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# Environmental Impact of Synthetic Dyes on Groundwater in Malaysia: Sources, Distribution, Transport Mechanisms, and Mitigation Strategies

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**ABSTRACT:** Synthetic dyes, extracted from natural sources like insects, plants, coal, and ochre, have become prevalent due to their advantages over natural dyes. However, their production has led to increased environmental pollution, particularly in groundwater. Groundwater contamination from synthetic dyes occurs through advection, dispersion, and retardation. This review aims to highlight the environmental impacts of synthetic dyes on groundwater, elucidate the mechanisms of dye transport, and propose effective strategies for monitoring and mitigating contamination. Urban runoff carries dyes from surfaces such as roofs, parking lots, and roads into stormwater systems, while agricultural runoff transports dyes from products like soil conditioners, fertilizers, and seed coatings into water bodies. In groundwater, dyes move through the aquifer via advection, dispersion, and retardation, all influenced by groundwater flow and geological conditions. The advection process involves the bulk movement of groundwater carrying dissolved dyes, while dispersion causes dyes to spread and dilute over time and distance. Retardation, which involves the adsorption of dye molecules onto soil particles, slows dye movement, prolonging their presence in groundwater. Understanding the sources, distribution, and movement of synthetic dyes in groundwater is crucial for developing strategies to protect water resources and reduce environmental and health impacts. The extensive use of dyes in industrial and domestic activities necessitates comprehensive monitoring and management to ensure sustainable groundwater quality.

**KEYWORDS:** Groundwater; aquifer; synthetic dye; contamination

## 1. Introduction

The term "groundwater" refers to the water found in the cracks and spaces within rocks, sand, and soil beneath the Earth's surface. It occupies the gaps created by underground geological structures known as aquifers. Over the years, the demand for water has continued to rise due to increasing pollution and the growing frequency of agricultural and industrial activities. The increasing pollution of surface water sources diminishes the availability of clean, safe water, forcing reliance on alternative sources like groundwater. As surface water bodies become more contaminated by pollutants, including synthetic dyes, the capacity to meet water demand decreases [1]. Due to the expeditious industrial development and urbanization, the water resources such as groundwater and the environment on Earth is also degraded at a rapid pace. Groundwater contamination poses as a serious problem for countries that primarily rely on groundwater supply. In terms of Malaysia, the total amount of freshwater supply that is groundwater is only 3% as the main source of water comes from river water, or surface water. While the current demand for of groundwater supply in Malaysia is still relatively low, the usage of groundwater is bound to increase as the continuous development of the country keeps on going. Malaysia has an estimated 5,000 billion cubic meters of underground water, with the capacity to process around 64 billion cubic meters annually. This substantial groundwater reserve can serve as a reliable alternative water source for the country [2].

Synthetic dye can be defined as the chemical compounds that are artificially made and utilized to provide colour to a variety of materials, such as plastics, textiles and many more. Synthetic dyes are used by most service providers, such as hospitals, universities, and the food sector. For the majority of dyes, there are no established maximum discharge restrictions or harmful impacts on the environment or public health. In general, the national rules establish a colour limit but do not specify restrictions for dyes. In certain cases, they just call for colour measurement and do not provide water limits. Synthetic dyes pose a significant environmental concern, particularly in the contamination of groundwater, due to their acute toxicity and genotoxicity, which can lead to severe health implications. Unlike natural dyes, which are typically derived from biodegradable sources such as plants and insects, synthetic dyes are chemically stable and more resistant to degradation, making them persist longer in the environment. This persistence increases the risk of long-term exposure to toxic compounds, which can accumulate in groundwater systems. Synthetic dyes can also pose environmental issues, as industrial effluent containing these dyes can decrease light penetration in water bodies, thereby affecting the photosynthesis process of aquatic flora [3, 4]. Assessing synthetic dyes in groundwater is crucial, as it helps determine the movement of these dyes and enables the development of mitigation methods for dye contamination. This review aims to highlight the environmental impacts of synthetic dyes on groundwater, elucidate the mechanisms of dye transport, and propose effective strategies for monitoring and mitigating contamination..

