Water Air Soil Pollut (2025) 236:655
https://doi.org/10.1007/s11270-025-08302-6

Methods and Composites for Surfactant Removal From Wastewater: A Review

Deepali Kulkarni · Dipika Jaspal · Nilisha Itankar

Received: 28 September 2024 / Accepted: 21 June 2025

Abstract The COVID-19 pandemic has exacerbated water quality issues due to the use of substances such as soaps, detergents, and hand sanitizers, which contain surfactants as their key ingredient. These products are modified to enhance their properties, thereby increasing their hazardous chemical impact on the environment, necessitating efficient remediation materials and methods. Surfactants are also released into the environment from various industrial processes. Compared to other surfactant removal techniques, adsorption offers several advantages, including ease of design, simplicity of use in the technical realm, and adaptability to various treatment formats. Adsorption operates across a wide pH range and in several environments. Adsorption is efficient, profitable, requires minimal energy, and has no harmful byproducts. Adsorbents can be developed using various biomass products, nanomaterials, polymeric materials, zeolites, and clays. Composites represent a much efficient alternative material for the elimination of surfactants. A composite of bentonite, sodium bisulfite, polyacrylamide, and aluminum sulphate confirmed a reduction in the surfactant concentration by 82 %, and Chemical Oxygen Demand (COD) by 65 % from a textile wastewater sample. Composite adsorbents made of zeolite and eggshells effectively removed surfactants from samples. The final adsorbent revealed 88% COD removal rate. The presented manuscript analyses the conventional methods for surfactant removal, especially focusing on composites as adsorbents. Future perspectives have been emphasized for the use of composites, and the performance of various composites for surfactant removal has been discussed at length.

Keywords Composites · Surfactants · Wastewater Treatment · Adsorption · Adsorbents

D. Kulkarni · D. Jaspal (✉) · N. Itankar
Department of Applied Science, Symbiosis Institute of Technology (SIT), Symbiosis International (Deemed University) (SIU), Lavale, Pune, Maharashtra, India
e-mail: dipikajaspal@gmail.com

1 Introduction

Water scarcity is a pressing issue, with only 2.99% of available water being fresh or accessible for drinking. Population growth, urban progress, pollution, and climate change contribute to this shortage. United Nations International Children's Emergency Fund (UNICEF) reports that 750 million people globally lack access to fresh water, and the World Water Council (WWC) predicts that 3.9 billion people will live in water-deficient regions by 2030. Initiatives like wastewater purification using sustainable techniques and materials are being implemented to address water scarcity issues. This ensures availability and sustainable management of surface water as per the requirement of Sustainable Development Goals (SDGs-6) of the United Nations (Obaideen et al., 2022). The

Published online: 04 July 2025

adsorption technique with various adsorbents for water remediation is one such aspect of water purification (Jaspal et al., 2023). Figure 1 depicts adsorption as a process aligned with United Nations Sustainable Development Goal 6. Wastewater streams from domestic and industrial activities contain organic compounds known as emerging contaminants (ECs), which comprise of insecticides, medications, hormones, plasticizers, food additives, wood preservers, detergents, surfactants, decontaminators, flame retardants, and other organic compounds. These contaminants are not subject to regular restrictions and can be fatal to aquatic and human life. Cost-effective tertiary treatment techniques are required since conventional primary and secondary water treatment facilities find it challenging to remove these harmful contaminants effectively. Owing to its affordable initial cost, high efficiency, and simple working model, adsorption is a viable technique for removing EC. According to research, EC is removed from water and wastewater using a variety of adsorbents, such as activated carbons, modified biochar, nano adsorbents, and composite adsorbents (Sophia and Lima, 2018).

Reclamation of wastewater is a sustainable approach to water scarcity; nevertheless, water contains significant amounts of detergents, including surfactants, which are hazardous to the environment and human health. Since surfactants impede the activity of microorganisms, biological remedies are inefficient. Options for chemical therapy can be expensive and affect the general consensus. Better adsorbents for treating and eliminating surfactants have been found in low-priced sustainable materials such as silica gel, zeolite minerals, activated carbon, biomasses such as mussel shells, rubber tyre granules, fly ash and powdered coarse blast furnace slag (James & Ifelebuegu, 2018).

Adsorption is an established technique that uses various materials to remove numerous contaminants, including organic pollutants. Metal oxides and their composites can be used for the adsorptive removal and photocatalytic degradation of organic pollutants comprising dyes, insecticides, fertilizers, pharmaceutical components, organohalides, phenols, surfactants, and even nutrients. The highly selective properties of nanostructured metal oxides and their composites, including their specific crystalline

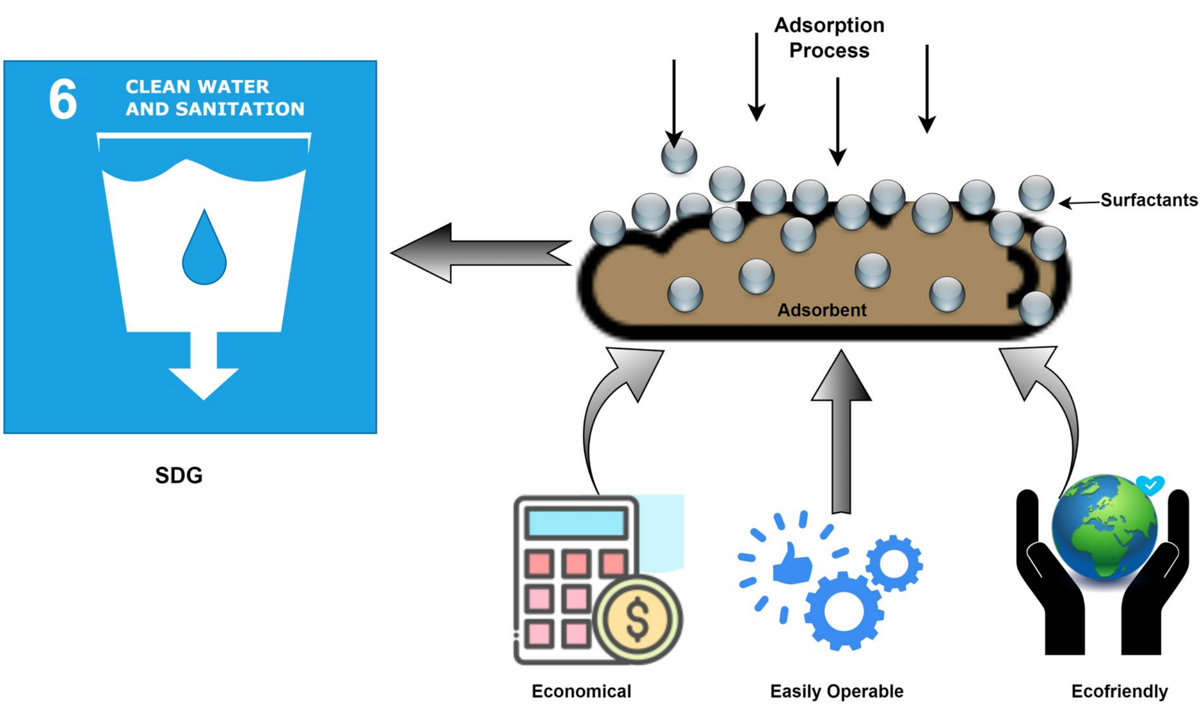

Fig. 1 Adsorption for SDG-6

nature, high surface area, variable surface chemistry, controlled morphological and textural features, make them ideal for the efficient exclusion of organic pollutants through adsorption and photocatalytic degradation (Gusain et al., 2019). Adsorption is a popular method for removing surfactants from wastewater due to its simplicity, excellent efficacy, and low operating costs. Various materials have been used to remove surfactants, including graphene, kaolinite, metal-based composites, nanoparticles, activated carbon and biomass-based adsorbents. Saponite clay and magnetite-based composite sorbents were suggested to have a high surfactant sorption capacity. These magnetic nanocomposite sorbents from clay and magnetite have shown higher effectiveness in wastewater treatment, with two to eight times greater sorption capacities than native clay minerals. These soft magnetic materials efficiently remove spent nanocomposites, making them technologically and economically advantageous solutions (Oksana Makarchuk et al., 2017).

Researchers are now increasingly fascinated by composites as a means of eliminating impurities not only through adsorption but also via flocculation, coagulation, ion exchange, electrostatic interactions, and membrane filtration. Composites are mixtures of two or more distinct component elements that offer product-specific attributes. Grafting, functionalization, and crosslinking are methods for fabricating composites that enhance their characteristics (Dutt et al., 2020). Polymer composites have demonstrated significant potential for implementation in desalination and water treatment processes when combined with other materials, such as carbon-based compounds and clays. These composite materials have enhanced recyclability, selectivity, and adsorption capacity. Depending on the nature of the adsorbent and adsorbate, the adsorption mechanisms involved may be chemisorption or physisorption(Berber, 2020).

Owing to their surface area, functionalization, and chemical approachability, composites must be more widely used than individual materials. Composites are developed by mixing various materials to give them unique characteristics. Composites comprise two distinct phases: a discontinuous dispersion phase and a continuous matrix phase. Composites can provide enhanced qualities like thermal insulation, low density, high specific stiffness, specific strength and many more. Combining materials with distinct qualities yields new materials with combined features that can be used in many scientific domains, including wastewater treatment(Maqsood et al., 2019; Mushtaq et al., 2019).

The present manuscript attempts to analyse the different surfactant removal methods and adsorbent materials that can be reconsidered, with some modifications, as composites for the efficient eradication of surfactants. A collection, analysis and in-depth review of materials as adsorbents in composites will help researchers working in this domain to easily identify the potential of materials efficient for the remediation of wastewater from surfactants. Such a study has not yet been carried out and is unique.

