dye pollutants. Each stage plays a distinctive role in ensuring the transformation of contaminated effluent into a form compatible with environmental standards.

Preliminary treatment

The journey commences with the equalization and mixing of wastewater streams from diverse manufacturing operations. This preliminary stage ensures a harmonious blend, establishing consistent temperature, pollutant load, and pH characteristics. This equalization process sets the stage for subsequent treatments, laying the foundation for a more efficient and streamlined purification process.

Primary treatment

Primary treatments unfold as a symphony of screening, sedimentation, and flotation. While these methods effectively tackle many pollutants, fine, suspended, and colloidal impurities pose challenges. Chemical coagulation emerges as a key player, employing substances like alum, polyelectrolyte,

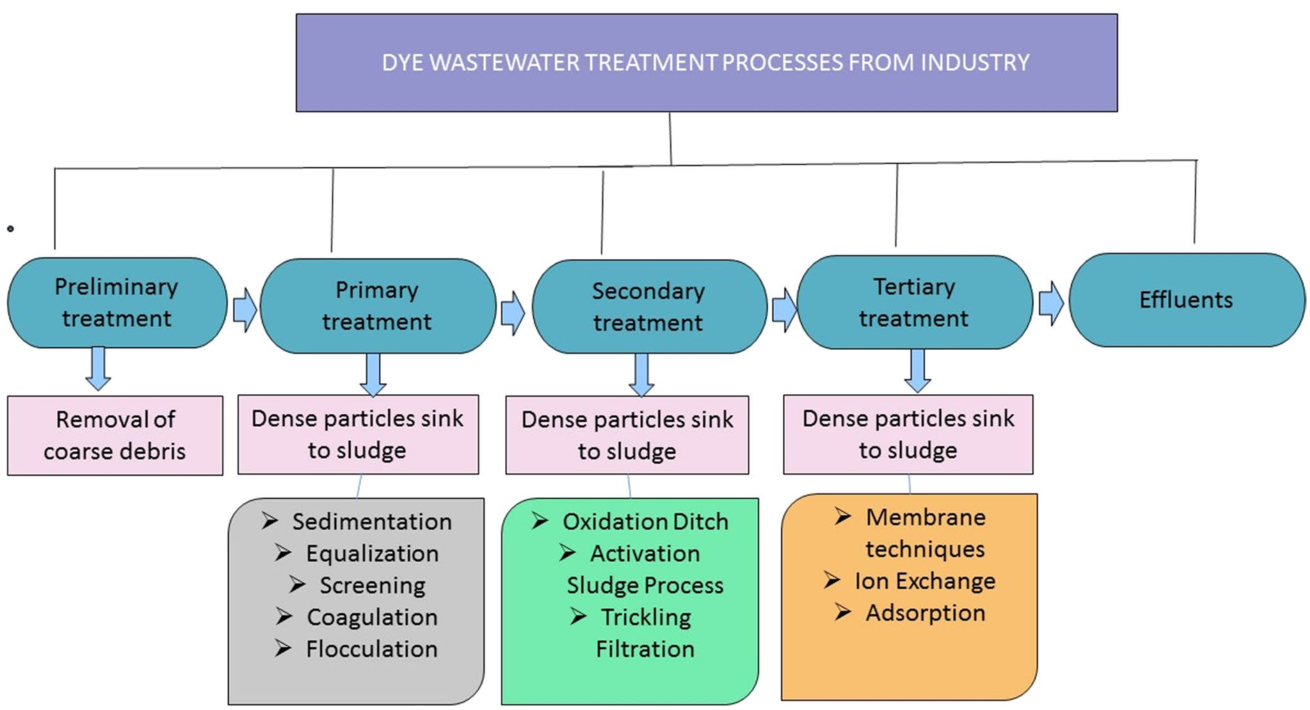

Fig. 6 Various treatment processes for the azo-dye degradation

ferrous sulfate, ferric chloride, and lime. This not only aids in flash mixing but also facilitates the reduction of COD and BOD. However, the chemical coagulation process proves more effective in decolorizing insoluble dyes than their soluble counterparts (Xue et al. 2019; Khouni et al. 2011).

Secondary treatment/biological treatment

Secondary wastewater treatment takes center stage in stabilizing color and dissolved organic components. Microbial wonders, including bacteria, fungi, and yeast, engage in a vital dance to complete this intricate process. Both anaerobic and aerobic processes come into play, providing a versatile approach. Anaerobic processes facilitate waste digestion, contingent on factors such as temperature, pH, oxygen levels, and the presence of toxic materials. In contrast, aerobic processes showcase the transformative prowess of microorganisms, progressively altering colloidal substances, oxidizing organic molecules, and converting organic nitrogenous substances. Though aerobic treatment has proven less effective for azo dyes, its utilization remains situational (Carmen et al. 2012; Popli and Patel 2015).

Tertiary treatment/chemical treatment

Tertiary treatment takes the effluent refinement to its zenith, addressing organic colorants, dissolved solids, and adsorption through membrane filtration methods. The wastewater from the dye industry, laden with hazardous colors, demands an enhanced treatment approach. The use of oxidizing agents like ozone in tertiary treatment proves instrumental in eliminating various contaminants, providing a final touch to the purification process.

Physical and chemical treatment of azo dye

The arsenal of methods for azo dye treatment includes both physical and chemical techniques, a testament to the multifaceted challenge posed by these synthetic colors. Physical approaches encompass filtration and adsorption, with activated carbon emerging as a preferred yet cost-prohibitive choice. Membrane filtration methods such as reverse osmosis, nano-filtration, and ultrafiltration find application for water reuse and chemical recovery, albeit with challenges like high upfront costs and the potential for membrane fouling.

Chemical treatment, on the other hand, deploys various substances and methods, including electrochemical processes, ozone, coagulation–flocculation, and Fenton's reagent. Flocculation and coagulation are succeeded by sedimentation in typical wastewater treatment facilities, although challenges persist, with some dyes proving resistant to conventional remedies. This underscores the urgency of exploring environmentally acceptable methods to manage synthetic colors, particularly the stubborn azo dyes.

As depicted in Fig. 7, diverse physicochemical methods, such as coagulation, adsorption, membrane separation, ion exchange, and more, contribute to the intricate tapestry of azo dye degradation. This visual representation serves as a comprehensive guide, outlining the array of physical and chemical techniques employed in the pursuit of sustainable and effective solutions.

As the treatment processes for azo dye degradation unfold, the imperative remains to navigate the complexities with a commitment to sustainability. Balancing industrial progress with environmental responsibility, the ongoing quest for safer, more efficient methods underscores the dynamic nature of wastewater treatment in the face of evolving challenges. Each stage in this journey is a testament to our collective responsibility, steering toward a future where the impact of dye pollutants is mitigated for the well-being of both ecosystems and future generations.

Coagulation

In the intricate symphony of wastewater treatment, coagulation stands out as a powerful pre-treatment process, renowned for its efficiency, simplicity, and minimal initial investment (Liang et al. 2014). This technique proves invaluable in the removal of turbidity particles and organic debris from the aquatic environment. A key application of coagulation emerges in the realm of dye removal, where it orchestrates the formation of flocs, destabilizing dye solution systems (Fig. 8) (Zhao et al. 2018).

Conventional metal coagulants, such as ferrous sulfate and ferric chloride, are gradually losing favor due to their limited applicability, propensity for excessive sludge formation, and sensitivity to pH variations (Zheng et al. 2020). The evolving landscape of coagulation has witnessed the emergence of various polymeric substances, both natural and synthetic, with exceptional flocculation capabilities. Notable examples include modified chitosan- and dextran-based substances, some even graft-modified, showcasing their prowess in the formation of effective flocs (Anjaneyulu et al. 2005).

In a study by Shi et al. (2007), coagulation with aluminum chloride ($AlCl_3$), polyaluminum chloride (PAC), and pure Al13 demonstrated efficacy in removing Direct black 19, Direct red 28, and Direct blue 86. The removal rate exhibited an upward trajectory with increasing coagulant doses, with the efficiency ranking as Al13 > PAC > $AlCl_3$. Man et al. (2012) delved into the realm of thermolytic coagulation–flocculation for curing G. Malachite color from contaminated water. The investigation revealed that coagulation–flocculation treatment of fresh green dye aqueous solution surpassed thermolysis,