## 2. Sources, Distribution, and Movement.

Synthetic dyes are derived from natural sources such as insects, plants, coal, and ochre, which are environmentally friendly and cause low levels of pollution. As civilizations continue to develop and flourish, synthetic dyes have become more favored over natural dyes, spreading throughout the world. The production methods and applications of dyes changed significantly with the discovery of synthetic dyes, leading to increased industrial development but also resulting in higher levels of environmental pollution. Groundwater contamination can be attributed to three primary processes: advection, dispersion, and retardation [4, 5].

### *2.1.Point sources.*

Synthetic dyes are considered as the largest group of all colouring substances, and it is estimated that around 1 million tons of synthetic dye is produced annually. The wasted dye will ultimately end up in water bodies, contributing to environmental pollution and posing risks to aquatic life due to the presence of toxic byproducts. During the dyeing process, at least 5% and a maximum of 50% of dye is wasted. The wasted dye will end up as coloured effluent that reaches to the surface water which is estimated to be around 200 billion litres [7]. Groundwater and surface water are interconnected as gravity can cause the chemical substances to seep into the soil. Thus, the effluent containing toxic properties might end up in the groundwater and causing potential groundwater contamination [8].

Similarly, wastewater treatment facilities do not always successfully remove pigments from effluent before releasing it into aquatic bodies. If the treatment process is inadequate or malfunctioning, dyes can permeate the system and contaminate groundwater. This occurs because different types of dyes possess various chemical compositions and properties, which affect their treatability in wastewater [9]. Wastewater containing dyes is generated during various dyeing processes, and the type of fabric and class of synthetic organic dyes used significantly influence the amount of dye lost. For instance, textile effluents from dyeing cellulose fibers may contain 10% to 40% sulfur dyes and 10% to 50% reactive colors. The textile industry alone generates approximately 200 billion liters of colored wastewater each year, with a significant portion of industrial effluents containing dyes being discharged directly into aquatic environments. An estimated 280,000 tonnes of dye are wasted annually and end up in aquatic ecosystems solely from the textile industry. Additionally, around 20% of industrial water contamination is directly attributed to the textile sector [10].

Wastewater from households is another point source of synthetic organic dyes. Even though individual homes might not create as much synthetic dye as industrial facilities, the combined impact of wastewater containing colour from several houses can lead to contamination of groundwater with synthetic dye in the environment. In fact, studies have shown that household wastewater contributes to around 20% of the total dye pollution in urban areas. Laundry activities are significant contributors to household pollution from synthetic dyes [4]. These dyes are commonly found in various commercial laundry detergents, fabric softeners, and laundry additives, enhancing textiles with vibrant colors and other desirable properties. During washing, synthetic dyes can leach from garments, dissolve in wash water, and ultimately enter the home’s wastewater system. In addition to laundry products, synthetic dyes are also present in many household cleaning supplies, such as dishwashing detergents, multipurpose cleaners, and toilet bowl cleaners. Residual dyes from these cleaning agents can wash away with wastewater, contributing further to the contamination of the sewage system. Furthermore, arts and crafts materials represent another source of synthetic dyes that can affect groundwater. Activities such as painting, tie-dyeing, and fabric dyeing often involve the use of synthetic dyes [11]. After these projects, residues containing dyes from surfaces, tools, and utensils can wash off and enter the wastewater stream, further exacerbating dye pollution.

*2.2.Non-point sources.*

Synthetic dye pollution from diffuse or dispersed sources that are challenging to link to specific sites or facilities is referred to as non-point sources of dye pollution in wastewater. Unlike point sources, such as sewage treatment facilities or industrial discharges, non-point sources contribute to dye pollution through runoff, leaching, or air deposition from various sources across large areas. Urban runoff is the primary non-point source of synthetic dye pollution in water bodies. This runoff originates from impermeable surfaces such as roofs, parking lots, and roads. During rainfall, synthetic dyes present in urban environments—found in paints, car coatings, consumer goods, and building materials—can wash off these surfaces and enter stormwater drainage systems [12]. Once in the drainage system, synthetic dyes may be released into receiving water bodies, either partially or fully treated. These dyes can contain hazardous or toxic substances that harm aquatic life, disrupt ecosystem functions, and degrade water quality. Additionally, synthetic dyes may alter the color of water bodies, reduce light penetration, and obstruct biological activities like photosynthesis [5].