2 Surfactants in Water

Surfactants and their mixtures are used in various industrial processes, including enhanced oil recovery, flotation, emulsification, corrosion inhibition, drug delivery, cosmetics, and dispersion or flocculation. Such applicability of surfactants is because of their capacity to alter the interfacial properties significantly. Thus, an enormous quantity of surfactants is released daily in the surrounding water bodies. Surfactants in water harm the microorganisms, affecting the overall biodegradation process(James & Ifelebuegu, 2018). Incomplete degradation products of surfactants mimic the hormones of aquatic life, impacting marine life and terrestrial ecosystems (Scott & Jones, 2000). Surfactants constitute a significant hazard to agricultural production and environmental sustainability. They are present not only in domestic and industrial wastewater but also in irrigation water streams being a major constituent of insecticides and pesticides. They may cause soils to become water-resistant and contribute to a decrease in soil hydraulic conductivity. Nearly all forms of water systems in the surrounding environment are now home to surfactants. Their improved solubility and hydrophobic nature reduce the bioremediation rates. All paraffin- or alkane sulfonates, like linear alkylbenzene sulfonates (LAS) and alkylbenzene sulfonates (ABS), are primary surfactants in washing detergents and health care products. Wastewater contains LAS, which prevents bacteria from decomposing organic materials. Cationic surfactants find applications in shampoos, conditioners for hair, textile softeners, bactericides, and beautifying creams. Because of their effective qualities, surfactants are also known as adjuvants for pharmaceuticals and pesticides (Kulkarni & Jaspal, 2023).

A large quantity of surfactants is now utilized and even further released in marine waters during oil recovery. Thus, the adsorption of these surfactants is crucial not only for more remarkable oil recovery from oil reservoirs but also for avoiding mixing in marine water. Many studies have emerged on surfactant removal by adsorption from oil reservoirs. The surfactant loss resulting from adsorption by the reservoir rocks reduces the oil-water interfacial tension and lowers the chemical effectiveness of the injected slurry. When the percentage of clay minerals in the adsorbents increased by around 5-20 % in the mixture, a direct correlation was observed between the quantity of nonionic surfactants that were adsorbed by the adsorbents and the amount of clay minerals present in the adsorbents (Amirianshoja et al., 2013).

3 Methods for Surfactant Removal

3.1 Biodegradation

3.1.1 Mechanism and Methodical Exploration

Primary biodegradation of surfactant functions when microorganisms structurally modify the parent molecule, resulting in the loss of its surface-active characteristics. The microbes degrade the surfactant, resulting in the formation of products like CO_2, H_2O, and mineral salts. This mechanism is controlled by the type and number of microorganisms, aerobic or anaerobic growth conditions, temperature, pH, nutrients, water content, and substrate bioavailability (Merrettig-Bruns & Jelen, 2009). In wastewater, Surfactants are biodegraded by microbes which consume them to produce energy, nutrients, or catabolism. The procedure of biodegradation is furthermore greatly affected by the chemical composition of the surfactant and the aerobic or anaerobic environmental conditions.

Aerobic degradation method accomplishes better results than anaerobic degradation. During the process of degradation, the high surfactant concentrations depolarize the bacterial cell walls, resulting in foaming and depriving the air supply. Nevertheless, biodegradation is constrained to wastewater with moderate concentrations, provoking doubts about its utilizations in water bodies with large surfactant concentrations (Palmer & Hatley, 2018). Hence, despite the fact that biodegradation of surfactants is a commonly observed phenomenon for their mitigation in wastewater treatment plants (WWTP), this process alone appears insufficient for successfully and completely removing surfactants. In anaerobic conditions, surfactants comprising fatty acid esters (FES), cationic surfactants, alkyl phenol ethoxylates (APE), fatty alcohol ethoxylates (AE), linear alkyl benzene sulphonates (LAS), and secondary alkyl sulphonates (SAS) are all to a certain degree prone to breakdown during the degradation process. The following represents the order of biodegradation: alkyl sulfates > alkyl ethoxy sulfates > secondary linear alkyl sulfates > primary alkane sulphonates > LAS (Scott & Jones, 2000).

An exploration of the biodegradability of a surfactant (XP-100) with yeast extract, was done in the presence of active hydrocarbon pollutants like naphthalene and hexadecane, revealing that the yeast extract presence accelerated the surfactant biodegradation process, when compared to its absence. Across the examined time frame, increase in surfactant concentration did not prevent its biodegradation. However, addition of organic pollutants enhanced surfactant biodegradation due to their synergistic effect. Compared to hexadecane, naphthalene decomposed more prominently. Surfactants increase the solubility of organic pollutants, making them more bioavailable for bioremediation. Although the surfactants themselves did not appear to be utilized for growth, they significantly contributed to improved biodegradation, by raising the number of pollutants and promoting bacterial growth on organic contaminants. The findings presented an advanced knowledge of the bioremediation process and the destiny of the hazardous organic compounds in the aquatic environment (Aly et al., 1998).

3.1.2 Role of Sustainability

Based on the type of surfactant, aerobic and anaerobic processes play vital roles in its biodegradation. The breaking down of surfactants during biodegradation via microbe's aids in environmental sustainability.

Surfactant metabolites released into nearby waterbodies are often resistant to further breakdown, and mimic the hormones of aquatic organisms. This adversely affects the life cycle of these aquatic organisms. Furthermore, due to their incomplete biodegradation, many surfactants pose severe hazards to the environment. Therefore, though biodegradation appears greener and ecologically sustainable, it is not a reliable surfactant mitigation technique. Since biodegradation is a time-consuming procedure, surfactant removal needs enhancements via standard methods like flocculation and aeration for eco-compatibility. Co-metabolism combined with flocculation or chemical treatments is one of the efficient hybrid approaches that help wastewater treatment facilities remove surfactants (Olkowska et al., 2013)

Biodegradation of LAS from greywater using microbial diversity in constructed wetlands is another trending methodology. In this approach anaerobic conditions dominate the system, with an average LAS and Chemical Oxygen Demand (COD) of 32 mg L^{-1} and 374 mg L^{-1} and removal rates of 43% and 66%, respectively. Pseudomonas predominated among the 15 species that degraded surfactants. *Rhodopseudomonas palustris* had the highest relative abundance of operational taxonomic unit (OTU)s in all samples and the highest richness in the anaerobic chamber, among all LAS degraders. Microbial community composition and environmental conditions indicate that LAS biodegradation occurred throughout the constructed wetlands system resulting in a widespread eco-effect. (Mascoli Junior et al., 2023).

3.1.3 Techno-Economic Analysis

Due to their low cost, extended shelf life, and enhanced performance at lower temperatures, petroleum-based surfactants are prominently utilized. However, the exploration for a new ecological, green, biodegradable substitute is essential due to their non-renewability and detrimental environmental impacts. Not only the biodegrading system but also the surfactants are explored to be more sustainable. Hence new biosurfactants are regularly investigated for real time applications. The price of raw materials accounts for roughly 30%–50% of overall biosurfactant production costs. Despite the widespread and environmentally friendly applications of biosurfactants, the scarcity and high cost of raw materials hinder industrial biosurfactant manufacturing. The market value of biosurfactants was \$1.9 billion in 2022, but the global trend of biosurfactant production mounted dramatically. By 2032, the market is anticipated to reach \$3.2 billion, growing at a compound annual growth rate (CAGR) of 5.4% (Singh et al., 2024).

In the manufacturing of conventional alkyl polyglucosides (APGs) and sucrose esters (SEs) as bio-based surfactants, the review by Stubbs et al. (2022) promotes the use of renewable feedstock, biodegradability, catalysis, atom economy, and safe chemical design as per the green chemistry principles. It encourages the use of bio-based surfactants as more environmentally friendly substitutes. The industry worldwide must create new and sustainable systems, business practices, and technology to promote bio-based surfactants and enhance the commercialization of APGs and SEs. As a conceivable substitute for synthetic surfactants, green surfactants such as biosurfactants and oleo surfactants, are being synthesized as a result of biotechnological advancements and are becoming more and more popular globally (Nagtode et al., 2023).

The commercial viability of anaerobic membrane bioreactor (AnMBR) integrating with forward osmosis (FO), reverse osmosis (RO) technologies for municipal wastewater treatment with energy and water generation was considered. AnMBR facilitated for wastewater treatment and energy generation, while RO aided in water production and draw solution regeneration. The FO assisted with pre-concentration of the AnMBR influent. Restraining the FO recovery to 50% in a closed-loop approach resulted in a minimal wastewater treatment expense of 0.81 euros m^{-3}. FO recoveries of 80% and 90% resulted in higher costs of 1.01- and 1.27-euros m^{-3}, respectively. The projected costs for producing fresh water were 0.80 and 1.16 € m^{-3} for a closed-loop strategy and an open-loop scheme that maximized water output, respectively. It was suggested that the FO membrane fluxes of 10 LMH would significantly increase the effectiveness of AnMBR technology and FO-RO. According to a sensitivity analysis, the low FO membrane fluxes were observed as a limiting factor (Vinardell et al., 2020).

3.1.4 Limitations, Industrial Applications and Future Advances

The increased utility of surfactants and the available degradation setups at the wastewater treatment plants show inconsistent and time-consuming results. Nevertheless, many attempts have been made to enhance the impact of biodegradation, especially associated with foul smell. In one such effort, the impact of ethyl alcohol and nitrate on the degradation of linear alkylbenzene sulfonate (LAS) was examined utilizing a central composite design (CCD). The CCD technique proposes a tool for optimizing processes and determining the significance of elements influencing them. It assists to understand process functionality and its application in industrial reactors on a small scale after defining optimal parameters. Nitrate and ethanol (co-substrate) affect in almost complete decomposition of surfactants, overcoming the fundamental limitation. Ethanol and nitrate substantially impact ($p < 0.05$) on the degradation of linear alkylbenzene sulfonate in batch reactors. 99.9% LAS was removed with ideal values of around 97.49 and 87.99 mg L^{-1} for ethanol and nitrate, respectively, under agitation at ≈119.9 rpm and 29.8°C (Andrade et al., 2017).

An extended granulated sludge bed reactor meant for the anaerobic digestion of domestic and commercial laundry wastewater was assessed at three stages, with a 36-hour hydraulic retention period. Tap water and mixing domestic sewage were used to dilute the wastewater stream. A reduction in the LAS exclusion rate from about 77 ± 15% (stage I) to around 55 ± 18% (stage III) resulted from the addition of domestic sewage, which raised LAS and organic compounds concentration in the influent. Thus, a substantial decline in the rate of LAS removal and an association between LAS removal and specific organic loading rate were revealed by data analysis, posing another limitation in removal of surfactant(de Faria et al., 2019).