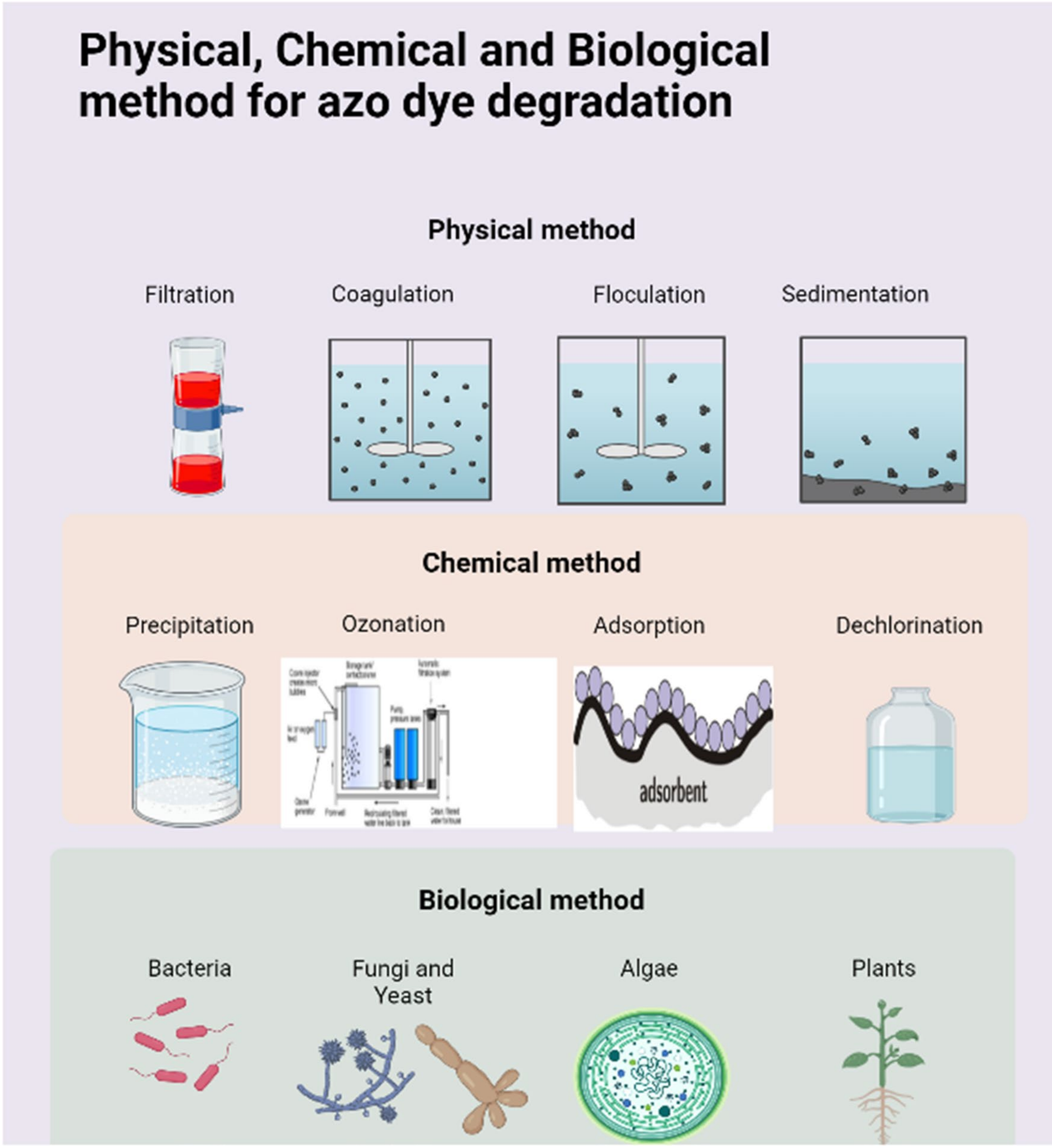

Fig. 7 Different physical chemical techniques used for azo dye degradation

resulting in enhanced malachite green dye treatment. The removal of approximately 90% of the color was achieved at basic pH levels.

As depicted in Fig. 8, the coagulation technique is visually encapsulated, showcasing its prowess in precipitating contaminants from wastewater. This visual representation serves as a concise guide, emphasizing the significance of coagulation in the larger framework of wastewater treatment. The coagulation process, with its nuanced ability to destabilize and remove pollutants, stands as a foundational pillar in the pursuit of cleaner and more sustainable water treatment processes. Its versatility and efficacy make it a crucial tool in the ongoing endeavors to address the environmental challenges posed by dye pollutants.

Ion exchange

In the intricate tapestry of wastewater treatment, the ion exchange process emerges as a strategic player, aiming to transform the molecular composition of wastewater. The fundamental objective is to guide wastewater through ion exchanger resin until each binding site saturates. While this method has demonstrated efficacy, a notable drawback surfaces—the ion exchanger's limited capacity to handle

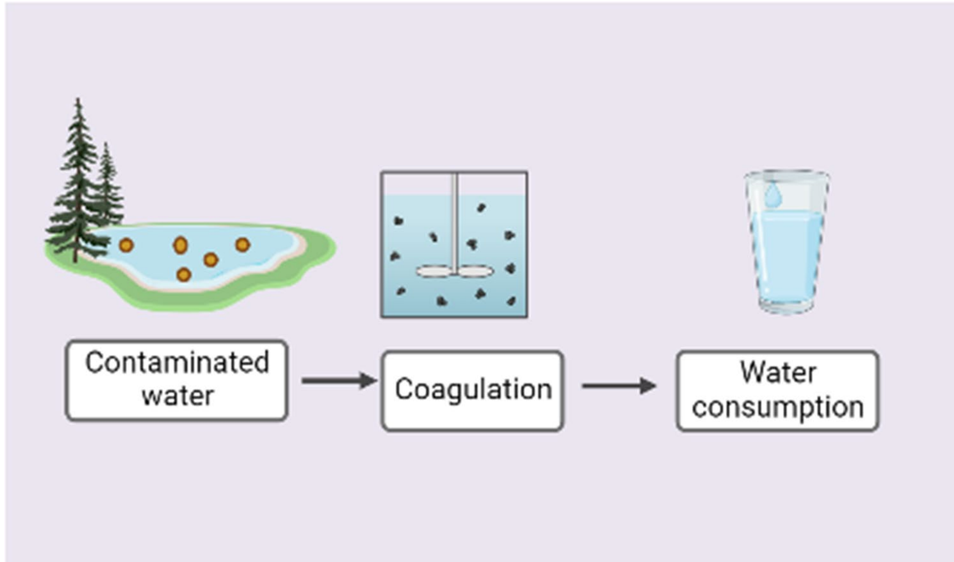

Fig. 8 Coagulation technique for removal of contaminants: a pictorial representation

a diverse range of dyes. Consequently, its application is somewhat restricted in treating effluents laden with dyes, especially considering the large sludge-producing capacities associated with this technique (Burakov et al. 2018).

Figure 9 provides a visual depiction of the ion exchange process for wastewater treatment. This schematic representation encapsulates the essence of the ion exchange technique, showcasing its operational principles in addressing wastewater challenges. The ion exchange process operates on the principle of selective exchange of ions between a solid phase (ion exchange resin) and a liquid phase (wastewater). This dynamic interaction facilitates the removal of specific ions or contaminants from the wastewater, paving the way for a more refined and purified effluent. While the ion exchange process may not be the panacea for all wastewater challenges, its targeted approach to ion removal renders it a valuable asset in the broader spectrum of wastewater treatment methodologies. As innovations continue to shape the landscape of environmental remediation, the ion exchange process stands resilient in its contribution to the pursuit of sustainable and effective wastewater treatment.

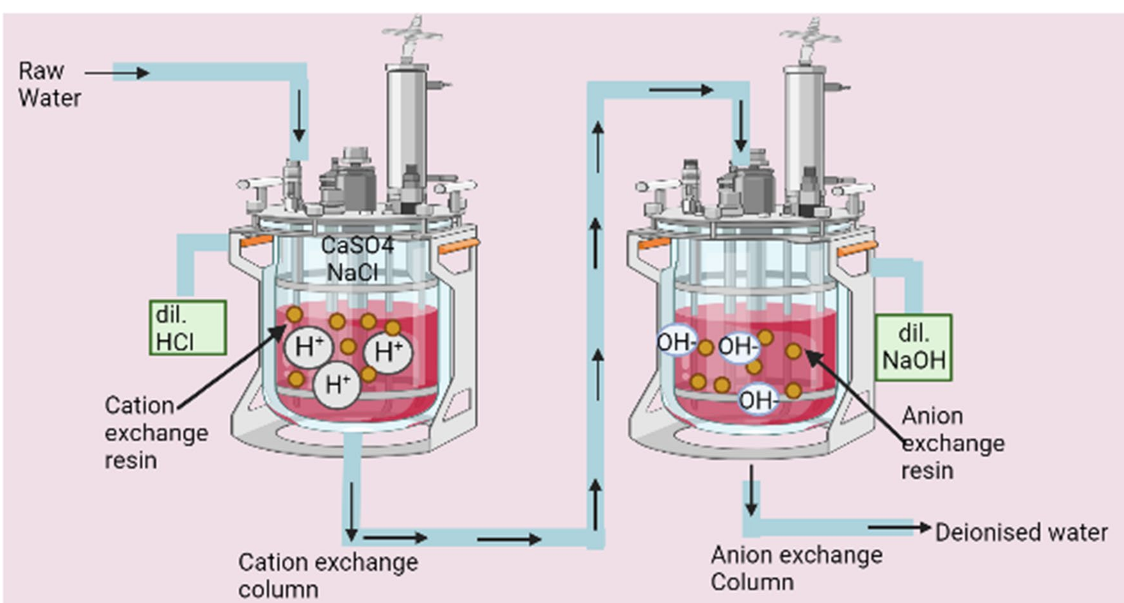

Fig. 9 Ion exchange process for wastewater treatment: a pictorial insight

Adsorption

The multifaceted phenomenon of adsorption stands as a pivotal paradigm in the realm of wastewater treatment, intricately weaving molecular dynamics and surface interactions. Defined by two distinct processes—chemisorption and physisorption—adsorption unveils a captivating molecular ballet, dictating the enthralling interplay between contaminants and solid adsorbent surfaces (Saravanan et al. 2022a, b). A symphony of forces governs the adsorption process, each force playing a unique role in the molecular tango. Electrostatic interactions, arising from the charge distribution of molecules, contribute to the initial attraction. Van der Waals forces, characterized by dipole–dipole interactions and London dispersion forces, accentuate the cohesive binding. Hydrophobic interactions further influence the adsorption landscape, orchestrating the affinity of non-polar molecules. Hydrogen bonding, a testament to molecular diplomacy, enhances the adhesive bonds between adsorbent and adsorbate (Saravanan et al. 2022a, b).

The ensemble of adsorbents participating in this molecular ballet is diverse, each bringing its unique characteristics to the performance. Zeolites, with their crystalline structures, display selective adsorption capabilities. Alumina, recognized for its surface reactivity, partakes in the adsorption repertoire. Silica gel, with its porous matrix, facilitates molecular entrapment. Activated carbon, the virtuoso of adsorbents, steals the limelight owing to its reusability and high adsorption efficiency (Samsami et al. 2020).

Among the virtuosos, activated carbon emerges as a luminary, offering a captivating performance in the adsorption spectacle. The meticulously crafted dance of methylene blue adsorption onto activated carbon derived from oil palm fiber epitomizes the nuanced equilibrium of pH, contact time, concentration, and temperature. With a BET surface area of 1354 m^2/g and a porous architecture, activated carbon unveils a mesmerizing act in rapidly attaining equilibrium during the adsorption process (Tan et al. 2009; Gomez et al. 2007).

In a parallel act, the bio-composite ensemble, comprising sugarcane bagasse chitosan, starch, and polyaniline, emerges as a dynamic participant. The performance unfolds with pH, retention durations, initial dye concentration, and temperature influencing the adsorption choreography. This bio-composite symphony, marked by exothermic nature, positions itself as an eco-friendly contender in the realm of dye removal (Noreen et al. 2020).

The walnut shell, an unconventional yet effective adsorbent, takes center stage in its own overture. Its prowess in removing Acid Red dye from aqueous solutions underscores the potential diversity in materials contributing to the grand tapestry of wastewater treatment methodologies (Mokri et al. 2015).