Agricultural runoff is another non-point source of synthetic dye pollution. Factors such as precipitation, irrigation techniques, and agricultural activities—like fertilization, pesticide application, and animal husbandry—contribute to this runoff. Rainwater and irrigation water can transport synthetic dyes into nearby water bodies. Certain agricultural products, such as soil conditioners, fertilizers, and seed coatings, may contain synthetic colorants [13]. For instance, colored seed coatings are sometimes applied to differentiate treated seeds from untreated ones. Synthetic dye pollution in agricultural runoff can occur when these dye-containing agrochemicals are improperly applied or managed, washing off fields during rainfall or irrigation. In some farming systems, synthetic dyes are used as feed additives, pharmaceuticals, or markers for animal identification. The runoff from livestock operations, such as grazing areas and concentrated animal feeding operations (CAFOs), may introduce dye residues from feed or other sources into adjacent water bodies [14].

### *2.3.Distribution and movement.*

The distribution and movement of contaminants introduced into groundwater can be categorized into three types of flow: advection, dispersion, and retardation. Advection refers to the movement of contaminants along the groundwater flow, where the velocity of the contaminants matches the average velocity of the groundwater. To determine the rate of fluid flow in groundwater, Darcy's equation is employed. The effective flow velocities are based on the bulk movement properties of groundwater, which flows through porous or fractured geological formations due to hydraulic gradients—differences in hydraulic head between various aquifer points. As groundwater undergoes advection, it carries dissolved materials from areas of higher hydraulic head to regions of lower hydraulic head.

Dispersion is the process by which contaminants spread over a large area due to variations in hydraulic conductivity and porosity. As contaminants travel through the porous media of an aquifer, they spread and mix with the groundwater. Physical processes, including turbulent flow, molecular diffusion, and mechanical mixing, contribute to dispersion in groundwater. As groundwater flows through the interconnected pore spaces of the aquifer, dye molecules follow distinct flow paths, mixing with adjacent groundwater parcels. Over time and distance, dispersion allows synthetic dyes to spread and elongate as they migrate through the aquifer, leading to diluted dye concentrations downstream from the pollution source [6].

Retardation refers to the slower velocity of contaminants compared to the velocity of groundwater as they pass through porous media. This phenomenon affects contaminant transport behavior and may result in a longer residence time in the aquifer. One of the primary mechanisms causing retardation is the adsorption or absorption of dye molecules onto soil particles or mineral grains in the aquifer matrix. Synthetic dye molecules can bond to soil surfaces through chemical bonding, physical adsorption, or electrostatic interactions. Once sorbed onto solid surfaces, these dyes are less mobile as groundwater flows through the aquifer.

While they may eventually desorb and return to the groundwater, the presence of adsorbed synthetic dyes can lead to greater travel distances and a lower rate of movement [6].

## 3. Challenges Faced by Synthetic Dye Groundwater Pollution.

Billions of people worldwide primarily obtain their drinking water from groundwater. This resource is especially crucial in rural and arid regions, where it serves as the main source of potable water. The health and vitality of wetlands, springs, streams, and other surface water bodies depend on groundwater. Additionally, groundwater provides a relatively stable supply of water, particularly during drought periods when surface water sources may be limited.