Therefore, in order to overcome this issue, the microalgal-bacterial processes were employed by high-rate algal pond (HRAP) systems to eliminate surfactants and other pollutants from household wastewater efficiently. In HRAPs, *Scenedesmus sp.* algae was introduced at concentrations of 1.4 g L^{-1} for total suspended solids (TSS) and 4.2 g TSS L^{-1} for activated sludge. In three high-rate algal ponds, the feeding schedule affected the removal of surfactants, nutrients, and biomass production. At 0.1h d^{-1}, the best results were obtained, with surfactant concentrations of 0.3 mg L^{-1} below the permissible limits for freshwater outflow (Serejo et al., 2020).

Peroxymonosulfate (PMS) was activated using sludge-derived biochar (SBC) to break down triclosan (TCS), a surfactant, in wastewater. SBC had a specific surface area of around 158 m^2g^{-1} and a porous structure. The ideal conditions for triclosan (0.034 mM) degradation in the activated SBC- PMS system was pH 7.2, with 0.99 g L^{-1} of SBC, and 0.79 mM of PMS at 25^0C. The results showed that SBC can serve as a useful PMS activator for the breakdown of surfactants in water and wastewater, with a TCS removal effectiveness of 66.7%, significantly better than the contributions of pure SBC and PMS (Wang & Wang, 2019).

Recent studies evidently suggest that oilfield dispersants build up in the water column and sink with oil to the sea bottom, particularly affecting the extremely delicate coral reefs and hazarding the marine ecology. Hence, the biodegradability of oilfield detergents comprising anionic surfactants was tested for water samples from the New Calabar river of the University of Port Harcourt, Nigeria, and the tap water was obtained from the laboratory taps. The detergents examined were Bio-Boost, SUR-500 (SURFONIC® OFS 500 polyol), a dispersant SW-1000, drilling detergent D.D-Y, and degreaser D.G-X. This analysis employed to track the biodegradation of methylene blue active substance (MBAS) while utilising sodium dodecyl sulphate (SDS) as a reference, signifying a biodegradation observation practice. *Proteus, Acinetobacter, Enterobacter, Staphylococcus, Bacillus, Pseudomonas, Arthrobacter, Corynebacterium,* and *Micrococcus* were the microorganisms that used the detergent. The detergents met biodegradability criteria with an average primary biodegradation rate of 91%–97 % (Osadebe et al., 2018).

3.2 Coagulation and Flocculation

3.2.1 Mechanism and Methodical Exploration

Coagulation and flocculation are vital processes in wastewater treatment, employed together on the principle to eliminate suspended particles by destabilizing them, causing them to clump together. As a result, these processes further facilitate effortless removal of the suspended water impurities like surfactants through sedimentation or filtration. Surfactant molecules consist both hydrophilic and hydrophobic ends and Anionic and nonionic surfactants can both be eliminated by coagulation (Amir Hossein et al., 2004). The coagulation mechanism for surfactant elimination involves neutralizing its charges and promoting accumulation. Coagulation-flocculation techniques can often achieve high removal rates while effectively lowering surfactant concentrations in wastewater. Adsorptive micellar flocculation (AMF) is a surfactant-based separation technique that eliminates water-soluble contaminants. In this technique first the contaminants in surfactant micelles are dissolved, which eventually flocculate and then precipitate out of the solution. The ability of surfactants to produce micelles, encapsulating and concentrating contaminants, is thus employed for their removal, in this procedure. The addition of polyvalent cations causes flocculation, amassing the micelles into bigger flocs that are readily removed by sedimentation or filtration. Due to its exceptional pollutant removal efficiency, coagulation-flocculation unit processes in wastewater treatment, has appealed significant consideration (Aboulhassan et al., 2006).

According to previous studies, ferric chloride, alum, and lime have commonly been used as coagulants. The survey by Jangkorn et al., 2011 examined the viability of recycling aluminum sulfate (alum) sludge as a coagulant or coagulation aid to reduce new alum dosage and improve removal efficiency. Experimentations were conducted in a jar-test system to simulate the coagulation-flocculation process for removing organic matter, anionic surfactants, suspended particles, and turbidity. The results demonstrated that alum sludge could effectively eliminate turbidity, Total Chemical Oxygen Demand (TCOD), and anionic surfactants at an initial pH of 10 and a fresh alum content of 400 mg L^{-1}. The use of both alum sludge and fresh alum improved the removal efficacy. The TCOD removal efficiency exceeded 80%, which was never achieved with fresh alum alone. The study suggests that alum sludge can be recycled to remediate industrial wastewater from the consumer goods industry. Another study by Tripathi et al. (2013) revealed that the electrocoagulation-electroflotation approach effectively removes residual surfactants from laundry wastewater, reducing COD by 80%, MBAS by 95%, and turbidity by 99.9%.

3.2.2 *Role in Sustainability*

Chemical coagulants are effective in surfactant treatment from water treatment plants (WT), but they are typically costly, hazardous, and responsible for health problems, and therefore not sustainable. Natural coagulants are a renewable substitute as they are easily accessible, affordable, simple to use, biodegradable, non-toxic, a greener approach to environmentally benign chemicals, efficient, and produce smaller volumes of sludge (Banchon et al., 2017; Turk et al., 2005). Natural coagulants, through an adsorption process similar to chemicals, and have a WT efficiency of 50-500 nephelometric turbidity units (NTUs). These coagulants can contribute to several health issues in developing countries. However, their acceptance, commercialization, and widespread industrial application are still low (Koul et al., 2022). When using *Cicer arietinum* powder as a bio-coagulant, the ideal coagulation and flocculation parameters were 2.26 g L^{-1} of coagulant, pH = 4, and flash mixing speed = 170 rpm. Turbidity, surfactant, and chemical oxygen demand (COD) removal efficiencies under this environment were 88.35 ± 4.10 %, 60.30 ± 3.10 %, and 54.25 ± 2.81 %, respectively. Thus, there is an urgent need to accept and commercialise natural coagulants like *Cicer arietinum* as a sustainable substitute to chemical coagulants (Dadebo et al., 2022).

To consider the process of coagulation and flocculation from the aspect of sustainability and green chemistry, an innovative green coagulant, like flaxseed mucilage (FSM), was used by Mirbahoush and his team in 2019. The optimal conditions for coagulation of anionic surfactant sodium dodecyl sulphate (SDS), employing the response surface methodological approach were a pH of 7.0, 100 mg L^{-1} of FSM, and 30 min. Heterogeneous photo-Fenton oxidation was employed in the post-treatment phase to ensure the complete removal of SDS using an $MnFe_2O_4$ nanocatalyst. Complete SDS removal was accomplished in the photo-Fenton oxidation process with 76 mg of the nanocatalyst and 1.07 mL of H_2O_2 at 17 min. Coagulants and flocculants are also further associated with changes in the chemical compositions of water bodies and are not entirely reliable.

3.2.3 *Techno-Economic Analysis*

Coagulation flocculation, though a simple, selective, and cost-effective method for treating wastewater, desires concern for the toxic by-products. Applying adsorptive micellar flocculation (AMF) directly to wastewater does not cause any eco-toxicity, and hence makes it a simple, selective, and economically feasible process. To treat industrial wastewater with a high concentration of surfactants, Aboulhassan et al., in 2006 investigated the effectiveness of the coagulation precipitation process worked, especially in terms of eliminating organic debris and surfactants. In this study, the treatment with $FeCl_3$ was found effective at the pH range of 7-9. In addition to increasing the BOD_5/COD index from 0.17 to 0.41, the procedure successfully reduced surfactants and COD, with improved removal rates of 99% and 88%, respectively.

A study investigated electrochemical coagulation utilizing Fe^{2+}ions as an alternative method for removing surfactants from water samples and model solutions. The results showed that a concentration of $10\,mg\ L^{-1}$ of surfactant was removed with 100% efficiency. The study also examined the impacts of applied current density, initial concentration, supporting electrolyte concentration, coagulant dosage, and pH on removal efficiency. This suggested that electrochemical coagulation is a promising method for treating detergents polluted water. The high concentration of iron hydroxide near the anode enhanced the coagulation of pollutants, while the negative electrode caused rapid floc movement, which did not significantly enhance coagulation. Energy consumption was lower when the reactor was anode. Evidently demonstrating a lower energy utilization technique. However, generating water with $1\,mg\ L^{-1}$ surfactant is more expensive than producing $2\,mg\ L^{-1}$ water, and should be considered for the economic evaluation of the process (Önder et al., 2007).

Eradication of anionic surfactants from wastewater from the cardboard industry using coagulation-flocculation was analysed. It was observed that the statistical approach of response surface methodology enables an efficient and cost-effective study of the interactions between diverse parameters used in coagulation-flocculation. With the use of cationic polyacrylamides (c-PAM), poly aluminium chloride (PAC), and pH at optimal levels, coagulation-flocculation eliminated the anionic surfactant nearly entirely and decrease COD by more than 95% (Harif et al., 2023). Electrocoagulation and electroflotation were used in a study by Akarsu and Deniz (2021) to investigate wastewater treatment from laundry. The response surface methodology (RSM) was utilized for optimizing the type of electrode (Al–Al, Al–Fe, Fe–Fe, and Fe–Al), initial pH (5–9), current (0.54–2.16 A), and time duration (15–60 min). Using a Fe-Al electrode at 2.16 A current at pH 9 and 60 min reaction time results in the most efficient elimination. The techno-economic study thus revealed that at an operating cost of \$1.32 m^{-3}, the best removal efficiency is obtained for COD, colour, surfactant, and microplastic.

3.2.4 *Limitations, Industrial Applications and Future Advances*

The efficiency of the coagulation-flocculation method depends on the coagulant dose and pH of system. Coagulants also generate harmful sludge adding to the impurities in water. As a result, additional filtration is necessary for complete mitigation of the contaminants in the sludges. Chemical hazards of coagulant material are another matter of great concern. The coagulation-flocculation is a regularly used process to treat industrial wastewater produced while manufacturing detergents, soaps, and other consumer goods and adding coagulators and utilizing chemicals to change the pH of these industrial effluents incurs a substantial cost. To decrease the quantity of fresh alum required and to improve the efficiency of the removal process, a study was conducted to see whether the aluminum sulfate (alum) sludge might be used again as coagulant or a coagulation aid. Examinations were carried out in flocculators to eliminate turbidity, suspended particles, organic debris, and anionic surfactants. An optimal starting pH of 10 and the addition of 400 mg L^{-1} alum resulted in the removal efficiencies for TSS, COD, anionic surfactants (AS), and turbidity within a range of 70-98% (Jangkorn et al., 2011) suggesting these as the optimum parameters for effective removal.