Figure 10 provides a visual crescendo, capturing the essence of molecular choreography in contaminant removal. This captivating dance not only showcases the scientific intricacies but also holds promise for sustainable and effective wastewater treatment modalities. The molecular ballet of adsorption continues to unfold, presenting a spectrum of possibilities in the pursuit of environmental stewardship.

Advanced oxidation

In the pursuit of decolorizing water tainted with the stubborn vestiges of pigments, advanced oxidation stands as a beacon of transformative environmental alchemy (Banerjee et al. 2018). This sophisticated arsenal of techniques encompasses an array of processes such as photolysis, photocatalysis, sonolysis, sonocatalysis, ozonolysis, moist air oxidation, and the Fenton process. Within this orchestration of environmental alchemy, photocatalysis emerges as the virtuoso, displaying unparalleled efficacy in the annihilation of dye residues from wastewater (Gayathri et al. 2019). The crown jewel within the realm of advanced oxidation, photocatalysis orchestrates a symphony of light-induced degradation. Leveraging semiconductors, often titanium dioxide (TiO_2) or zinc oxide (ZnO), as catalysts, this process harnesses the transformative power of photons to initiate radical generation. The ensuing radicals, such as hydroxyl radicals (•OH), embark on a molecular crusade, dismantling dye molecules with precision and efficacy (Cotillas et al. 2018). Delving into the avant-garde, Cotillas et al. (2018) unfurled the prowess of conductive-diamond electrolytic oxidation in the removal of Red MX-5B dye from wastewater. The catalytic dance of diamond electrodes, under the influence of electrolysis, engendered the electrogeneration of oxidizing chemicals. This catalytic choreography rendered Red MX-5B dye utterly vanquished, marking a triumph in the realm of electrolytic oxidation.

Membrane separation

In the dynamic landscape of wastewater treatment, the avant-garde prowess of membrane separation emerges as a beacon of precision and efficiency, particularly in the removal of recalcitrant azo dyes. This sophisticated physical technology harnesses the principle of selective permeability to orchestrate the removal of dye molecules, heralding a new era in water purification (Behera et al. 2021). At the forefront of membrane separation, nanofiltration (NF) stands as a technological marvel with membranes characterized by minuscule pores, typically ranging between 0.5 and 0.2 nm in diameter (Dasgupta et al. 2015). This meticulous engineering allows for the separation of color molecules in polluted water solutions based on both size and electrostatic repulsion

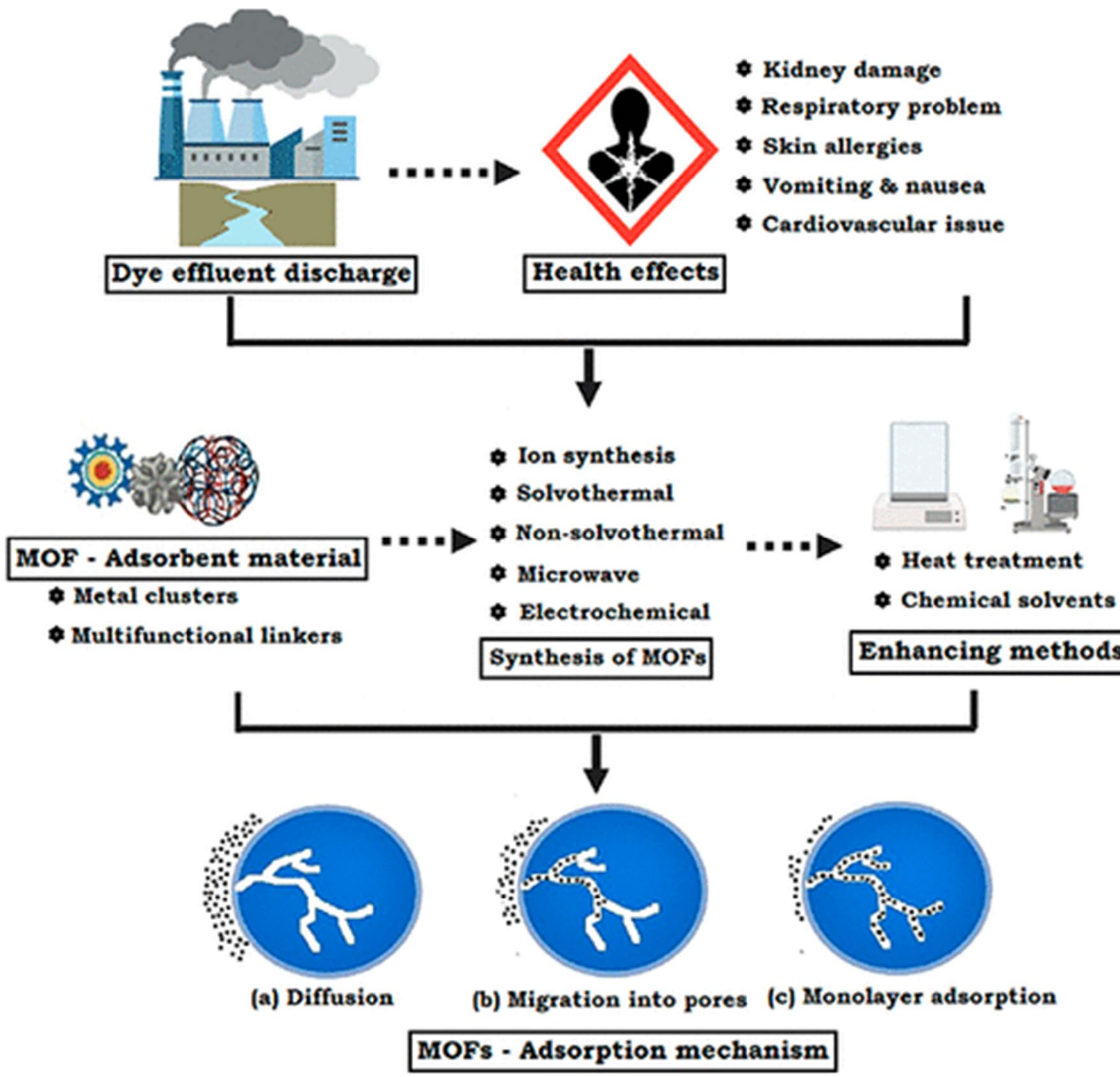

Fig. 10 Adsorption process: a visual overture of contaminant removal

principles. The result is a dye-free solution, epitomizing the finesse of nanofiltration technology (Wang et al. 2020a).

In tandem with membrane filtration, reverse osmosis (RO) unfurls its capabilities as a stalwart in industrial water purification. The membranes utilized in RO, acting as selective barriers, facilitate the concentration and separation of contaminants without necessitating a change in state or the deployment of thermal energy (Wu et al. 2022). This elegant process ensures the production of high-quality water, substantiating its widespread application in the treatment of water laden with dyes (Wang et al. 2020b; Liang et al. 2021).

Delving into the specifics, Wu et al. (2008) delved into the efficacy of cation exchange membranes in the removal of methyl violet dye (2B) from aqueous solutions. Employing a batch approach, the investigation unfolded with a focus on estimating desorption efficiency. The findings highlighted that cation exchange membranes wield formidable prowess in efficiently removing cationic dye methyl violet from water, ensuring maximal dye recovery through desorption. Figure 11 unfolds the tapestry of membrane separation techniques, each thread weaving a narrative of precision and selectivity. As environmental custodians navigate the intricate realm of membrane separation, the promise of water purification and azo dye degradation stands resilient, offering a glimpse into a purified and sustainable future.

Biological methods for the discoloration of azo dyes

Amidst the evolving landscape of textile wastewater treatment, the spotlight turns toward the realm of biological methods, where the orchestration of microbial symphonies becomes a cost-effective and environmentally responsible choice. Within this paradigm, the paramount goal is the breakdown, mineralization, and detoxification of pernicious

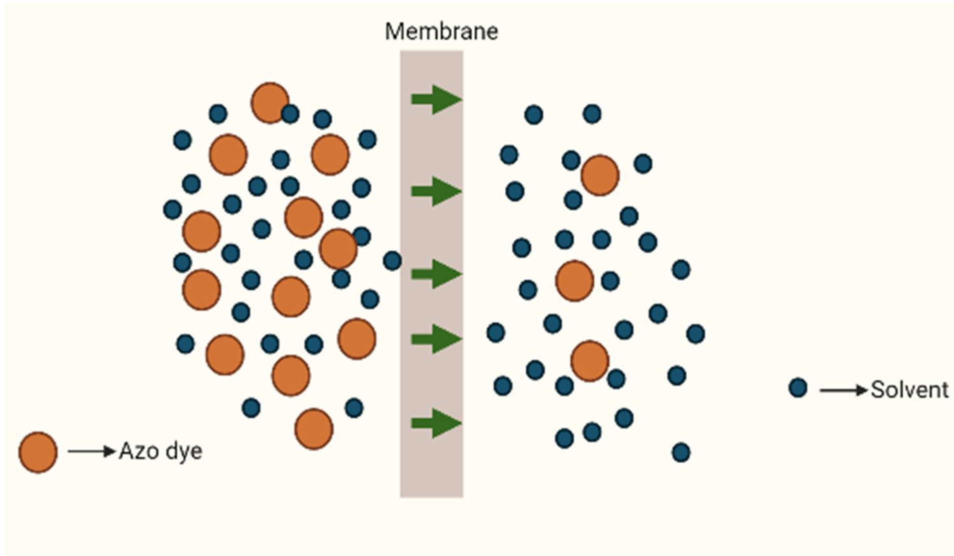

Fig. 11 Membrane separation technique for azo dye degradation

azo dyes, transmuting them into forms less menacing to the ecosystem. The biological ballet unfolds through biodegradation, where intricate hues are decolonized, and complex color structures are dismantled into more manageable constituents.

Biodegradation, the virtuoso performance orchestrated by populations of bacteria, fungi, algae, and yeasts, manifests its efficacy in both oxygenic and non-oxygenic conditions. This environmentally conscious approach champions the breakdown of azo dyes, charting a course toward remediation of the world's wastewater challenges (Shah 2014). The ascendancy of biological methods in wastewater treatment is underpinned by their economic viability and eco-friendly disposition.