### *3.1.Drinking water shortage issue.*

Groundwater pollution from synthetic dyes can significantly affect groundwater availability, especially in areas where it is the major source of drinking water [15]. Insufficient groundwater can lead to a scarcity of water for industrial, agricultural, residential, and other essential uses. Consequently, communities may be compelled to rely on alternative water sources, such as surface water, desalinated water, treated wastewater, or imported water supplies. While these alternatives may alleviate short-term water shortages, they can also pose environmental challenges, technological constraints, and increased costs. Moreover, communities lacking access to clean drinking water face serious health risks. Inadequate supplies may force people to use contaminated or unsafe water sources, raising the likelihood of diseases such as cholera, typhoid, and diarrhea. Vulnerable populations, including children, the elderly, and those with weakened immune systems, are particularly susceptible to waterborne infections. Insufficient drinking water can also lead to social and economic disruptions. Competition for limited water resources can exacerbate disputes over water rights, increase tensions among users, and erode community cohesion. Furthermore, reduced water supply can negatively impact water-dependent industries such as manufacturing, tourism, and agriculture, resulting in job losses, income inequality, and unstable economic conditions [16].

### *3.2.Agricultural productivity decline.*

Insufficient groundwater availability due to pollution can lead to reduced agricultural yields or even crop failures, particularly during dry spells or prolonged water shortages. When there is inadequate water for irrigation, crops may suffer from water stress, wilting, slower growth, and decreased output, resulting in financial losses for farmers. This decline can affect local, regional, and national food production levels. In response to dwindling groundwater supplies, farmers may be forced to switch to less water-intensive crops or develop drought-tolerant varieties that require less irrigation. While these adjustments can help mitigate the effects of water scarcity and sustain agricultural production, they may also lead to changes in cropping patterns, agricultural practices, and market dynamics. Moreover, groundwater depletion can exacerbate land degradation and soil salinity, particularly in areas where irrigation water contains high levels of dissolved salts. As groundwater levels drop, the water table may rise closer to the surface, allowing saline groundwater to come into contact with shallow-rooted crops. This situation can ultimately lead to salt accumulation in the root zone, soil salinization, and a decline in soil fertility, further diminishing agricultural output and the land’s suitability for farming [17].

## 4. Impact to Environments

Many synthetic dyes contain harmful chemicals, including heavy metals, which are toxic to aquatic organisms such as microorganisms, invertebrates, and fish. For instance, the dark coloration of water from dyes reduces light penetration, affecting photosynthesis in aquatic plants, which forms the base of the food chain. This leads to reduced oxygen levels and destabilizes the habitat for fish and other organisms. The impact on biodiversity is severe, as many synthetic dyes contain toxic, carcinogenic, or mutagenic compounds. These chemicals can directly affect aquatic organisms, causing mortality, reproductive failures, or developmental issues [3]. For example, the dye Congo Red has been shown to have toxic effects on fish, leading to population declines and reduced species diversity in polluted ecosystems. In aquatic ecosystems, synthetic dyes interfere with nutrient cycles and disrupt ecological balance [18]. Algal blooms, which thrive in polluted water, can be stimulated by certain dyes, leading to eutrophication, where oxygen depletion creates “dead zones” incapable of supporting life. This drastically reduces the productivity of ecosystems, as key species decline, and the overall function of the ecosystem is impaired [19]. Moreover, these disruptions can have cascading effects on human communities that rely on these ecosystems for fisheries, agriculture, and clean water, exacerbating the socio-economic impacts of synthetic dye pollution. This demonstrates the pressing need for effective management of dye-containing wastewater to protect ecosystems and biodiversity [20, 21].

## 5. Human Health Impacts.

The presence of synthetic dyes in contaminated groundwater can pose various health risks to humans when consumed in significant amounts. When groundwater mixed with synthetic dyes is used for food and drink, these dyes can inadvertently enter the human body [23]. Prolonged exposure to high concentrations of synthetic dyes can lead to symptoms such as headaches, nausea, fatigue, muscle and joint pain, and dizziness. In more severe cases, certain dyes may cause serious health hazards, including cancer.