Recent innovative trends in this sector recommended a microbubble-enhanced flotation approach that successfully removed over 95 wt. % of surfactants, from laundry wastewater (Zhao et al., 2024). Polyacrylamide (PAM) was also discovered to be an effective coagulant aid for polymeric aluminium chloride (PAC) to increase floc characteristics in a dual-coagulation procedure used for surfactant-kaolin wastewater (Li et al., 2024). *Moringa oleifera* shows notable coagulation skills far earlier than other recently used bio coagulants like *Cicer arietinum* (Dadebo et al., 2022) and flaxseed mucilage(Mirbahoush et al., 2019). *Moringa oleifera* seed extract was shown to remove surfactants from aqueous effluents effectively. Among them, Polyoxyethylene (3.5) sodium lauryl ether sulfate (SLES), a long-chain anionic detergent, was chosen as an exemplary molecule to evaluate the coagulation reaction. The system coagulant-detergent demonstrated high efficacy and stability across various temperatures and pH levels. The *M. oleifera* promises as an efficient coagulant, with a coagulation capability of 0.245 mg L^{-1}. Experiment design identified the optimal coagulant dose and initial concentration of surfactant as 234 mg L^{-1} and 76 mg L^{-1}, respectively (Beltrán-Heredia et al., 2012). Further, research is therefore crucial to explore the mode of action, adoption, and commercialization of similar natural coagulants as a sustainable alternate for a circular economy.

3.3 Photocatalytic Degradation or Advanced Oxidation

3.3.1 Mechanism and Methodical Exploration

Photocatalytic degradation, an advanced oxidation process (AOP), incorporates light energy in presence of a catalyst and converts pollutants into innocuous molecules such as CO_2 and water by producing reactive oxygen species. Photocatalytic techniques effectively treat waterbodies contaminated with organic and inorganic contaminants. Photocatalytic procedures operate to mineralize a wide range of surfactants along with many insecticides, dyes and other such hazardous chemicals. The use of photoactive semiconductors is a favorable approach for these methods. For photocatalytic applications, titanium dioxide is the most commonly utilized semiconducting material. Combining TiO_2-based photocatalysis and sonolysis is a potential mechanism for reducing organic contaminants like surfactants (Szabó-Bárdos et al., 2008). Advanced oxidation process (AOP) yields extremely reactive intermediates known as hydroxyl radicals (HO•) by utilizing strong oxidants such as O_3 or H_2O_2. This hydroxyl radical breaks down the organic compounds quite efficiently. Surfactants, including all other organic molecules, are essentially disintegrated by the (HO•) once it is created. As a result, the organic component mineralizes due to hydroxyl radical assault. Thus, organic pollutants are reduced by AOPs from several hundred parts per million to fewer than five parts per billion. The AOP generates an organic radical (•R) by removing a H atom from an organic molecule (RH) using (HO•). Numerous oxidation products are produced due to the several chemical changes the organic radical (•R) goes through. Fenton's reagent (H_2O_2-Fe^{2+}), O_3, and H_2O_2 are the most often utilized oxidants in AOP (Krishnan et al., 2016).

A hybrid treatment system mechanism was designed to treat synthetic wastewater spiked with 10.00 ± 0.46 mg L^{-1} sodium dodecyl sulfate (SDS), including an up-flow microbial fuel cell (MFC) with TiO_2 or titanium dioxide as a photocathode catalyst. After passing through a raw laterite sand filter, the anodic chamber of the MFC's effluent was followed by a photo cathodic chamber with a UV-exposed TiO_2-coated cathode. The hybrid system was run in an MFC anodic chamber for varied hydraulic retention times (HRT). The hybrid system achieved over 96% removal efficiency of SDS and ≈70.99% removal efficiency of organic materials at various HRTs (Sathe et al., 2020).

3.3.2 Role in Sustainability

The photocatalytic technique oxidizes the water pollutant in a more sustainable and efficient sequence of processes. The method is used to effectively decontaminate and sterilize wastewater and sanitize groundwater. Wastewater, including surfactants, heavy metals, medications, chlorinated hydrocarbons, pesticides, dioxins, diseases, and microorganisms, a widespread of water impurities can be treated by photocatalytic oxidation. The photo-catalytic methodology is more practical, energy-efficient, and chemical-free than traditional oxidation techniques. Additionally, photocatalytic degradation works at moderate temperatures and pressures, and the method becomes more effective when heterogeneous photocatalysts are used (Ahtasham Iqbal et al., 2024). suggesting sustainable and readily available application conditions. Photo catalysts can alter the chemical compositions of water reservoirs during treatments(Joseph et al., 2022).

Hence, the appropriate selection and use of reagents associated with green chemistry is necessary for sustainable wastewater treatments.

Structural effects of surfactants lead to the development of photodegradation products with higher toxicity than the parent molecule. Recently, catalytic photodegradation of cationic, anionic, and non-ionic surfactants was explored by Wysokowska et al. (2024) to determine the effect of their breakdown products on phytotoxicity of sorghum (cereal grain). As a result, heterogeneous photocatalysis successfully mitigates surfactants only at low concentrations in the aquatic environment. Photodegradation efficacy for all surfactants improved proportionally to a range of 41-50% for anionic surfactants, 64-70% for non-ionic chemicals, and 38-43% for cationic cetrimonium bromide (CTAB) and Didecyl dimethyl ammonium chloride DDAC, while the efficiency of benzalkonium chloride reached 94%. Non-ionic surfactants provided the finest toxicity reduction outcomes, followed by anionic chemicals, whereas cationic surfactants were correlated with a more substantial negative impact adding to more toxicity. In contrast to anionic and non-ionic chemicals, cationic compounds degrade more slowly due to their decreased reactivity, which is hampered by their positive charge, thus affecting the phytotoxicity.

3.3.3 Techno-Economic Analysis

Surfactant removal is a developing concern due to its stubborn nature, which hinders conventional biological treatment from meeting wastewater discharge standards. A laboratory-scale photocatalytic degradation system employing UV-H_2O_2 was recommended as an additional treatment for a mixed multiple anaerobic system facility in Guayaquil, Ecuador, which had inadequate surfactant removal (45.9%). The system proved the synergistic effect of mixing H_2O_2 with UV radiation for 60 min in successfully removing surfactants (94.3±4.3%) and reaching the treatment objective. After 60 min of continuous treatment with a flow rate of 0.6 mL s^{-1} and a hydrogen peroxide concentration of 26.6 mg s^{-1}, the highest elimination of anionic surfactant was 92.3±2.5%. The techno-economic analysis of this study estimates that removing surfactants in an ideal full-scale system, combined with a decentralized wastewater treatment plant would cost 0.7 \$ m^{-3} (Jennifer et al., 2024).

Recently, electron beam radiation, a clean and sustainable method for SDBS degradation in wastewater, was explored by Chu et al. (2024). Changes in SDBS micelles, elevated interfacial tension, and reduced foaming power resulted from the breakdown process. With a COD removal rate of 7–20%, the results demonstrated a removal efficiency of almost 100%. Advanced electro-oxidation has become a predominant method for treating complex wastewater. For domestic wastewater effluent from the wastewater treatment facility in Ecuador, an electrochemical degradation method employing a *DiaClean*® cell in a recirculating system with boron-doped diamond (BDD) as the anode and stainless steel as the cathode was found to be economically beneficial (Cisneros-León et al., 2023).

3.3.4 Limitations, Industrial Applications and Future Advances

The requirement for large space, high operation expenses, high reagents utilization, and high energy requirements are the commonly observed limitations of photocatalytic techniques. Municipal effluent samples and distilled water-spiked samples containing 100 mg L^{-1} of SDS were tested for an advanced oxidation process employing UV-H_2O_2. The impacts of process parameters on SDS degradation, such as latency, initial SDS concentration, oxidant H_2O_2 dosage, and UV absorbance of wastewater at 250 nm, were analysed. The rate of SDS breakdown increased with reaction time. Depending on the initial SDS concentration, degradation accelerates with increasing oxidant dose and decreases even further with growing oxidant dose This confines that degradation does not increase with increasing the oxidant dose. Through 200 mg L^{-1} of initial concentration, the quadratic model predicted that the maximum SDS degradation percentage would be over 80% in 7 min. For the same, a UV absorbance of around 0.2 at 254 nm was obtained using a dosage of 2 mol of H_2O_2 per mol of SDS (Mondal et al., 2019).

The effectiveness of the electro-hybrid ozonation-coagulation process (E-HOC) for surfactant and microplastic exclusion from laundry wastewater was investigated at various current densities and ozone dosages. At ideal circumstances (current density 15 mA cm^{-2}, ozone dosage 66.2 mg L^{-1}), surfactant and microplastic removal efficiency exceeds 90%. The E-HOC method has a better exclusion efficiency of COD, turbidity, and

LAS than the ozonation and conventional electrocoagulation processes proposing a better practical approach. The electro-hybrid ozonation-coagulation process was optimized for three laundry wastewaters: washing wastewater (15mA cm^{-2}, 66.2 mg L^{-1}), primary effluent (10 mA cm^{-2}, 36.6 mg L^{-1}), and secondary effluent (10 mA cm^{-2}, 36.6 mg L^{-1}). COD, turbidity, and LAS were removed from washing wastewater at rates of 93.9%, 99.7%, and 99.9%, respectively (Luo et al., 2022).

Photocatalytic degradation combined with adsorption is a hybrid approach boosting traditional yet affordable processes. As surfactants are discharged into wastewater in huge quantities, they are detrimental to aquatic and terrestrial life, necessitating removal. A recent study attempted to eliminate SDS surfactant through photocatalytic degradation and adsorption utilizing Zn (+2) Al-layered double hydroxide and TiO_2-Zn (+2) Al-layered double hydroxide coprecipitation materials. The acquired experimental results were analysed using the Temkin and Langmuir and the Freundlich adsorption isotherm models. The photocatalytic degradation of SDS over Zn (+2) Al-layered double hydroxide and TiO_2-Zn (+2) Al-layered double hydroxide exhibited pseudo-first-order kinetics at 9.99 to 100.1 mg L^{-1} concentrations. The results showed that TiO_2(3.59)-Zn (+2) Al-layered double hydroxide displayed substantial photocatalytic activity compared to the Zn (+2) Al-layered double hydroxide sample (Aoudjit et al., 2019).