Dye degradation unfolds harmoniously in diverse environmental conditions, encompassing both anaerobic and aerobic milieus. This versatility empowers microbial communities to thrive and perform their biotransformational feats, demonstrating the adaptability and resilience of biological approaches in diverse wastewater scenarios. At the heart of this microbial alchemy lies a repertoire of microbial enzymes, each playing a pivotal role in the decolorization of azo dyes. Azo reductases, NADH-DCIP reductase, and ligninolytic enzymes such as laccase (Lac), manganese peroxidase (MnP), and lignin peroxidase (LiP) emerge as the enzymatic virtuosos orchestrating the transformative dance of dye molecules (Kalyani et al. 2009). The substrate specificity and catalytic finesse of these enzymes contribute to the efficiency of dye decolorization, unveiling the biochemical ballet underlying the microbial remediation of azo dyes.

Biological methods stand as stalwart custodians of the environment, offering a symphonic solution to the challenges posed by azo dyes in textile wastewater. As microbial maestros continue their transformative play, the stage is set for a sustainable and eco-friendly future in wastewater treatment.

Decolorization and deterioration of azo dye by bacteria

In the realm of wastewater treatment, bacteria emerge as versatile virtuosos, capable of adapting to diverse environmental conditions encompassing variations in oxygen levels, pH, and temperature. Their prowess in industrial wastewater treatment is underscored by their agility and efficiency, often surpassing fungi in the decolorization process (Carvalho et al. 2008; Lin et al., 2008). Bacterial decolorization, notably faster than fungal counterparts, becomes especially pronounced in anoxic environments, eliciting the production of aromatic amines (Carliell et al. 1994).

Despite the inherent resilience of azo dyes to bacterial attack in oxygenated conditions, certain aerobic bacteria deploy azo reductases to initiate the breakdown of azo bonds (Olukanni, 2009). The reductive cleavage of the -N = N bond serves as the catalyst for bacterial degradation of synthetic dyes. Bacterial cohorts, spanning various taxonomic groups, exhibit the capacity to decolorize azo dyes under diverse conditions including non-oxygenic (methanogenic), anoxic, and oxygenic environments. This diverse spectrum of bacteria sourced from unmixed cultures, mixed cultures, anaerobic sediments, granular anaerobic sludge, and activated sludge under non-oxygenic conditions, illustrates the broad applicability of bacterial involvement in the degradation of azo dyes (Wuhrmann et al. 1980; Carliell et al. 1994; Ali et al. 2019). The interplay between bacterial prowess and environmental conditions is exemplified in instances such as Reactive dye decolorization by *Micrococcus* species, showcasing a discrepancy in decolorization periods between anaerobic (24 h) and aerobic (6 h) environments (Walker 1970).

Various bacterial species, including but not limited to *Klebsiella*, *Bacillus*, *Rhodococcus*, and *Shigella*, have been identified as capable agents in the breakdown of azo dyes (Erden et al. 2011; Guo et al. 2020; Chen et al. 2021a, b; Wang et al. 2022). The utilization of bacteria in azo dye degradation is accentuated by their ease of cultivation, faster specific growth rates compared to other microbes, and a diverse catalytic repertoire for the mineralization of azo dyes in contaminated water (Patil et al. 2022).

Figure 12 demonstrates a typical schematic for the bacterial-assisted biodegradation of azo dyes. Initially, the azo dye molecules permeate the aquatic environment, originating from industrial wastewater effluents. These synthetic hues, though visually striking, pose environmental hazards. The bacterial warriors, portrayed as resilient microorganisms, are the key players in this ecological drama. These bacteria, carefully selected for their adeptness in azo dye degradation, wield enzymatic tools to commence the intricate process. Enzymes such as azo reductases, NADH-DCIP reductase, and ligninolytic enzymes stand as the weaponry in the bacterial arsenal. These enzymes, secreted by the bacterial forces, target the azo bonds within the dye molecules. A pivotal moment in the narrative unfolds as the bacterial enzymes engage in precise azo bond cleavage. This biochemical maneuver disintegrates the azo bonds, breaking down the complex dye structures into simpler, less harmful components. The byproduct of azo bond cleavage includes aromatic amines. Under anaerobic conditions, reducing equivalents generated during the microbial degradation process contribute to the creation of aromatic amines. The process culminates in the complete biodegradation of azo dyes, rendering the once vivid pollutants into innocuous substances. This marks a triumph for bacterial-assisted biodegradation in mitigating the environmental impact of azo dyes.

This schematic encapsulates the essence of the intricate ballet orchestrated by bacteria in dismantling the chromatic threat of azo dyes, emphasizing the pivotal role of microbial communities in sustainable wastewater treatment practices. Table 1 exhibits a list of bacteria used for the degradation of azo dye with their % decolorization. Table 1 stands as a testament to the prowess of various bacterial species enlisted in the noble quest of azo dye degradation. Each entry in this tableau represents a bacterial champion, armed with enzymatic weaponry, striving to decolorize and detoxify industrial wastewater tainted by vibrant synthetic dyes. The percentages of decolorization associated with each bacterial hero serve as metrics of their efficiency in dismantling the chromatic threat. As we delve into the microbial hall of fame, we witness the diverse bacterial forces contributing to sustainable and eco-friendly solutions in the battle against azo dye pollution.

Decolorization and deterioration of azo dye by fungi

Fungi, with their intricate and adaptive metabolisms, emerge as adept artisans in the biodegradation ballet of azo dyes. Flourishing in diverse environments such as soil, active plants, and organic waste, filamentous fungi is ubiquitous, offering potential as both biosorbents and biodegraders of dyes. The ability of mushrooms to swiftly modulate their metabolism in response to varying carbon and nitrogen sources is crucial for their survival.

Fungi, characterized by their filamentous structure, represent an advantageous bioadsorbent owing to their abundant biomass, cost-effectiveness, and remarkable chemical

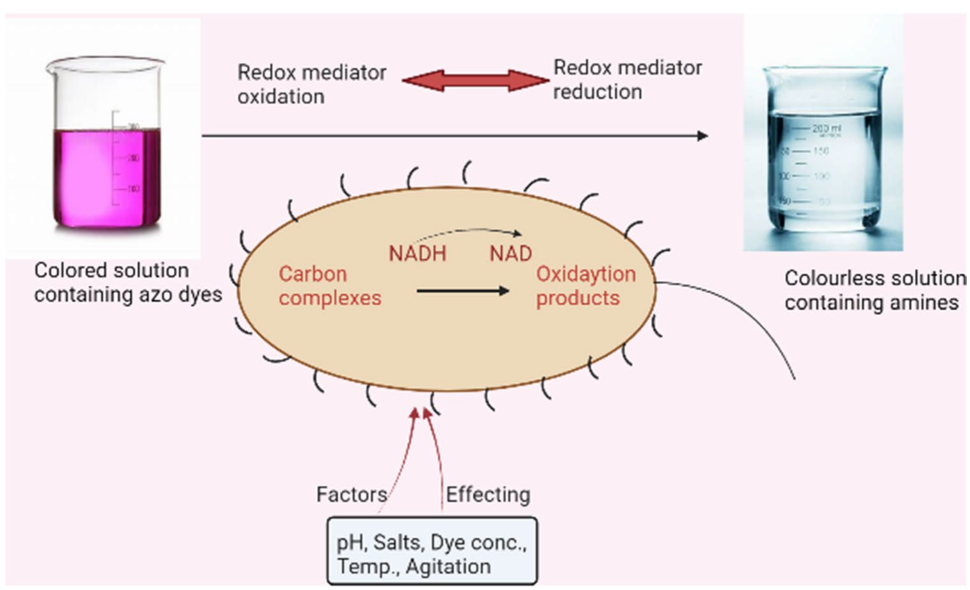

Fig. 12 A typical schematic for the bacterial-assisted biodegradation of azo dyes

Table 1 Different bacteria used for the degradation of azo dye with their % decolorization

S. No	Bacterial culture	Dye	pH Time (hr)	Decolorization (%)	Reference
1	*Proteus mirabilis*	Red RBN	-, 20 h	95	Chen et al (1999)
2	*Acinetobacter* sp. SRL8	Disperse Orange S- RL	7.0, -	90.20	Zhiqiang et al. (2015)
3	*Alishewanella* sp. KMK6	Reactive Blue 59	7.0, 6 h	95	Kolekar and Kodam, (2012)
4	*Bacillus cereus*	Cibacron Black PSG,	7.0, 5 days	67	Ola et al. (2010)
5	*Brevibacillus laterosporus* MTCC 2298	Golden HER Yellow	7.0, 48 h	87	Gomare et al, (2009)
8	*Acinetobacter baumannii* YNWH 226	Congo Red	7.0, -	99.10	Ning et al. (2014)
9	*Bacillus subtilis*	Reactive Red M8B	8–9, 5 days	97	Arulazhagan, (2016)
10	*Micrococcus luteus* strain SSN2	Direct Orange 16	8.0, 6 h	96	Singh et al. (2015)
11	*Comamonas* sp. UVS	Direct Red 5B	6.5, 13 h	100	Jadhav et al., (2008)
12	*Enterococcus* faecalis YZ66	Direct Red 81	7.0, 1.5 h	100	Sahasrabudhe et al., (2014)
13	*Geobacillus stearothermophilus* (UCP 986)	Orange II	5.0, 24 h	96–98	Evangelista-Barreto et al. (2009)
14	*Micrococcus glutamicus* (NCIM- 2168)	Reactive Green 19 A	6.8, 42 h	100	Saratale et al. (2009a)
15	*Sphingomoas paucimoboils*	Methyl Red	9.0, 10 h	98	Ayed et al. (2011a, b)
17	*Pseudomonas entomophila* BS1	Reactive Black 5	5–9, 120 h	93	Khan and Malik, (2016)
18	*Shewanella* sp.	Acid Orange 7	-, 6 h	98	Wang et al. (2012)
19	*Rhodopseudomonas palustris* 51ATA	Reactive Red 195	-, -	100	Celik et al. (2012)
20	*Alcaligenes* sp. AA04	Reactive Red 198	7.0, 24 h	90	Pandey et al., (2007)
22	*Staphylococcus aureus*	Sudan III	-, 48 h	76	Pan et al. (2011)
23	*Staphylococcushominis* RMLRT03	Acid Orange	7.0, 60 h	94	Singh et al. (2014)
24	*Staphylococcus aureus*	Orange II	48 h	97	Pan et al. (2011)
25	*Bacillus cereus*	Cibacron Red P4B	7, 5 day	81	Ola et al. (2010)
26	*Micrococcus luteus* 24 M	Congo Red	-,11 day	99	Ito et al. (2018)
27	*Brevibacterium sp.* VN-15	Reactive Red 198, Reactive Black 5	-,128 h,148 h	97.95	Franciscon et al. (2012)
29	*Aeromonas hydrophila*	Red RBN	-, 8 days	90	Chen et al. (2003)

and mechanical stability in both acidic and alkaline environments. The rigid structure of macrofungi enhances biosorption, with temperature and dye reaction kinetics influencing their adsorptive capacity. However, challenges such as adsorbent surface deactivation or a reduction in the number of active sites can be encountered during the process (Asgher et al. 2008).