Synthetic dyes that are toxic to humans can be categorized into acute toxicity and chronic or genotoxicity. Some dangerous characteristics of synthetic dyes include acute toxicity, carcinogenicity, mutagenicity, and allergic reactions. Acute toxicity arises from ingesting synthetic dyes orally or through inhalation, resulting in immediate symptoms like dizziness, vomiting, and nausea. Many artificial dyes, particularly azo dyes containing aromatic amines, have been linked to cancer, with extended exposure increasing the risk of developing conditions such as bladder cancer [25]. Additionally, certain synthetic dyes possess mutagenic properties, which can lead to genetic mutations in cells, resulting in adverse health outcomes such as congenital malformations, developmental irregularities, and reproductive issues.

Moreover, some synthetic dyes can trigger allergic reactions. For individuals with sensitivities, these dyes may cause skin irritations, rashes, and respiratory symptoms like asthma attacks [26]. Workers in dye manufacturing plants and those involved in the dyeing process face various health risks due to exposure to reactive dyes. Evidence shows that prolonged exposure can lead to negative side effects such as allergic reactions, rhinitis, dermatitis, and occupational asthma. This is primarily caused by the interaction of human serum albumin with reactive dyes, resulting in the formation of dye-human serum albumin (HAS) conjugates, which are considered antigens. To minimize exposure risks, it is essential to avoid dye dust. Using liquid and low-dusting formulated dyes, along with personal protective equipment, is recommended [26].

Disperse dyes are particularly notorious for causing allergic reactions, especially when used in products that come into close contact with the skin, such as tight-fitting clothing.The disperse dyes responsible for this issue are primarily those that exhibit low levels of perspiration fastness. Perspiration fastness refers to a dye's ability to resist fading or washing out when exposed to moisture, such as sweat. Disperse dyes is not a threat if the dye is on polyester as the item has a high level of perspiration fastness. On the other hand, disperse dyes becomes a problem when the perspiration fastness of the item is low, such as acetate rayon and polyamide [27].

## 6. Technologies Applied for Contaminated Groundwater Treatment.

Groundwater serves as the primary water source for factories and agricultural industries. However, the quality of groundwater has continued to deteriorate due to irresponsible dumping of effluents and accidental spills of toxic substances. Consequently, wastewater treatment is essential before discharging water into the environment. Various technologies used for the removal of synthetic dyes from wastewater are described in Table 2.

### *6.1.Activated carbon treatment.*

Activated carbon is highly effective for removing synthetic dyes from wastewater due to its large surface area and strong adsorption capacity. During this process, wastewater passes through beds or columns of activated carbon, allowing dye molecules to be absorbed onto the carbon surface. Key parameters that affect the dye adsorption rate include the dye's solubility and molecular size. Water-soluble, hydrophilic dyes tend to have a low adsorption rate because of the non-polar nature of carbon and the polar characteristics of the dyes [28]. Research indicates that reactive and acid dyes with relatively low molecular masses also exhibit low adsorption rates. In contrast, disperse dyes, which are hydrophobic, show high adsorption rates due to their higher molecular masses. The activated carbon adsorption method is highly versatile, suitable for both continuous and batch treatment processes, and is relatively easy to operate and maintain. Moreover, it is environmentally friendly as it does not require additional chemicals, and it can save on operating costs due to its reusability [29].

### *6.2.Chemical coagulation and flocculation treatment.*

Chemical coagulation and flocculation are widely used methods for removing colors from wastewater. In this process, chemicals such as polymers, ferric chloride, or aluminum sulfate are added to destabilize dye molecules, leading to the formation of flocs. These flocs can then be easily removed through filtration or sedimentation techniques. Although coagulation primarily removes only a portion of the color, it can also reduce Chemical Oxygen Demand (COD) depending on the coagulant used. Flocculation is defined as the subsequent addition of flocculants, typically polymers, after the coagulation stage to create larger and more stable flocs. Flocculants facilitate the collision and aggregation of smaller flocs by bridging them during coagulation. Coagulation-flocculation methods are particularly effective for removing color from water-insoluble sulfur and disperse dyes [30]. However, their capacity for coagulation-flocculation is lower when treating water-soluble dyes, such as acid and reactive dyes. Additionally, the sludge produced during the coagulation-flocculation process contains high levels of ferric salts and aluminum, which can be toxic to aquatic organisms if disposed of without further treatment. Using a commercial organic flocculent and four inorganic coagulants, which are $FeCl_3$, $Ca(OH)_2$, $Fe_2(SO_4)_3$, $Al_2(SO_4)_3$ and a organic flocculent, the efficiency of coagulation for effluent from a cellulosic dyeing unit was evaluated. The outcome of the experiment shows that the reactive dyes could be eliminated up to 90% using commercial organic flocculent, whereas up to 99.5% of colour removal could be achieved using fibreglass filter. The advantage of using chemical coagulation and flocculation is that the method is capable of handling a variety of wastewater types and compositions [31]. It is also compatible with various methods of treatment, including filtration, disinfection, and sedimentation. **Error! Reference source not found.** shows the process of coagulation, flocculation, and sedimentation.