Photocatalytic degradation is a developing trend that is globally used for surfactant removal to achieve water remediation. Lately, photocatalytic degradation combined with adsorption on Fe_2O_3-activated carbon catalyst was found effective in the degradation of surfactants like linear alkylbenzene sulfonate. When the concentration of Fe is changed to 2%, 4%, or 6%, the capacity of the surfactant waste degrading reaction using the kernel of coconut catalyst at a time frame of three hours was determined to be nearly 6.8 mmol g^{-1}, 3.2 mmol g^{-1}, and 1.6 mmol g^{-1} catalyst, respectively (Amelia et al., 2020).

3.4 Membrane Filtration

3.4.1 Mechanism and Methodical Exploration

Porous membranes featuring specific pore diameters are used in membrane filtration methodology. Surfactants develop micelles or other more significant structures, depending on their concentration and degree of aggregation. These aggregates are physically confined and unable to flow through the membrane as their size exceeds the membrane pore size. This isolates them from the water stream. The size exclusion mechanism is the key component in separating surfactants from water in microfiltration (MF) and ultrafiltration (UF) procedures, where the pore diameters range from micrometres to nanometers (Xiarchos et al., 2003). Utilizing a semi-permeable membrane, the filtration technique employs a pressure differential phenomenon to separate components in aqueous solutions. This pressure difference mechanism permits smaller molecules to flow through, thus retaining bigger molecules in situ. The technique is based on factors including size, molecular properties, or charge. As a pre-treatment technique, membrane filtration (MF) is frequently used to remove various components from wastewater suspension, whereas ultrafiltration (UF) suggests a way to eliminate surfactants from aqueous solutions with critical micelle concentration (CMC). Nevertheless, nanofiltration (NF) is a more successful removal method when the concentration is as low as that of monomer. Because of the high concentration of surfactant monomers, the membrane filtration technique enables the permeate to be reused during the cleaning process. In the early 1970s, UF was the first membrane technique to separate surfactants (Suárez et al., 2012).

Composite membranes of silica, titania nanorods, and nanotubes, with photocatalytic capacity, were explored to remove sodium dodecylbenzene sulfonate (SDBS). Using the sol-gel method, colloidal silica-titania sols have effectively created a multifunctional composite membrane. Blending photocatalysis with membrane filtration was an innovative trial that resulted in an 89% elimination of SDBS after 100 min, according to the experimental results (H. Zhang et al., 2006). Babaei and team in 2019 (Babaei et al., 2019) studied the effectiveness of multi-layer slow sand filter, microfilter (MF) and ultrafilter (UF) hybrid systems in removing COD, TSS, LAS and turbidity from greywater, and the impact of OLRs on the performance of the system during 5 months. The finest removal efficiencies were 98.22% for COD, and >99.97% for TSS, LAS and turbidity also. Furthermore, the average turbidity, TSS, and LAS outputs in the hybrid system were 1.04 NTU, 0.04 mg L^{-1}, and 1.55 mg L^{-1}, respectively.

To treat surfactants from detergent wastewater, a combination method using the multimedia biological aerated filter (MBAF) and the up-flow multimedium biological aerated filter (UMBAF) was studied by Ji et al. (2019). The combined system had an optimal filtration rate of 1.4 m hr^{-1} and performed best with an air-to-water ratio of 2:1. Total phosphate (TP), linear alkyl benzene sulfonate sodium (LAS), and Chemical Oxygen Demand (COD) were removed at average rates up to 40%, 88%, and 91%, respectively.

3.4.2 *Role in Sustainability*

Growing international apprehension about scarcity of clean water and environmental sustainability drives revolution in water reclamation techniques. Research by Barambu et al. (2020) reveals the ability of a tilted panel system to maximize the impact of air bubble contact with the membrane surface, hence imposing control over membrane fouling and emerges as a greener methodology. This technology offers a simple method for recovering detergent and reusing water. Hydraulic performance improves when rate of aeration and tilting angle are adjusted to attain permeability, implying that almost all reversible fouling can be avoided. The plateau aeration resulted in a 83% higher permeability than the unaerated condition, with value of about 200. Tilting the membrane panel 15 degrees to the air bubbles increased permeability to around 220. The method further provides 32% detergent recovery. Overall, the technique proposes a compelling method for membrane fouling management.

Research by Mostafazadeh et al. (2019) focuses on the treatment and reuse of laundry wastewater utilizing an innovative and sustainable sequential integrated system. Total suspended particles, turbidity, COD, and surfactants such as nonylphenol ethoxylates ($NPEO_3$−17) are eliminated by polyether sulfone (PES) membrane in ultrafiltration (UF) of raw wastewater and adsorption (AD) procedures of the filtrate. The UF process separates the wastewater into an effluent with a minimal organic pollutant; ≈400 mg L^{-1} of dissolved COD, and a concentrate with a total COD upto 1200 mg L^{-1}, with around 200 mg TSS L^{-1}. Thus, using UF and AD procedures, successfully eliminates $NPEO_3$−17 surfactant from the concentrate and filtrate efficiently.

3.4.3 *Techno-Economic Analysis*

Recently a microfiltration membrane system with cationic exchange proceeding a weak-acid-based resin was proposed to eliminate surfactants and lower effluent alkalinity from the washing phase. The recovery efficiency of the system was 88%. About 68% of the cooling tower water was treated using the ultrafiltration and reverse osmosis processes, which were determined to be the most successful in eliminating salts and biocides. The techno-economic feasibility for the system was assessed, with an anticipated cost of EUR 245 thousand for the washing phase and EUR 582 thousand for the cooling towers. The revenue from the treatment techniques was expected to be EUR 0.07 per car for the washing phase and cooling towers with EUR 0.13. This study highlights the benefits of membrane treatment in the environmental policy of the automotive sector, leading to water reuse and lower effluent discharge (Carvalho et al., 2025).

As per a survey by Šostar-Turk et al. (2005), Slovenia implemented two initiatives that enforced technological and ecological standards for treating wastewater from modern laundry. On examining prospective market for membrane water treatment applications, it was discovered that most Slovenian laundering facilities, out of 140 at that time, employed traditional techniques such as filtration, flocculation, and sedimentation. Only three laundries with annual water flows ranging from 35,000 to 45,000 m^3 had ultrafiltration installed. To resolve this issue, a membrane treatment system combining ultrafiltration and reverse osmosis was developed in a laboratory, enabling 75% of water to be recycled. Ten prospective laundries in Slovenia were found qualified for this system, with five having water flows ranging from 35,000 m^3 to 100,000 m^3 per year.

3.4.4 *Limitation, Industrial Applications and Future Advances*

Despite the beneficiary membrane filtration treatment on effluent from laundry, particularly when reusing water and detergent, membrane fouling and regeneration significantly limit its performance, particularly when operated at high transmembrane pressure. Chemical resistance and strength of the membrane are crucial factors affecting filtration methods. Hence recently, Bilad et al. (2020) conducted research to evaluate a low-pressure immersed membrane filtration system for processing wastewater from laundry to overcome the fouling issue. A solution of 15 wt% polysulfones, 1 wt% polyethene glycol, and dimethylacetamide was employed to fabricate the membrane in this analysis. This polymeric membrane promises efficient elimination of surfactant turbidity, total nitrogen, phosphorus, and chemical oxygen demand of 52%, 13%, 65%, and 97%, respectively. The system additionally offers 78% detergent recovery from spent laundry effluent, proving its potential.

Unique modules of ceramic membrane with a pore size of 0.14 µm can demonstrate high efficacy in surfactant wastewater treatment, reducing TOC, COD, and turbidity by 95%, 93%, and 99%, respectively, when the process was run in concentration mode, resulting in the recovery of nearly 50% of the permeate. The study examines the composition of industrial wastewater, its purification, and concentration processes using the modules of ceramic membrane. The wastewater was produced from a plant that manufactures cationic surfactants and was exposed to membrane filtration in a semi-pilot plant. The regeneration operation using NaOH solution was successful, although the permeability of the module was not fully restored. Applying an acidic washing agent can reduce the intensity of membrane blockage. Filtration tests with model solutions confirmed that the sieve effect dominates surfactant separation during UF and MF processes. Modules with their pore diameters similar to or smaller than the size of the surfactant micelles (150 kDa and 0.45 µm) have more significant retention coefficients (above 94%). They are less susceptible to surfactant fouling (Klimonda & Kowalska, 2021).

In order to remove 18 per- and poly-fluoroalkyl species (PFAS) from drinking water, Johnson et al. (2022) proposed an amphiphilic coating to functionalize aluminum oxide hydroxide membrane. Eleven of the 18 PFAS in the challenge water were removed with >99% efficiency using dynamic filtration. Fifteen were removed with greater than 90% efficiency using gravity filtration. For perfluorooctanoic acid adsorption capacity, the novel amphiphilic coating performs better than granular activated carbon (GAC) under dynamic filtering conditions, and even better for perfluorooctane sulfonic acid. The free energy, enthalpy, and entropy of interactions between six PFAS pollutants and coatings were calculated using molecular dynamics simulations.

Membrane-based technologies provide a novel approach for reclaiming water from laundry wastewater (LWW), with pollutants being removed at an efficiency of 85-95% when appropriately adjusted. These systems are adaptable and provide water that is suitable for laundry reuse. Investigate advancements in both independently operable and hybrid membrane systems for treating LWW. Membrane-based techniques can remove critical LWW components such as surfactants and suspended particles. The combination of membrane processes and conventional techniques improve performance by 45-50% while reducing energy consumption by up to 25% (Zakaria et al., 2025).