The employment of fungi as a sensible approach for dye decolorization is underscored by its cost-effectiveness, environmental safety, and the potential for complete dye degradation. Fungi exhibit a rich repertoire of intracellular and extracellular enzymes that contribute to the degradation of complex organic pollutants, including polyaromatic hydrocarbons, organic waste, azo dye effluents, and steroid chemicals (Bhatia et al. 2022; Jiku et al. 2021).

Among the fungi with noteworthy decolorizing capabilities, those inducing white rot, such as *Phanerochaete chrysosporium*, stand out as particularly effective (Lim et al. 2010; Robinson et al. 2001). Despite their prowess, the use of fungi for color removal from textile effluents presents challenges, including prolonged developmental and sludge retention phases required for complete decoloration and the need for nitrogen-less conditions. Table 2 provides a list of fungi used for the degradation of azo dyes with their % decolorization.

Decolorization and deterioration of azo dyes by algal species:

The realm of azo dye remediation expands to embrace the chlorophyll-rich allies—algae. Table 3 unfolds the botanical warriors enlisted in the cause, showcasing their formidable decolorization capabilities against the vibrant onslaught of synthetic dyes. Algae, including species like *Chlorella vvulgaris*, *Oscillatoria rubescens*, *Elakatothrix viridis*, *Lyngbya lagerlerimi*, *Nostoc linckia*, and *Volvox aureu*s, emerge as key players in this eco-friendly battle against dye pollution.

These photosynthetic powerhouses utilize their diverse cell wall functional groups, featuring carboxy, carbonyl, hydroxy, phosphoryl, and amide groups, as strategic arsenals for dye decolorization (Mishra et al. 2020). The enzymatic prowess of azoreductase, found within algae, becomes a catalyst for the breakdown of azo dyes into less harmful aromatic amines (Khataee et al. 2011). In aquatic ecosystems, these algal superheroes not only combat the detrimental impact of dye-contaminated water on marine life but

Table 2 Different fungi used for the degradation of azo dyes with their % decolorization

S. No	Fungal culture	Dye	pH, Time(h)	Decolorization (%)	References
1	*Armillaria* sp. F022	Reactive Black 5	4.0, 96 h	< 80	Hadibarata et al. (2012)
3	*Coriolus versicolor*	Acid Orange II	-, -	85	Hai et al. (2012)
4	*Cunninghamella elegans*	Reactive Orange II	5.6, 120 h	93	Ambrosio et al. (2012)
5	*Fusarium oxysporum*	Yellow GAD	-, 144 h	100	Porri et al. (2011)
6	*Ganoderma* sp. En3	Methyl Orange	5.5, 72 h	96.7	Zhuo et al. (2011)
7	*Phanerochaete chrysosporium*	Direct Red 180	4.5, 72 h	100	Sen et al. (2012)
8	*Phanerochaete chrysosporium*	Astrazon Red FBL	-, 2 days	87	Sedighi et al. (2009)
9	*Pleurotus eryngii* F032	Reactive Black 5	3, 72 h	93	Hadibarata et al. (2013)
10	*Pleurotus sajor-caju*	Reactive Blue 220	-, 11 days	100	Munari et al. (2008)
11	*Schizophyllum commune* IBL-06	Solar Brilliant Red 80	4.5, 7 days	100	Asgher et al. (2013)
12	*Trametes* sp.	Orange II	-, 10 days	100	Grinhut et al. (2011)
13	*Trametes trogii*	Remazol Brilliant Blue R	4.5–7.0, 30 min	82	Grassi et al. (2011)
15	*Aspergillus niger*	Synozol red HF-6BN	-, 24 days	88	Ilyas and Rehman (2013)
16	*Nigrospora sp.*	Synozol red HF-6BN	-, 24 days	96.0	Ilyas and Rehman (2013)
17	*Oudemansiella canarii*	Congo red	60 h	80.0	lark et al. (2019)
18	*Peurotus florida*	Remazol blue	72 h	94.6	Montiague et al. (2020)
19	*Aspergillus terreus*	Direct Blue-1	168 h	98.4	Singh and Dwivedi (2020)
20	*Aspergillus fumigatus*	Disperse red1	–	85.0	Ameen et al. (2021)
22	*Trametes trogii*	Indigo Carmine	4.5–7.0, 30 min	75	Grassi et al. (2011)
23	*Ganoderma* sp. En3	Crystal violet	5.5, 72 h	75	Zhuo et al. (2011)

Table 3 Different algae used for the decolorization of azo dye with their % decolorization

Algal strain	Incubation time (Days)	Azo dyes	Decolorization (%)	References
Chlorella vulgaris	4	Methyl Orange	82	Ajaz et al. (2019)
Chlorella pyrenoidosa	8	Congo Red	80	Shi et al. (2021)
Scenedesmus obliquus	10	Orange II	75	Shi et al. (2021)
Anabaena variabilis	20	Direct Blue 15	70	Shi et al. (2021)
Nostoc muscorum	22	Basic Red 46	90	Shi et al. (2021)
Spirulina platensis	24	Reactive Yellow 145	85	Shi et al. (2021)
Synechocystis sp.	28	Direct Black 22	80	Shi et al. (2021)
Sc. Bijugatus	–	Tartrazine	57	
Volvox aureus	–	Basic cationic (10 ppm)	82	El-Sheekh et al. (2009a, b)
Chlamydomonas reinhardtii	26	Acid Yellow 23	75	Shi et al. (2021)

also stand as cost-effective champions due to their ability to harness solar energy for photosynthesis. The percentages of decolorization associated with each algal species in Table 3 shed light on their individual contributions to the collective mission of azo dye degradation.

Decolorization and deterioration of azo dyes by yeast

In the vast kingdom of microorganisms, yeasts stand out as swift responders and survivors in challenging environmental conditions. With a repertoire that includes both adsorption and enzymatic disintegration, yeasts, akin to fungi, join the ranks of nature's champions in the crusade against azo dye pollution (Dilarri et al. 2018). The yeast arsenal boasts key players such as *Galactomyces geotrichum* and *Saccharomyces cerevisiae*, exhibiting their prowess in absorbing significant concentrations of dye. Glucose emerges as a vital carbon source for the yeast-driven degradation of dyes, setting the stage for the development of oxidases, reductases, and yeast NADH-DCIP reductase in response to azo dye exposure (Singh and Singh 2015).

Table 4 Different yeast used for the degradation of azo dye with their % decolorization

Yeast strain	Incubation time (h)	Decolorization (%)	Different azo dyes	References
Enterococcus durans GM13	36	70–100	Remazol Navy Blue	Adya et al. (2016)
Candida tropicalis	24	90	Acid Orange 7	Ajaz et al. (2020)
Issatchenkia orientalis JKS6	36	95–99	Reactive Orange 16	Jafari et al. 2014
Issatchenkia orientalis JKS6	36	98	Reactive Black 5 (at 500 mg/l)	Jafari et al. (2014)
Issatchenkia orientalis JKS6	12–18	Up to 90	Reactive Black 5	Jafari et al. (2014)
Enterococcus durans GM13	36	70–100	Reactive Green-19	Adya et al. (2016)
Issatchenkia orientalis JKS6	36	95–99	Direct Blue 71, Direct Yellow 12, Direct Black 22	Jafari et al. (2014)
Candida tropicalis	24	90	Acid Red 88	Ajaz et al. (2020)
Enterococcus faecalis	3	95–100	Acid Red 27	Handayani et al. (2007)
Enterococcus faecalis	12	95–100	Reactive Red 2	Handayani et al. (2007)
Candida tropicalis	24	90	Acid Red 388	Ajaz et al. (2020)

Thriving in harsh environments and matching the rapid multiplication rates of bacteria, yeasts from the *Candida* genus take center stage in the process of dye decolorization. Employing diverse strategies such as biosorption, biodegradation, or bioaugmentation, these yeasts, showcased in Table 4, contribute their unique percentages of decolorization to the collective symphony of biological azo dye degradation. Figure 13 encapsulates the biological degradation for the removal of azo dyes from our ecosystems.

Factors affecting the dye degradation

In the intricate world of microbial treatment, various parameters wield a significant influence on the efficacy of dye degradation. For a microbial orchestra to achieve its highest rate of dye reduction, a delicate balance in oxygen content, temperature, pH, initial dye concentration, types of dye, and redox potential must be maintained within optimal ranges.

Oxygen Content: The availability of oxygen is a critical factor, determining whether the microbial players engage in aerobic or anaerobic degradation pathways. The

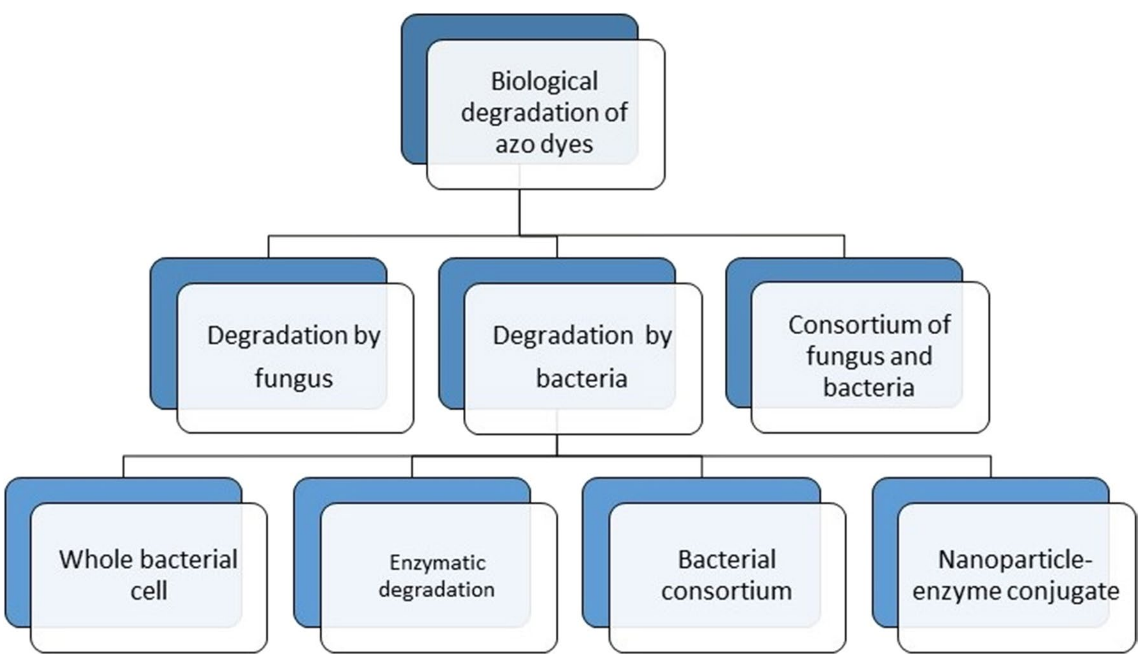

Fig. 13 Biological degradation of azo dyes

oxygen dance profoundly impacts the efficiency of dye reduction.