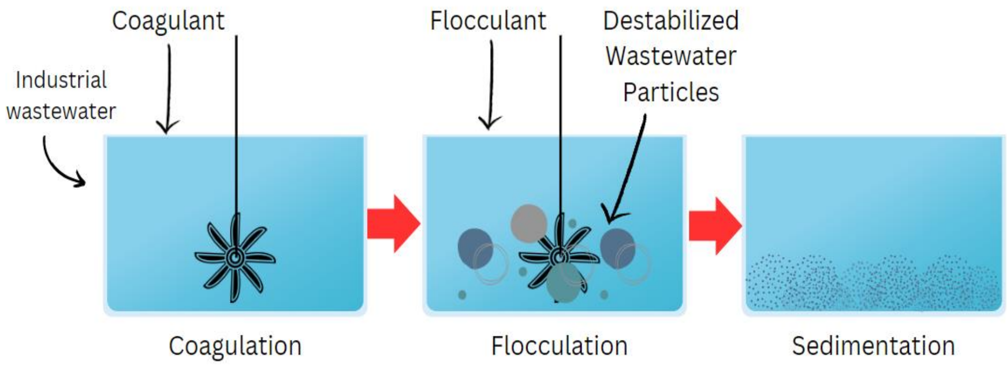


**Figure 1.** Process of coagulation, flocculation, and sedimentation.

*6.3.Biological treatment.*

Utilizing microorganisms, biological treatment techniques break down or metabolize organic contaminants found in wastewater, including synthetic colours. This can involve procedures like sequencing batch reactors, biofilters, and activated sludge treatment. Wastewater and a culture of microorganisms are combined in an aerated tank or basin during the activated sludge process. As they develop and proliferate, the microbes metabolize the organic contaminants found in the wastewater. Following biological treatment and aeration, the wastewater is subjected to secondary clarifier to separate the treated water from the biomass, which may either be disposed of or recycled back into the aeration tank [32]. One of the most common biological treatment methods is using aerobic degradation. Aerobic degradation of dyes with the aid of microorganisms has been proven as a safe method. When the bacteria are in contact with oxygen, an azoreductase enzyme will be produced. Under stable conditions, the enzyme can greatly reduce the dyes within the azo group [33]. The activated sludge system, which suspends microorganisms in aerated wastewater, is the most widely used aerobic treatment technology for dye wastewater. It is anticipated that a lot of dyestuff, namely disperse, direct and basic dyes, will be removed from the wastewater by adsorption onto the activated sludge. Reactive and acid dyes, on the other hand, have poor adsorption values and hence mostly pass through the activated sludge. The chemical structure, quantity, and location of substituents inside the dye molecule, among other dye characteristics, are the primary determinants of dye adsorption on activated sludge. The advantages of using biological treatment for synthetic dyes is that the degradation rate of pollutants such as synthetic dye is very high when compared with other treatment methods [33]. Biological treatment also converts the harmful pollutants into harmless by-products such as water and carbon dioxide. Figure 2 shows the biological approaches for effluents.