4 Adsorption for Surfactant Removal

4.1 Mechanism and Methodical Exploration

Surfactants primarily adsorb on adsorption surfaces by electrostatic attraction and van der Waals forces. The cationic surfactant adsorbs when the positive charge on its headgroup attracts negative charges on the adsorptive surface. Anionic surfactants with a negative charge on their headgroup and the positively charged adsorptive surface may be attracted to each other electrostatically. The principal adsorption mechanism for nonionic surfactants is hydrogen bonding (Kalam et al., 2021b, 2021a). Surfactant adsorption, or the concentration of surfactant molecules at interfaces, is triggered by various forces comprising electrostatic attraction, hydrophobic interactions, and hydrogen bonding. It is further contingent on the surfactant and surface attributes (Siyal et al., 2020). Adsorption depends on various physicochemical properties of the adsorbents and the surrounding atmosphere. Pore size, temperature, adsorbent dose, the concentration of surfactant to be removed, pH, and functional groups on adsorbents are the common governing factors for adsorption. One such comparative study showed that adsorbents and ion exchange resins with functional groups impede mass movement of the surfactant perfluoro-octane sulfonate (PFOS), which lowers the sorption rate. The sequence in which the total PFOS capacities of adsorbents rise is polymer adsorbents > activated carbons > anion exchange resins; the selectivity of functional groups influences the adsorption process (Schuricht et al., 2017). Surfactant adsorption on polymers is crucial for maintaining polymer latex colloidal stability. Ionic surfactants bind neutral polymers through hydrophobic interactions, whereas oppositely charged polymers bind surfactants through electrostatic and hydrophobic interactions. The efficiency of surfactant adsorption depends upon the capacity of the polymer surface and the molecular structure of surfactants. The hydrophobicity of the polymer surface, its ionic nature, its curvature radius, the structure of the surface-active material, and the bulk fluid phase parameters such as temperature and electrolyte concentration are the factors governing adsorption (El Feky et al., 2010).

Various minerals and soil types also facilitate surfactant removal. A study observed the extent of adsorption of anionic surfactant and amphoteric surfactants betaine and sulfo-betaine during oil recovery. Adsorption of ionic surfactants on sandstone and dolomite was lower than that of amphoteric surfactants, while amphoteric surfactants adsorbed similarly or lower on limestone. Adsorption of anionic surfactants followed an electrostatic mechanism, while amphoteric surfactants adsorbed through a complex interplay (Mannhardt et al., 1992).

As adsorbents play a vital role in the adsorption of surfactants, some major adsorbents with implemented modifications used previously for surfactant removal are listed in Table 1

4.2 Role in Sustainability

Biodegradable adsorptive materials, including biomass or biopolymers, are essential for protecting the environment, especially in wastewater treatment. Biopolymers, like chitosan, alginate, and tannin composites, have shown potential as attractive adsorbents for the future. They may substitute traditional adsorbents like silicates, aluminates, and activated carbon, offering competing adsorption capacity, cost-effectiveness, and biocompatibility. However, their applications for wastewater treatment have not been thoroughly explored, indicating a need for further exploration (Biswas & Pal, 2021). Sen et al. (2012) used pine cone biomass to remove sodium dodecyl sulfate, an anionic surfactant. Using *Posidonia oceanica (L.),* a cheap, plentiful, and renewable marine biomass, adsorption has been used in batch mode to remove anionic and non-ionic surfactants (Ncibi et al., 2008). Post-treatment of primary and secondary sewage wastewater utilizing slow sand filtration and adsorption by activated carbon (AC) made from eco-friendly residual coffee dregs reduced surfactants and turbidity by approximately 95% and 94%, respectively (Marcelo & Alexandre, 2021). Lately, Nacar et al. (2022) successfully removed up to 90% of detergent (Sodium Lauryl Sulphate) and achieved an average of 68% COD removal from the car wash wastewater using *Phragmites australis,* a sustainable species in a subsurface flow constructed wetland. Many biomass-based adsorbents satisfying green technology and suitable for surfactant removal are already listed in Table 1.

4.3 Techno-Economic Analysis

Using synthetic (e.g., nanosized) materials for pollutant removal makes adsorption techniques distinctive. Because of their low cost and ease of use, modified clay minerals and biochar have shown excellent potential for eliminating organic and heavy metal pollutants from drinking, industrial, and eutrophic wastewater, despite activated carbon being the most widely used adsorbent (Han et al., 2019). Biochar can absorb physicochemical pollutants like surfactants, costing 60% less than granular activated carbon (GAC) (Kumar et al., 2018). James and Ifelebuegu (2018) researched a few inexpensive, environmentally friendly materials for detergent treatment and removal. Activated carbon (19-2.5 \$ kg^{-1}), silica gel (1-1.5 \$ kg^{-1}), mussel shells (1.5-2.3 \$ kg^{-1}), and zeolite (1.5-2.2 \$ kg^{-1}) are among the biomasses that are promising and potentially sustainable adsorption materials for the reclamation of grey water, according to this study. The commercial price of some easily accessible biomass and mineral adsorbents, such as chitosan (5–10 \$ kg^{-1}), red mud (0.025 \$ kg^{-1}), bagasse fly ash (0.02 \$ kg^{-1}), and carbonaceous adsorbent from fertilizer industry waste (0.1 \$ kg^{-1}), reclaims these materials as sustainable, cost-effective, and potential adsorbents for wastewater treatment(De Gisi et al., 2016). Adsorption is therefore a relatively inexpensive and environmentally benign technique for removing surfactants. Still, it has to be improved further by using new, innovative, environmentally friendly, and easily accessible biomass adsorbents. The degradation of surfactants with a single application of adsorbent is problematic and is hence a

Table 1 Adsorbents and their modifications for surfactant removal

Type of Adsorbents	Materials with their modifications	Type of Wastewater or Surfactant Removed	Results	References
Carbon-Based Adsorbents	Sludge-derived Biochar (SBC) activated by peroxy monosulfate (PMS)	Triclosan surfactant TCS	TCS (0.034 mM) degradation; pH≈7, 0.99 g L^{-1} of SBC; 0.8 mM concentration of PMS at 25°C	Wang & Wang, 2019
	Citrus macroptera peels (CMPs) Biochar	Textile wastewater	Adsorption capacity (qm) 139.7 mg L^{-1}	Roy et al., 2022
	Carbon nanotubes (CNTs)	DDBAC-Dodecyl dimethyl benzyl ammonium chloride, TDBAC-tetradecyl dimethyl benzyl ammonium chloride, CTAB-hexadecyl trimethyl ammonium bromide	All CNTs have 100% removal efficiency for TDBAC (exception OH-MWCNT8). For DDBAC, only SWCNTs have 100% removal efficiency. R_{eff} of CTAB by Pristine MWCNTs with diameter (outer) OD<8 nm is around 50.5 %, while that by OH-WCNTs with OD<8nm is nearly 22.8%.	Gao et al., 2020
	Activated carbon cloth (ACC)	BS -Benzene Sulphonates, TS-*p*-toluene, OBS-4-octylbenzene, DBS-4-dodecylbenzene	Kinetic model parameters for surfactant adsorption on ACC obtained by linear regression analysis showed *r*> 0.999 for pseudo-2nd-order and r≈ 0.95 for pseudo-1st-order. BS < TS < DBS~OBS.	Ayranci & Duman, 2007
	Activated carbon cloth (ACC)	Ammonium chloride of Benzyl trimethyl (BTMACl), benzyl triethyl (BTEACl), benzyl tributyl (BTBACl), benzyl dimethyl decyl (BDMDACl), benzyl dimethyl tetradecyl (BDMTDACl), benzyl dimethyl hexadecyl (BDMHDACl), and pyridinium chloride of N-dodecyl (N-DPCl) N-cetyl (CPCl)	All surfactants almost complete removal (>98%) (Exception BTMACl, BTEACl) Minor adsorption of BTMACl and BTEACl due to their lesser hydrophobicity than the others.	Duman & Ayranci, 2010
	Powdered activated carbon (PAC)	Linear alkyl benzene sulfonate (LBAS); CTAB	For CTAB and LABS, maximal sorption was observed at around 1.1 and ≈0.499 mmol g^{-1}, respectively.	Basar et al., 2004
	Activated carbon (AC)	Mixtures of cationic and anionic surfactants: dodecyl pyridinium chloride-sodium octane sulfonate (DPC-SOS) and octyl triethylammonium bromide-sodium dodecyl benzenesulfonate (OTEAB-SDBS)	Isotherms showed the presence of 4.0 mmol dm^{-3} SOS decreases the adsorption of DPC, whereas presence of 0.5 mmol dm^{-3} OTEAB reduces the adsorption of SDBS	Xiao et al., 2005
	Dolochar from industrial waste	Sodium dodecyl sulfate (SDS)	A removal rate of 98.91% for SDS observed with the optimal settings of adsorbent dosage≈16.6 g L^{-1}, contact time≈40 min, initial concentration≈47 mg L^{-1}	Shami et al., 2020
	Coconut/coal-based steam-activated carbons; Wood-based, acid-activated carbons	Octanoic acid and dodecanoic acid (C8- and C12-acid)	Amount of C12 adsorbed >> C8 for a common adsorbent and solution phase. The amount of surfactant adsorbed and the adsorbent oxygen content are correlated. Steam-activated carbon(A) > adsorption than phosphoric acid-activated carbon (C)	Wu & Pendleton, 2001
	Multi-walled carbon nanotubes (MWCNT)	Triton (TX-100), CTAB and SDBS	Optimal values for TX-100, SDBS and CTAB are pH= 6, 2 and 8; temperature between 35 to 45°C; removal capacities= 359, 312, and 156 mg g^{-1} respectively	Ncibi et al., 2015
	Fly ash of local coal thermal power plant	SDBS	SDBS adsorption was most effective with an adsorbent dose of ≈9.99 g L^{-1} and a contact period of around 4.30 hours. A maximum adsorption capacity of 6.83 mg g^{-1} was achieved	Siyal et al., 2018
	Commercial carbons Ceca AC40 (C), Merck (M), Sorbo-Norit (S), Almond shells carbon (A)	SDBS	Adsorption capacity calculated by Langmuir equation (for SDBS) on C= 322.4 mg g^{-1} M= 348.1 mg g^{-1} S= 265.4 mg g^{-1} A= 468.8 mg g^{-1}	Bautista-Toledo et al., 2008
	Novel substrate hydro-thermal processing of fly ash and TiO2 Degussa P25 nano-powder	1-hexadecyl trimethyl ammonium bromide-HTAB; SDBS	As per pseudo-2nd-order kinetics, (Cd^{2+} + SDBS) adsorption is 125.0 mg g^{-1}, (Cd2+ + HTAB) is 123.4 mg g^{-1}	Visa & Duta, 2013
	Coal fly ash (CFA) thermal power plants	SDS	Using ≈99.9 g L^{-1} of CFA, the capacity of SDS removal is around 97%.	Zanoletti et al., 2017

Table 1 (continued)