Temperature: The temperature of the microbial habitat acts as a maestro guiding the tempo of microbial activities. Fluctuations in temperature can either invigorate or impede the microbial symphony, influencing the rate of dye decomposition.

pH Levels: The pH of the milieu serves as the conductor's baton, directing the microbial ensemble. Optimal pH conditions ensure that the microbial performers are in harmony, accelerating the reduction of dyes.

Initial Dye Concentration: The starting concentration of dyes in the wastewater sets the stage for microbial action. Microbes exhibit varying degrees of proficiency based on the intensity of the color challenge they encounter.

Types of Dye: The diverse array of dye genres, from acidic and basic to direct, dispersion, metal-complex, reactive, sulfur, and vat, poses a palette of challenges. Understanding the microbial capacity to tackle this spectrum is crucial for effective treatment.

Redox Potential: The redox potential orchestrates the electron exchange ballet, influencing microbial reactions. A balanced redox environment is pivotal for optimal dye degradation by microbial agents.

Textile Wastewater Composition: The composition of textile wastewater is akin to the musical composition of a symphony, with organics, nutrients, salts, sulfur compounds, poisons, and colors playing diverse roles. The microbes' ability to navigate this diverse composition impacts their effectiveness in global cycles of carbon, nitrogen, and sulfur.

As depicted in Fig. 14, these factors converge in a complex interplay, affecting the biological degradation of azo dyes. The understanding of these parameters serves as a compass, guiding the optimization of microbial treatments and paving the way for sustainable and effective solutions in the realm of dye pollution.

Impact of pH

The pH of microbial media is akin to the conductor of a symphony, orchestrating the intricate interplay of decolorization and dye degradation. This crucial parameter profoundly influences not only the degree of decolorization but also the solubility of the dye and the overall hue of the solution.

In the microbial world, fungi and bacteria showcase distinct pH preferences in their decolorization endeavors. Fungi typically exhibit heightened decolorization and degradation activities in acidic or neutral pH environments, while bacteria showcase optimal prowess in basic or neutral pH conditions. The movement of dye molecules across cell membranes, a pivotal phase in the decolorization process, is intricately linked to pH dynamics.

For fungi, the acidic range emerges as the sweet spot for optimal dye decoloration. Effluent pH plays a pivotal role in dye biodegradation, with the highest dye-degrading capacity observed in neutral to slightly alkaline pH conditions (Ghaly et al. 2014; Pinheiro et al. 2022). A nuanced understanding of the effluent pH becomes imperative for successful bacterial growth, as dormant bacteria render dye degradation impossible. Strategic adjustments to effluent pH or the selection of bacteria resilient to specific pH conditions become vital considerations in the pursuit of effective dye degradation.

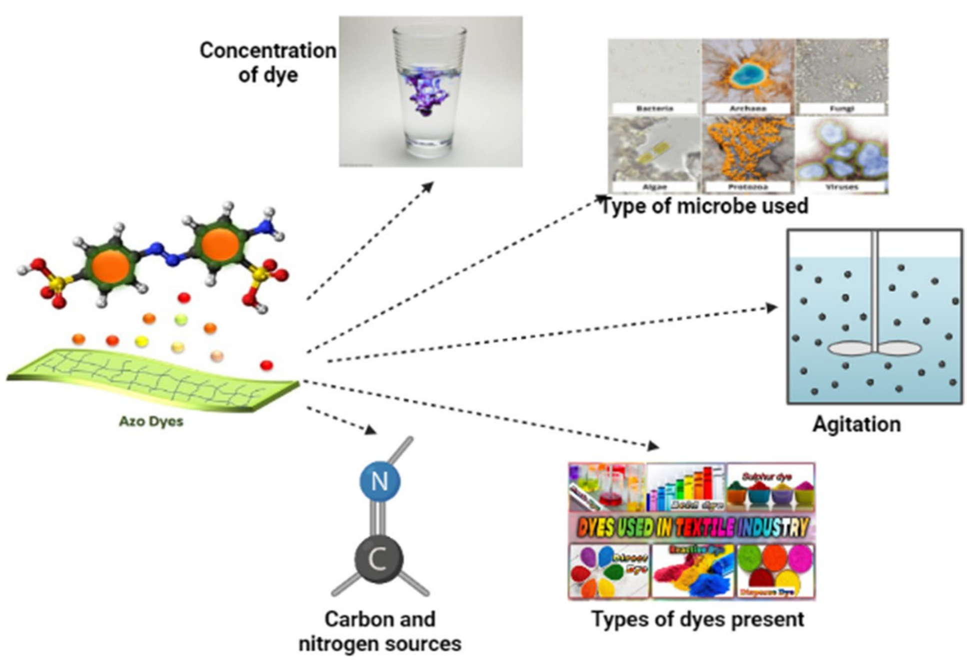

Fig. 14 Factor affecting the biological degradation of azo dyes

Effect of dye concentration

The concentration of dyes in the reaction media serves as a metabolic threshold, significantly influencing the efficiency of dye degradation or decolorization. Textile effluent presents a spectrum of dye concentrations, with documented levels ranging between 10 and 50 mg/L (Laing 1991) and others reporting concentrations between 10 and 250 mg/L (Sharma et al. 2016).

In the microbial realm, the effectiveness of bacteria in industrial applications hinges on their capacity to efficiently break down or decolorize target dyes without succumbing to inhibition at these concentrations. Studies underscore that an escalation in dye concentration exerts a diminishing effect on bacterial efficiency, primarily due to the toxicity of dyes at higher concentrations. This toxicity imposes constraints on the metabolic processes of bacteria, limiting their efficiency (Cui et al. 2014; Kapoor et al. 2021).

Several factors contribute to decreased breakdown efficiency at elevated dye concentrations, including an inadequate biomass-to-dye ratio and the impediment of enzyme active sites by excess dye molecules (Chang et al. 2001). Striking a delicate balance between dye concentration and bacterial metabolic capacity becomes paramount in optimizing dye degradation efficiency.

Impact of temperature

Temperature emerges as a pivotal determinant influencing microbial growth, metabolism, and ultimately, dye degradation. The ideal temperature creates a conducive environment for bacterial growth, survival, and metabolic processes. The rate of color loss exhibits a positive correlation with temperature, with the optimal growth temperature aligning with the temperature conducive to the highest rate of color removal.

However, the ballet of temperature influence is nuanced. A rise in temperature fosters an increase in the rate of color removal, but a subsequent decline is attributed to the loss of cell viability or denaturation of azoreductase enzymes. Microorganisms, governed by enzymes, display varied temperature adaptations, directly impacting the pace of enzymatic reactions and microbial growth (Çetin et al. 2006).

Conversely, low or excessively high temperatures can impede the degradation rate of bacteria, either due to cell inactivation induced by low temperatures or denaturation at higher temperatures (Lalnunhlimi et al. 2016). Thus, temperature functions as both an accelerant and a potential deterrent in the microbial theater of dye degradation.

Effect of dye structure

Microbial efficiency in removing azo dyes is intricately linked to the structural complexity of the dyes. While certain azo colors pose greater challenges for microbial removal, those with simpler structures and lower molecular weights are more frequently subjected to successful color removal.

Microbial enzymes, particularly azo reductases, exhibit remarkable selectivity toward specific dye structures. For instance, the azo groups in orange I and its derivatives are selectively broken down by orange I azoreductase when hydroxy groups are positioned in the para position. Another enzyme, orange II azoreductase, exclusively acts on compounds of the orange II type with the hydroxy group in the ortho position.

Structural nuances play a significant role in the microbial breakdown of azo phenol. Electron-donating methyl and methoxy substituents accelerate enzymatic breakdown, while electron-withdrawing chloro, fluoro, and nitro substituents impede oxidation (Verma et al. 2017).

The pH, dye concentration, temperature, and dye structure intricately choreograph the microbial ballet of dye degradation. The mastery of these parameters is essential for crafting efficient and sustainable strategies in combating dye pollution, paving the way for environmentally conscious wastewater treatment.

Effect of agitating and non-agitating conditions

The efficiency of bacterial biodegradation encounters yet another variable—the rhythmic dance between agitating and non-agitating conditions. This nuanced interplay, as highlighted by Cui et al. (2014), significantly shapes the efficiency of bacterial degradation processes.

Under the spotlight of agitating conditions, a notable transformation occurs—the augmentation of dissolved oxygen levels. This surge in oxygen becomes the fuel for microbial enzyme activity, fostering an environment conducive to heightened bacterial metabolic activity (Benkhaya et al. 2020). The result is an enhanced capacity of bacteria to degrade dyes, a phenomenon intricately linked to the high metabolic activity of bacterial enzymes.

However, this seemingly beneficial symphony of agitation is not without its caveats. While shaking conditions elevate the degradation rate, a delicate balance must be maintained. Excessive oxygen in the reaction medium, a consequence of vigorous agitation, can hinder the functionality of reductive enzymes, such as azo reductase. The heightened oxygen levels create a stronger redox potential, steering the reductive enzymes toward the reduction of the redox mediator rather than the targeted dye. This unintended diversion diminishes the degradation rate of bacterial species, underscoring the need for a judicious balance in agitation dynamics (Chang et al. 2001).

In the dynamic realm of microbial dye degradation, the choice between agitation and stillness becomes a strategic consideration. Striking the right balance is akin to orchestrating a symphony, where each note—whether stirred or tranquil—contributes to the harmonious efficiency of bacterial biodegradation.