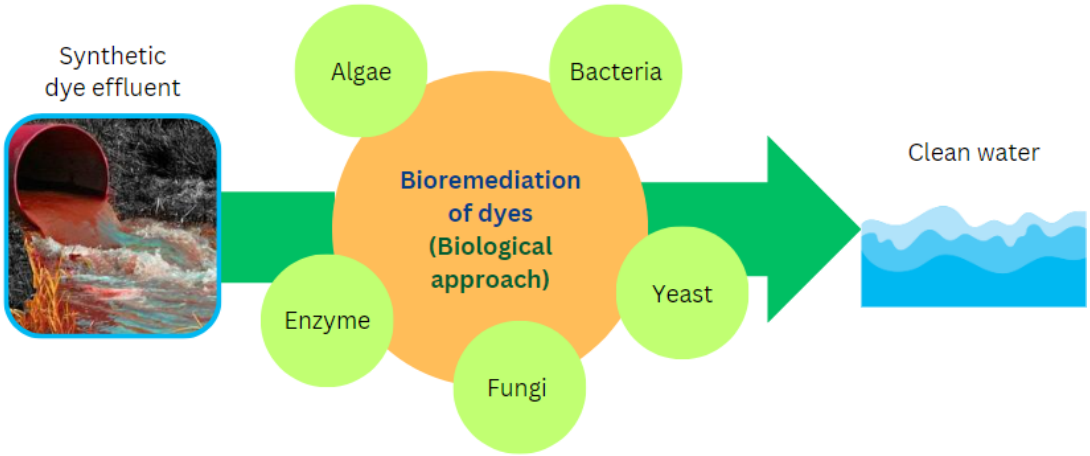


**Figure 2.** Biological approaches for effluents.

*6.4.Membrane filtration treatment.*

Membrane filtration technology encompasses various separation techniques, including microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. These methods effectively physically separate dye molecules from water, enabling the removal of synthetic colors from wastewater. Many of these techniques can be utilized to remove synthetic dyes from wastewater without the need to differentiate between dye types. Membranes can physically block certain components in wastewater while allowing for the removal and potential reuse of dyes, chemicals, and treated water. Extensive documentation exists on the application of membrane filtration for removing water-soluble colors from textile effluents. Several parameters influence the design specifications of a membrane system handling dye waste, including the dyeing process, the type of dye to be removed, the chemical composition of the waste stream, and, most importantly, the maximum permissible cost. Membranes designed for color removal can effectively separate organic dyes from textile effluent due to their acceptable chemical and thermal stability, high flux operation, and resistance to a broad range of pH levels, temperatures, and solvents. Ultrafiltration has successfully recycled water, auxiliary chemicals, and high molecular weight insoluble dyes, such as indigo and disperse dyes [34]. Various polymers are employed as membranes for reverse osmosis and ultrafiltration, including polyamides, styrene-based polymers, polyacrylonitrile, polysulfides, polycarbonate, and fluorocarbon-based polymers. Nanofiltration and reverse osmosis processes have effectively removed hydrolyzed reactive colors from textile effluent, which are typically challenging to eliminate using traditional color removal techniques. This filtration technology can aid water recycling in synthetic dye facilities, particularly when the effluent has a low dye concentration. However, it does not reduce the dissolved solids content, making water reuse a complex operation. The advantages of using membrane filtration technology include minimal chemical requirements for operation and a high removal rate for contaminants, including suspended solids, colloids, dissolved compounds, and synthetic dyes. Figure 3 illustrates an example of a filtrate membrane.