Type of Adsorbents	Materials with their modifications	Type of Wastewater or Surfactant Removed	Results	References
Carbon-Based Adsorbents	Powdered active carbon (PAC)	CTAB	As the equilibrium concentration of CTAB rises to 328 or 348 K, with 18 and 14 mV Zeta potential values of carbon particles	Gurses et al., 2003
	Grafting of arene diazonium salt Phenyl tetra ethylene glycol (PTEG) on Graphene Oxide (GO)	TX-100; Cetyl trimethyl ammonium bromide (DTAB)	The highest removal capacities of GO-PTEG for TX-100 and DTAB were around 1690 and 714 mg g^{-1}.	Cheminski et al., 2019
	Activated carbon (AC) obtained from leftover coffee dreg	Primary and secondary sewage wastewater	Turbidity and surfactants were reduced by around 94% and 95%	Marcelo & Alexandre, 2021
	K_2CO_3 and KOH (activation agents AA), chemically activated carbon (AC) from pine tree cone biomass	SDBS	K_2CO_3 saturation ratio of 0.75 wt% min and max adsorption capacity and removal efficiency are (≈36 mg g^{-1}, 35% for w/o AA) and (≈98 mg g^{-1}, 95% for AC)	Valizadeh et al., 2016
Nanomaterial-Based Adsorbents	Mesoporous nanomaterial MCM-41	CTAB	Surfactant removal by MCM-41, processing time decreased from 14 hrs (calcination) to 5 min (microwaves) saving 72% energy.	López-Pérez et al., 2020
	Graphene oxide (GO); Reduced graphene oxide (rGO) nanomaterials	TX-100	Exclusion capacities of 1683 mg $g^{-1}$for rGO; 1203 mg g^{-1}forGO after 3 removal cycles adsorption capacity of rGO ≈1050 mg g^{-1}.	Prediger et al., 2018
	Zero-Valent Iron (nZVI)	Hexadecyl pyridinium chloride surfactant (HDPCl); SDBS	Removal efficiency of HDPCl ≈ 99% and of SDBS ≈93 %	Abd El-Lateef et al., 2018
	Nanoporous nickel phosphate (nano-NiPOx) particles	Cetylpyridinium chloride (CPC)	NiPOx shows max adsorption of 360.5 mg $g^{-1}$for CPC	Touny et al., 2019
Biomass-Based Adsorbents	Chitosan	SDBS	Maximum effectiveness of SDBS removal is 97.3 % at pH 4 with adsorbent dose 0.3 g, initial SDBS concentrations 25 mg L^{-1}, at 25^0C and 60 min, adsorption of 6.38 mg g^{-1}.	Parhizgar et al., 2017
	Corncob Adsorbents	Anionic Surfactants	Nearly 97 % COD; 97.4 % BOD; 72 % Phosphate; 81.68 % Ammonia and 92 % Surfactant were removed	Priyanka et al., 2020
	Chromium-containing leather waste	SDBS, Cationic-- dodecyl trimethyl ammonium bromide (DTB) andTX-100	Poor adsorption of DTB, TX-100 on Cr- Leather. Adsorption capacity of SDBS increased with temperature, reaching its highest at 293 K at 375 mg g^{-1} and its highest at 313 K at 423 mg g^{-1}.	Mi-Na et al., 2006
	Rice husk-derived biochar (RHB)	Shipboard bilgewater (SBW) Sodium dodecyl sulfate	Optimal conditions with surfactant removal efficiency 96.6 %; flow rate- 5 mL min^{-1}; bed depth-16 cm gives	Dadebo et al., 2023
	Citrus macroptera peels biochar	Synthetic wastewater	Maximum adsorption capacity, qm was 139.7 mg g^{-1},	Roy et al., 2022
	Artocarpus heterophyllus seed powder	Residential laundry wastewater	Removal efficiency for surfactant≈ 92%, COD≈83%, BOD ≈78%, and turbidity ≈85%, optimal initial pH 6, a dose of 2.5 g L^{-1}, and duration of ≈ 30 min	Deressa et al., 2019
	Crosslinked biopolymer-based Chitosan Films	SDBS	High adsorption capacity (qm) for SDBS≈ 714 mg g^{-1}at pH= 2, 180 min.	Kahya et al., 2018
	Chitosan hydrogel beads	SDS	As per Langmuir adsorption isotherm SDS adsorption (Qmax≈ 77 mg g^{-1})	Pal et al., 2013
	Amino crosslinked chitosan microspheres (ACCMs)	SDBS, SDS and sodium lauryl sulfate (SLS)	Adsorption saturation for ACCMs for SDBS≈1219 mg g^{-1}, SLS≈890 mg g^{-1}, and SDS≈824 mg g^{-1}at pH 3.0 and around 300 K.	Zhang et al., 2017
	Strychnos potatorum seeds and activated carbon from *Colocasia esculenta*	Laundry Wastewater	Reduction in total dissolved solids from 168 ppm to 12 ppm (≈ 93% reduction), and turbidity lowered from 132 NTU to 10 NTU	Sriram, 2019

Table 1 (continued)

Type of Adsorbents	Materials with their modifications	Type of Wastewater or Surfactant Removed	Results	References
Polymer	Polyvinyl alcohol (PVA) and polyacrylic acid (PAA)	Tetradecyl poly-oxy-ethylenated monolaurate [La $(EO)_{14}$]; tetradecyl poly oxy ethylenated monooleate [Ol $(EO)_{14}$],	Amount adsorbed (m mol g^{-1}) = 0.2020; 0.0730 on PAA and 0.065; 0.050 on PVA. Equilibrium concentration, Ceq x 10^3 mol dm^{-3}= 0.039; 0.070 on PAA and 0.051; 0.040 on PVA. Minimum area occupied by surfactant on the polymer, A_{min} $(A^{0\,2})$ = 0.82; 2.27 on PAA and 2.59, 3.32 on PVA.	El-Feky et al., 2009
	Poly (ethylene glycol) poly (ethylene) block copolymers	SDS, Disponil AFX 1080	Langmuir Isotherm K [m^3 mol^{-1}] = 0.064 ± 0.002 for (SDS), and 7.4 ±_ 1.2 for Disponil AFX 1080. a $_{CMC}$[$Å^2$] = 29 ± 5 for (SDS), and 24 ± 9 for Disponil AFX 1080.	Meconi et al., 2016
	Organic resin (Lewatit VPOC 1064 MD PH)	CTAB, SLES (sodium dodecyl ether sulfate)	Max removal of adsorbate is around 11 times > for SLES than for CTAB.	Gönder et al., 2010
Mineral or Clay (Others)	Fly ash-based geopolymer (FAGP)	SDBS	Optimal parameters pH 2, 180 min of contact, 1 g L^{-1} adsorbent dosage. Max adsorption capacity ≈ 715 mg g^{-1}; activation energy ≈4.05 kJ $mole^{-1}$.	Siyal et al., 2019
	Sandstone with Ca-montmorillonite kaolinite clays	Alkyl ethoxy carboxylate (AEC) for Enhanced Oil Recovery (EOR)	Sandstone with 15% Ca-montmorillonite and kaolinite clay has lower surfactant adsorption than at 10% and 25% concentrations.	Herawati et al., 2022
	Chilean zeolite modified with CTAB -cetyl trimethyl ammonium bromide	SDBS	Maximum adsorption capacity of SDBS is ≈ 31 mg g^{-1}at CTAB loading of 660% external cation exchange capacity.	Taffarel & Rubio, 2010
	Granite sand	Triton X-100	Adsorption TX-100= 2.16 × 10^{-4} g^{-1}; temp= 32^0C; pH≈ 6; amt of sand= 7.0 g; time =15 min	Khan & Zareen, 2004
	α-Alumina (Al_2O_3) beads	SDS	SDS adsorption (pH=4) For 0.001 C (M NaCl); Γ^∞=1.20(mmol m^{-2}) For 0.01 C (M NaCl); Γ^∞=1.55(mmol m^{-2}) For 0.1 C (M NaCl); Γ^∞=1.67 (mmol m^{-2})	Pham et al., 2015
	Natural zeolite	SDS; CTAB	CTAB has a larger adsorption capacity on zeolite than SDS, with capacities of 284 mg $g^{-1}$and 113 mg g^{-1}, respectively.	Haruyunyan & Pirumyan, 2015

leading drawback of adsorption. An admirable strategy for improving surfactant removal and process cost-effectiveness would be blending with other removal methods that tend to degrade.

4.4 Industrial Applications and Future Advances

The successful removal of synthetic surfactants from industrial wastewater (≈99.9%) was exhibited by a hybrid ion exchange fibre material (FM) that improved its operational cycle to 200 L. A hybrid ion exchange FM with both anion-active (A-FM) and cation-active matrices (C-FM) was created by blending different ratios. In four sorption columns with varying ion-exchange fibre material compositions, working life tests of the hybrid IFM were carried out concurrently. These columns processed industrial wastewater at a rate of 0.13 L min^{-1}, pre-purified on a ceramic membrane. Hybrid ion exchange FM, utilized in the ratio of C-FM (3): A-FM (7), achieved the highest and most steady degree of purification(Artemenko et al., 1997).

Recently, a study revealed the efficiency of Iraqi reed (IR) as a biomass precursor for IRAC synthesis and anionic surfactant removal from industrial wastewater. Iraqi reed (IR) biomass waste was recently processed into activated carbon (AC) using a pyrolysis-assisted H_3PO_4 activation process. In contrast to the IR surface area of 0.5542 m^2 g^{-1}, the BET surface area significantly increased upon pyrolysis. SDBS a model anionic surfactant, was eliminated using Iraqi reed-activated carbon (IRAC). The adsorption kinetics and equilibrium data demonstrated that SDBS adsorption follows the pseudo-second-order and Langmuir models under kinetic and equilibrium conditions. The maximum adsorption capacity for SDBS was 121.5 mg g^{-1} (Ahmed et al., 2023).

Zeolites can eradicate many organic pollutants, including cationic surfactants. Zeolites are employed in various applications because of their appreciable capacity for cation exchange, specific surface area, and lattice stability. The tendency of reversible sorption in zeolites makes them reusable. Nano-zeolites (N-Zeo), inorganic-N-Zeo composites, polymer-N-Zeo composites, and zeolite-nanoparticle composites have all been developed to eliminate pollutants like surfactants using sorption or ion exchange batch techniques (Rahman et al., 2022). Innovative materials like β-cyclodextrin-functionalized coffee husk biochar(de Benedicto et al., 2024), activated carbon obtained from waste tires(Ramírez-Arias et al., 2020), pine wood activated carbon (Azoulay et al., 2023), metal oxides using quartz crystal microbalance with dissipation (Medina et al., 2020) are a few of the recent advances in surfactant adsorption.