Mechanisms of degradation of azo dyes degradation

Mechanisms of degradation of azo dyes degradation with the help of bacteria

Understanding the intricate mechanisms employed by bacteria in the degradation of azo dyes unveils a symphony of biochemical transformations, shedding light on the dual processes of direct decolorization and indirect/mediated decolorization. These processes, governed by a repertoire of enzymes, hold significant promise for environmentally friendly and effective azo dye treatment (Verma et al. 2017).

In the realm of azo dye degradation, bacteria employ two distinct approaches: direct decolorization and indirect/mediated decolorization. These methodologies rely on a suite of enzymes to dismantle the intricate structures of refractory substances within microbial systems (Verma et al. 2017). The arsenal of enzymes includes laccase, azoreductase, lignin peroxidase, NADH-DCIP reductase, and hexane oxidase, each contributing to the breakdown of complex chemical compounds.

The dichotomy of oxygenic and non-oxygenic environments serves as the stage for bacterial experiments in azo dye degradation. While both environments have been explored, anaerobic reductive cleavage of azo bonds by the azoreductase enzyme takes center stage in most bacterial dye degradation processes. This anaerobic reductive cleavage, occurring in two stages, involves the transfer of four electrons, resulting in the decolorization of the dye and the production of colorless amines. The subsequent aerobic breakdown of these aromatic amines in the second stage completes the microbial degradation cycle (Hsu et al. 2012).

A prelude to the biodegradation spectacle is bacterial adsorption, a physical technique involving the efficient adsorption of dye molecules onto biomass. However, the limitations of this method emerge as dye molecules saturate the biomass quickly, necessitating a more robust and sustainable approach for long-term treatment. Yet, the significance of this initial adsorption step lies in its role as the launchpad for the subsequent stages of microbial dye degradation (Adenan et al. 2021).

Following physical adsorption, the biodegradation of azo dyes unfolds in a captivating two-step dance within bacterial cells. In the first stage, the azo bond (–N=N–) of the dye undergoes reductive cleavage, facilitated by azoreductase enzymes. This transformative step yields aromatic amines, typically colorless but potentially hazardous. The second stage, set in an aerobic environment, orchestrates the degradation of these aromatic amines, ensuring a comprehensive and environmentally benign breakdown of azo dyes (Maniyam et al. 2020).

In the fungal realm, laccase takes center stage, playing a pivotal role in the asymmetric cleavage of azo dye structures. The fungus strain *Lentinus* sp. showcases the prowess of laccase in the biodegradation of anthraquinone and azo dyes. Additionally, *Brevibacillus* sp. (Z1) and *Anoxybacillus gonensis* P39127 contribute to the removal of various azo dyes, showcasing the diverse enzymatic repertoire harnessed by microorganisms in dye degradation (Singh, 2014).

The efficiency of azo dye degradation is further heightened by the strategic use of redox mediators. Studies reveal the accelerated biodeterioration of azo dyes upon the addition of redox mediators, such as artificial electron carriers, anthraquinone-2-sulfonate, or quinone molecules. These mediators act as catalysts, expediting the breakdown of azo dyes. Notably, alternative redox mediators like activated carbon, carbon black, and carbon nanotubes emerge as cost-effective options, ensuring the application of bacteria-mediated decoloration (Verma et al. 2017).

Bacteria exhibit a dual role in the decolorization of azo dyes—a symphony of biosorption and biodeterioration. Biosorption involves the adsorption of azo dye onto bacterial cells, initiating a transformative process where bacterial cells alter the color of adsorbed dye molecules. This alteration is perceptible through a decrease in the dye's absorption spectrum. On the other hand, biodeterioration breaks down the dye structure to its fundamental components, as evidenced by the disappearance of dye absorption peaks or the emergence of new peaks indicative of metabolite production (Adenan et al. 2021).

A noteworthy discovery in the realm of azo dye degradation is the strategic use of dead bacterial cells. Studies on malachite green (MG), methyl violet (MV), crystal violet (CV), and cotton blue (CB) demonstrate that both dead and living Streptomyces bacillaris bacterial cells are integral to the decolorization process. While living cells actively engage in dye degradation, dead cells play a crucial role in adsorption, providing insights into the synergy between different microbial states in the removal of azo dyes (Mishra et al. 2020).

In conclusion, the mechanism of azo dye degradation by bacteria is a multifaceted symphony, encompassing enzymatic transformations, adsorption, and biodeterioration. This orchestrated interplay unfolds in oxygenic and non-oxygenic environments, showcasing the adaptability of bacteria in tackling diverse dye structures. The strategic use of enzymes, redox mediators, and the dual role of biosorption and biodeterioration highlight the intricate strategies employed by bacteria in their quest for environmentally

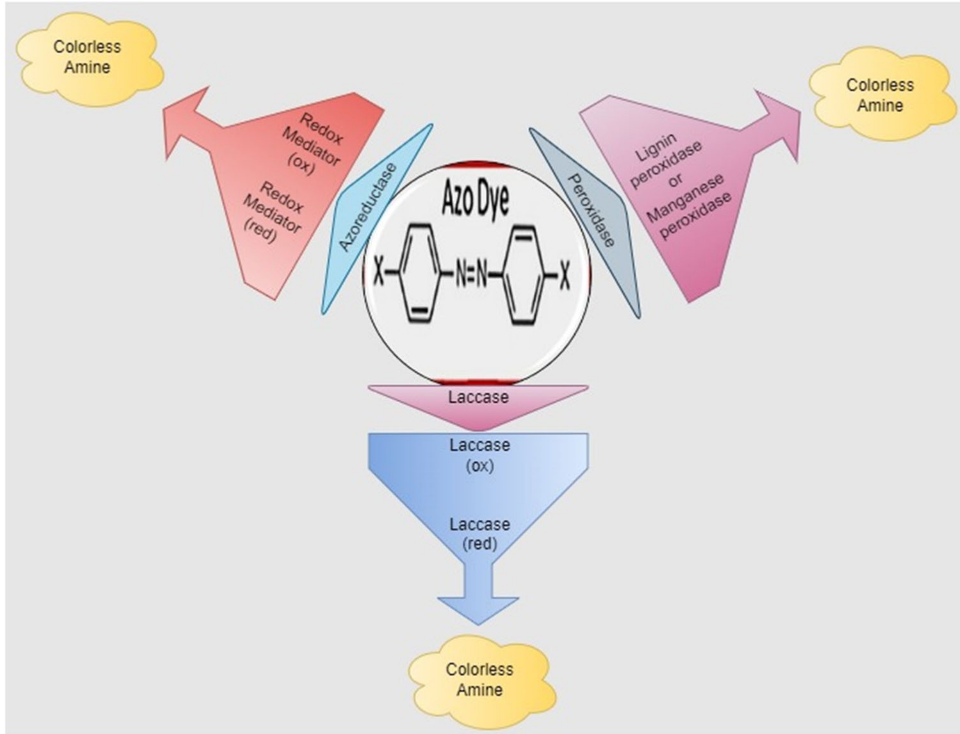

Fig. 15 Mechanism of azo dye degradation by bacteria

benign and effective azo dye treatment. Figure 15 serves as a visual representation, encapsulating the essence of this biochemical symphony, where bacteria emerge as virtuosos in the figure.

Mechanism of azo dye degradation by white rot fungi

In the realm of wastewater treatment, White Rot Fungi stand as nature's virtuosos, showcasing an impressive mechanism for the degradation of azo dyes. These fungi have garnered significant attention for their remarkable capacity to tackle industrial wastewater laden with intricate contaminants (Kumar et al., 2020).

At the heart of White Rot Fungi's prowess lies the production of extracellular lignin-degrading enzymes, primarily lignin peroxidase (LiP) and manganese peroxidase (MnP). These enzymes serve as the maestros orchestrating the biochemical symphony within the fungal kingdom. Through redox reactions, LiP and MnP generate reactive radicals, potent oxidizing agents with the ability to degrade a diverse array of complex and persistent pollutants present in industrial wastewater (Morsi et al. 2020; Sun et al. 2023).

The reactive radicals generated by LiP and MnP play a pivotal role in the degradation process. These radicals act as highly effective oxidizing agents, initiating a cascade of oxidative transformations within the pollutants. The mechanisms include the removal of hydrogen atoms, breakdown of chemical bonds, and other oxidative processes that dismantle recalcitrant pollutants with finesse (Morsi et al. 2020; Sun et al. 2023). The enzyme-based degradation orchestrated by White Rot Fungi is akin to a precision orchestra. LiP and MnP, as enzymatic virtuosos, target and dismantle the complex structures of pollutants, ensuring a comprehensive and efficient breakdown. This mechanism highlights the adaptability of White Rot Fungi in tackling a wide range of contaminants encountered in industrial wastewater (Morsi et al. 2020). White Rot Fungi don't rely solely on enzymatic prowess; they also harness biosorption and bioprecipitation processes as part of their cleanup repertoire. The fungal cell wall, fortified with chitin and other polymers, becomes an efficient tool for binding and storing metal ions and pollutants through electrostatic interactions, complexation, and ion exchange (Javanbakht et al. 2014).

In a fascinating display of fungal alchemy, White Rot Fungi induce the precipitation of metal ions as salts or hydroxides. This process is triggered by the fungi altering the pH or redox conditions in wastewater treatment systems. The ability to manipulate these environmental factors underscores the multifaceted nature of White Rot Fungi's approach to pollutant removal (Chandra et al., 2019).