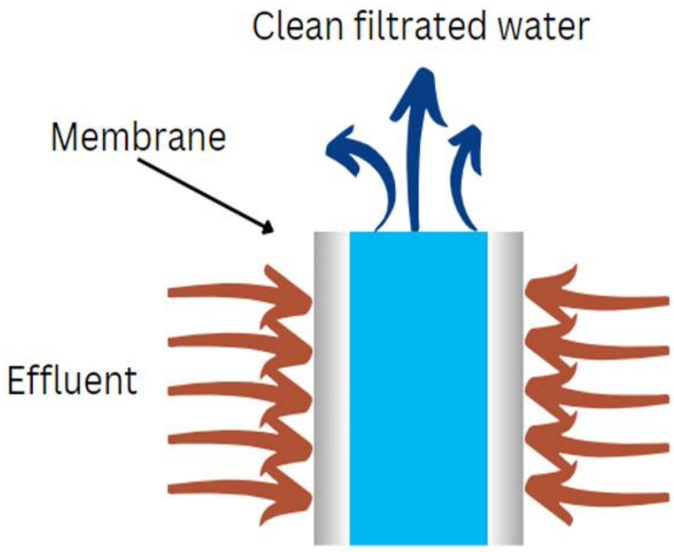


**Figure 3.** Filtrate membrane mechanism.

**Table 2.** Types of treatment and the advantages.

| Technology | Process | Advantages | Reference |
|---|---|---|---|
| Physical | Activated carbon treatment; | Easy to use, save cost, environmentally friendly | [30, 31] |
| | Membrane filtration treatment | | [34] |
| Chemical | Chemical coagulation and flocculation | Handle various wastewater, compatible with other treatment methods | [30, 31] |
| Biological | Phytoremediation | Low cost, Environmentally friendly | [32, 33] |

*6.5. Combination of treatment.*

New advanced technologies for synthetic dye removal from the environment employ a synergistic combination of physical, chemical, and biological methods, significantly enhancing effectiveness in addressing dye pollution [34, 35]. One promising approach utilizes nanotechnology, where nanomaterials, such as nanoparticles or carbon-based materials, are engineered to adsorb and degrade dyes from wastewater. These nanomaterials possess high surface area and reactivity, allowing for efficient removal of dyes even at low concentrations [36]. Advanced Oxidation Processes (AOPs) are another innovative technique, involving the combination of chemical agents—like ozone, hydrogen peroxide, or titanium dioxide—with ultraviolet (UV) light. This powerful combination generates hydroxyl radicals that effectively break down complex dye molecules into less harmful, biodegradable substances [37]. In parallel, biological methods leverage the natural capabilities of engineered microorganisms or enzymes to metabolize synthetic dyes, converting them into harmless byproducts. This biological approach is particularly appealing due to its sustainability and lower energy requirements. Integrating these diverse technologies enhances removal efficiency and reduces the need for harsh chemicals, minimizing the environmental footprint of dye remediation efforts [20, 35]. Collectively, these advanced methods offer a comprehensive solution for managing dye pollution, promoting healthier ecosystems and safeguarding water quality.

## 7. Conclusion

Synthetic dyes, derived from insects, plants, coal, and ochre, have become widespread due to their advantages over natural dyes. However, their production has increased environmental pollution. Groundwater contamination from synthetic dyes occurs through advection, dispersion, and retardation. Point sources include industrial effluents and household wastewater, with significant dye losses during the dyeing process leading to polluted effluents that infiltrate groundwater. Non-point sources, such as urban and agricultural runoff, also contribute to groundwater contamination by carrying dyes from various surfaces and agricultural products. Once in the groundwater, dyes move through the aquifer via advection, dispersion, and retardation, influenced by groundwater flow and geological conditions. Groundwater, a primary water source for factories and agriculture, deteriorates due to irresponsible effluent dumping and toxic spills, necessitating wastewater treatment. Key technologies for synthetic dye removal include activated carbon treatment, which utilizes carbon's adsorption capabilities and is effective for hydrophobic dyes; chemical coagulation and flocculation, which uses chemicals to destabilize and remove dye molecules but produces toxic sludge; biological treatment, which employs microorganisms to degrade organic contaminants into harmless by-products; and membrane filtration, which effectively separates dye molecules in low dye concentrations but does not reduce dissolved solids. Each technology has specific advantages and limitations.


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## Author Contribution

Alfred Chan: Writing, Data Collection; Rubiyatno: Writing, Review, Methodology, Zarina Akhmetov: Methodology, Conceptualization, Review.

## Conflict of Interest

The authors declare no conflict of interest.

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