Figure 16 serves as a visual gateway into the intricate mechanism of azo dye degradation by White Rot Fungi. The figure encapsulates the enzymatic precision, radical-driven oxidative transformations, biosorption capabilities, and the fungal alchemy of metal ion precipitation. It's a visual testament to the versatile and effective nature of White Rot Fungi

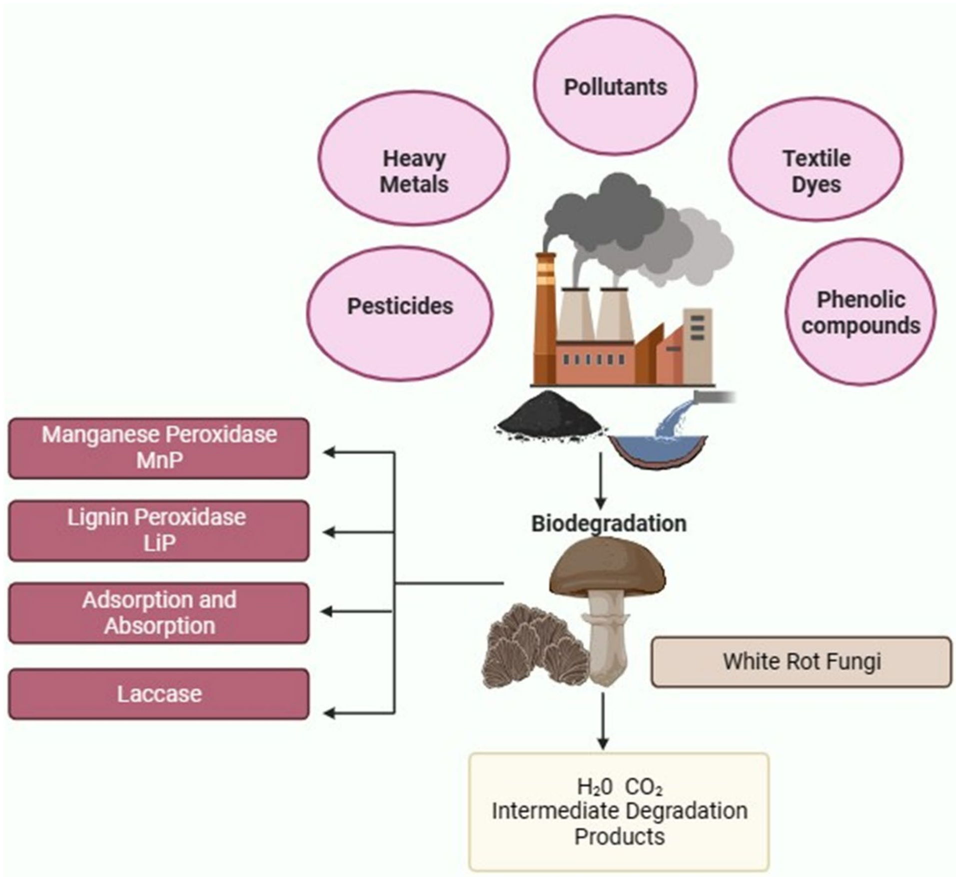

Fig. 16 Mechanism of azo dye degradation by fungi

in addressing the complex challenges posed by industrial wastewater laden with azo dyes.

In essence, the mechanism of azo dye degradation by White Rot Fungi is a harmonious interplay of enzymatic brilliance, radical-driven transformations, and nature's cleanup strategies. As guardians of environmental balance, these fungi showcase a repertoire of tools to dismantle pollutants, offering a sustainable and effective approach to wastewater treatment. Figure 16 encapsulates this symphony, where White Rot Fungi emerge as conductors of nature's orchestra, orchestrating the breakdown of azo dyes with finesse.

Other strategies used for the degradation of azo dyes

In the relentless pursuit of sustainable solutions for environmental challenges, cutting-edge scientific technologies have emerged as potent tools in the degradation of azo dyes. This technological symphony encompasses system biology, omics (proteomics and glycomics), nanotechnology, and gene editing tools, pushing the boundaries of bioremediation efficiency.

System biology stands out as a beacon of promise in unraveling the intricacies of microbial communities across diverse environmental settings. This approach provides a holistic understanding of the dynamic interactions within these communities, offering insights crucial for efficient bioremediation strategies (Chakraborty et al. 2022).

The omics revolution, featuring proteomics and genomics, has revolutionized our ability to analyze genetic and protein-level regulations governing bioremediation processes. Techniques such as sequencing, MALDI-TOF, and the exploration of new functional genes have become indispensable tools in deciphering the pathways involved in pollutant degradation (Chakraborty et al. 2022).

As genetic engineering strides forward, the role of genetically modified organisms, metagenomics, and metabolomics is taking center stage. These advancements aim to deliver cost-effective and reliable methods for azo dye degradation (Gaur et al. 2018). The exploration of genomic methods, including PCR-based techniques, isotope distribution analysis, DNA hybridization, and metabolic engineering, further enhances our understanding of the intricate biodegradation processes (Hakeem et al. 2020).

Polymerase chain reaction (PCR)-based techniques play a pivotal role in genotypic fingerprinting. These techniques, including amplified ribosomal DNA restriction analysis (ARDRA), amplified fragment length polymorphisms (AFLP), randomly amplified polymorphic DNA analysis (RAPD), terminal-restriction fragment length polymorphism (T-RFLP), single strand conformation polymorphism (SSCP), and length heterogeneity, empower researchers to analyze bacterial species, construct functional structural models, and generate genetic fingerprints in the exploration of soil microbial communities (Domínguez-Rodríguez et al., 2022).

Figure 17 serves as a visual testament to the diverse array of technologies employed in the removal of azo dyes. From system biology to advanced genetic engineering tools, this image encapsulates the scientific prowess harnessed to combat environmental challenges. It signifies a collaborative effort across disciplines, portraying the convergence of innovation for a cleaner and more sustainable future.

The technological symphony in azo dye degradation is an evolving narrative, where each innovation adds a unique note to the harmonious orchestration of environmental stewardship. As we delve deeper into the intricacies of microbial communities and molecular regulations, these technologies promise not only effective solutions but also a deeper understanding of our role as custodians of the planet.

Conclusion and future perspectives

The widespread utilization of azo dyes within the textile industry has ignited a growing environmental predicament, characterized by the release of dye-laden effluents into ecosystems. These electron-deficient xenobiotic chemicals, featuring azo (–N=N–) groups and aromatic functionality, not only bestow vibrant hues upon textiles but also raise serious environmental concerns due to their inherent toxicity, mutagenicity, and carcinogenicity. The imperative to address the environmental repercussions of dye-containing wastewater is evident, necessitating effective solutions to mitigate the impact of textile industry effluents.

Biological methods have emerged as a promising avenue, surmounting the limitations of conventional physicochemical approaches. Microorganisms such as bacteria, fungi, yeast, algae, and plants offer a sustainable, environmentally benign approach to the removal of azo dyes from effluents. The scope of these biological processes, elucidated in this study, lies in their affordability and adaptability to a diverse array of dye structural types. Among these microorganisms, bacteria stand out as preferred agents for dye removal from textile effluents, owing to their ease of cultivation, resilience in challenging environments, and rapid decolorization capabilities in comparison to other microorganisms.

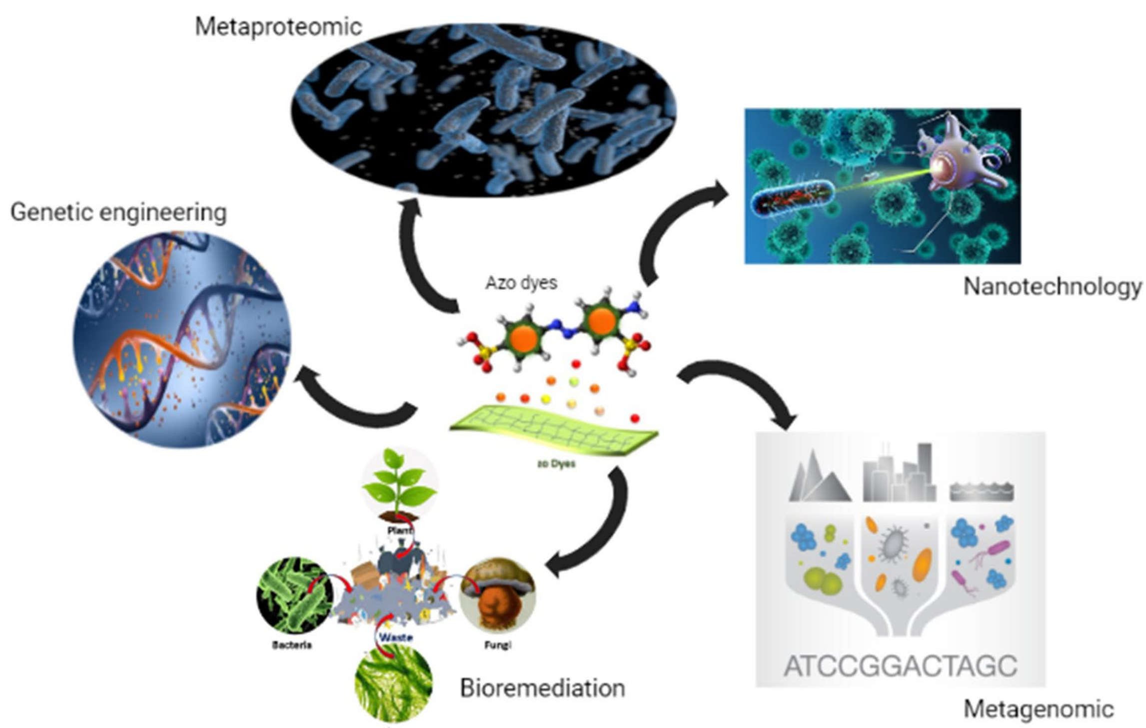

Fig. 17 Technologies used for removal of azo dyes

Looking toward the future, the amalgamation of nanotechnology with traditional biological processes heralds a paradigm shift in environmental protection strategies. Nanotechnologies, when synergized with biological methods, hold the promise of significantly enhancing the efficiency of azo dye remediation. This integration opens new frontiers for sustainable solutions to the challenges posed by colored wastewater in textile dyeing industries.

The path forward in research necessitates a deeper exploration of enzyme profiles, intermediate metabolites, and the intricate mechanisms governing simultaneous dye and metal-dye complex removal. Genome and proteome studies are poised to play a pivotal role in unraveling the complexities of microbial processes, guiding the optimization of bioreactors, and shedding light on the (non)toxicity and biodegradation processes of azo dye compounds.

Moving forward, the research agenda involves a concerted effort to streamline variables hindering microbial activity, amplify the effectiveness of biodegradation, and optimize the operating conditions of bioreactors. Advanced molecular biology approaches will be instrumental in delving into the genetic and enzymatic intricacies of azo dye treatment. This holistic understanding will provide researchers with novel perspectives on biodegradation mechanisms, propelling the field toward innovative and sustainable solutions.

In conclusion, as we navigate the intricate terrain of azo dye remediation, the seamless integration of biological methods with cutting-edge technological innovations holds the key to a cleaner, more sustainable future. The strides made in this research underscore the potential for transformative change, where environmental stewardship aligns seamlessly with scientific progress. This synergy promises not only the remediation of azo dye pollutants but also the establishment of a blueprint for sustainable environmental practices in the broader context of industrial processes.

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Data availability All data collected and reviewed are included in this article and properly referenced.

Declarations

Conflict of interests The authors declare no competing interests.

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