Fortifying new materials for the enhancement of adsorbents can be helpful for improved adsorption of surfactants on their surface. Various chemicals, nanoparticles, biomaterials and minerals modify the adsorbents (Liu et al., 2021; Zhou et al., 2018). Developing new composites from such modifications is an emerging field in surfactant adsorbents. The following section discusses the employment of such composite adsorbents for surfactant removal. Figure 2 illustrates the mechanism of surfactant adsorption through fortifying adsorbents for composite formation.

5 Composites for Surfactant Removal

Advanced technologies such as photo-catalysis, Fenton, electro-Fenton, adsorption, and catalytic ozonation processes have employed metal composites based on biochar (BC) due to their good efficiency and cheaper cost. These metal composites have also been used to break down surfactants (Ahmad et al., 2022). Composite adsorbents appear to be a better option than normal adsorbents since they combine two or more components, imparting strong adsorbent ability to the resultant material, cost reduction and are readily available(Aguilar-Bolados et al., 2019). Water pollution is a significant issue in the modern era, and research relies on building effective polymeric adsorbents and membranes. The fabrication of polymeric nanocomposites that are non-toxic, biocompatible, economical, and effective continues to be explored, though. The use of nanofillers or nanoparticles enhances the mechanical, thermophysical, and physicochemical properties of these nanocomposites. Methods of fabrication and enhancement include mixing, in-situ polymerization, melt-mixing, electrospinning, and selective laser sintering. Emerging technologies strive to create polymer nanocomposites that are efficient, long-lasting, and profitable, with uniform dispersion and minimum errors. Polymer nanocomposites serve as adsorbents and filter membranes to remove organic pollutants and surfactants from aqueous media (Adeola & Nomngongo, 2022).

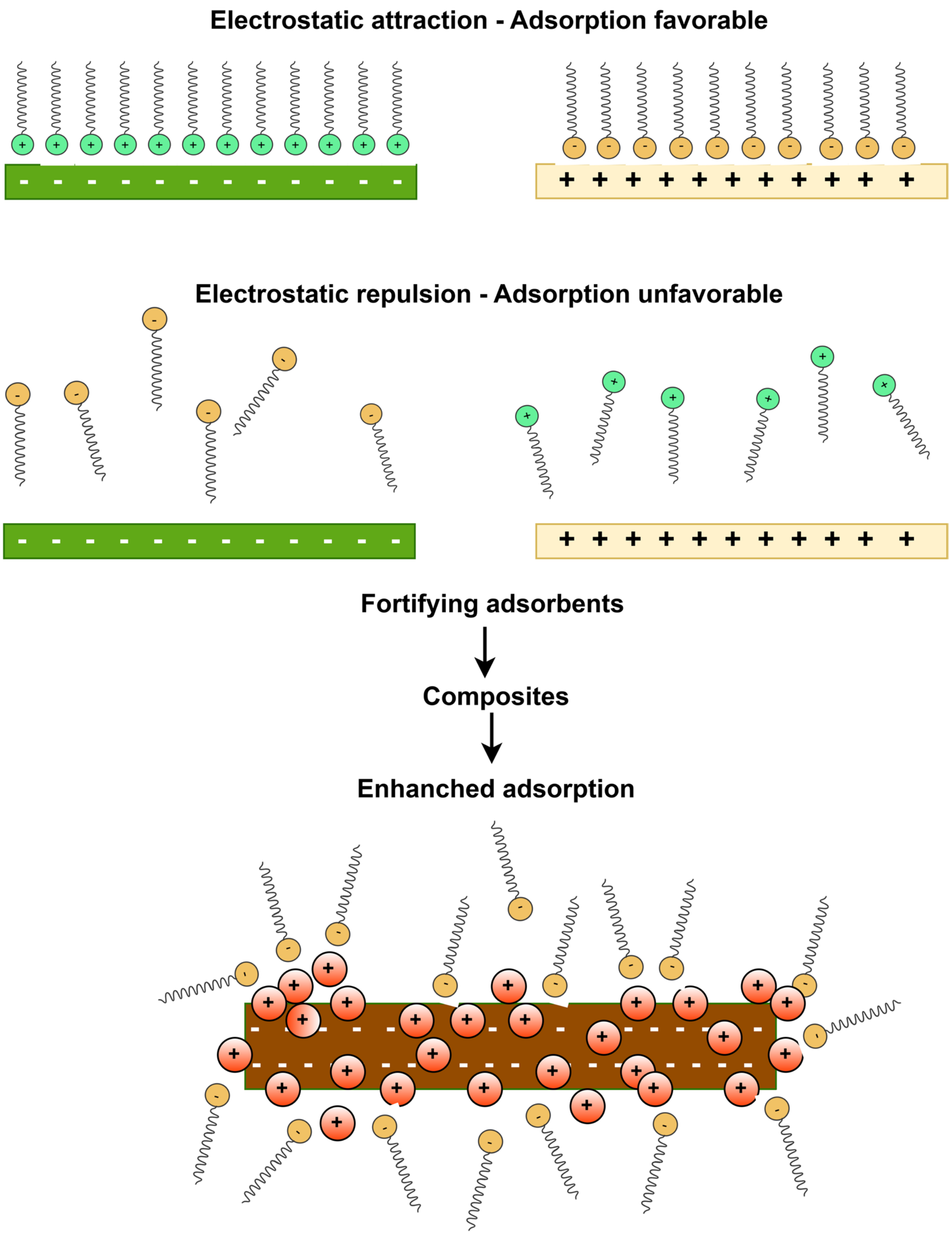

Fig. 2 Fortifying adsorbents for composite formation

Figure 3 illustrates various adsorbent materials used in composites for surfactant removal. Composites can facilitate better, cheaper, and eco-friendly adsorption processes for easy pollutant removal from wastewater. Designing a composite based on the requirements of functional groups, cheaper biomass with easy availability and disposal ability is currently being explored to the maximum.

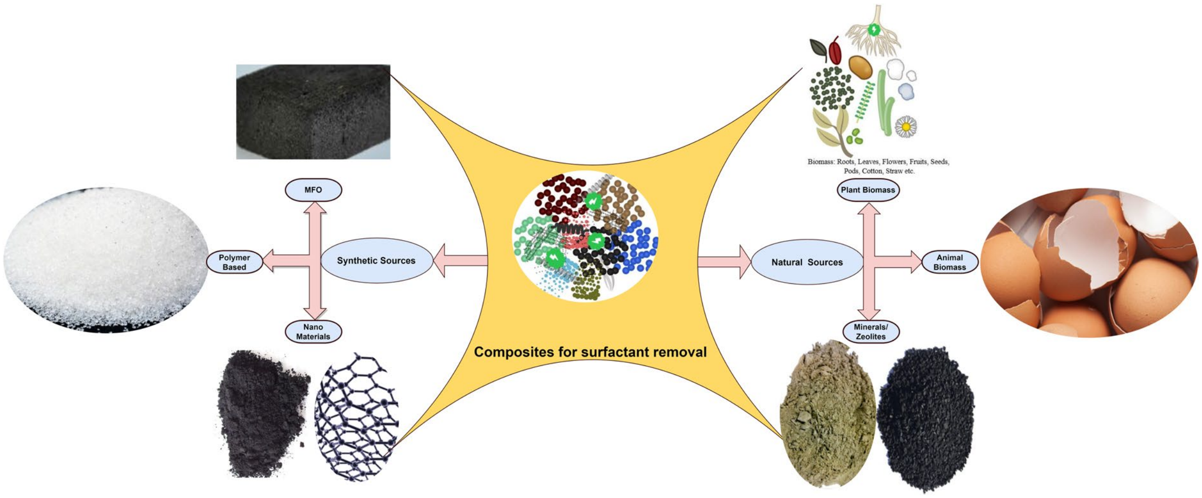

Fig. 3 Adsorbents for composites

A composite of PEI-PVA nanospheres was developed by combining polyvinyl alcohol (PVA) with polymer polyethyleneimine (PEI). This combination applied a series of chemical changes, utilizing the adequate oxygen-containing functional groups on the PVA surface. Under acidic and alkaline conditions, PEI-PVA composite nanospheres showed admirable adsorption effects for anionic surfactants in the wastewater. The adsorption capacity increased as the treatment duration was extended, eventually stabilizing after 24 hours (Liu et al., 2023). Some composites for surfactant removal to date have been enlisted in Table 2.

6 Future Perspectives

Membrane filtration, coagulation, flocculation, and sedimentation are the standard pre-treatment processes that selectively remove harmful pollutants from wastewater units. Though these approaches are practical for surfactant removal, they unavoidably raise overall operating costs and environmental impact. Subsequently, the future opportunity rests in making them cheaper and more environmentally friendly. Hence, hybrid approaches can be helpful for surfactant removal in addition to obligating the least energy, labour, and operating costs.

Green adsorbents as composites appear to be a better option in this consideration. Exploring more agricultural wastes as surfactant adsorbents is necessary to sustain the market for adsorbent composites while lowering production costs (Faccenda et al., 2021). Enhancing the processability of biomass feedstock (Ramírez-Arias et al., 2020) and pretreatment methods to make it more suitable for use as an adsorbent in surfactant removal will be advantageous. Degradable waste material is another aspect that needs to be explored while designing composites. An amalgamation of low-cost biosorbent carriers with polymers, minerals, nano adsorbents or other materials to increase bulk production at low cost can be explored. Figure 4 portrays an ideal composite design for surfactant removal during water remediation.

Investigating novel functional materials and developing hybrid technologies can improve the surfactant adsorption efficiency of composites. Improving composites under various optimal environmental circumstances by thoroughly examining the adsorption mechanism to comprehend the science underlying the surfactant adsorption behaviors is essential.

Table 2 Composites for surfactant removal

Sr.No.	Composite Material Used	Surfactant Removed or Type of Wastewater	Results	References
1.	Carboxylated carbon nanotubes (CCNT)-TiO_2 loaded onto polyethyleneimine-chitosan aerogel (PCA) CCNT-TiO_2@PCA	SDBS	Surfactant removal rate > 91%. Max adsorption capacity of CCNT- TiO2@PCA ≈ 3155 mg g^{-1}	Fan et al., 2023
2.	Lignite (LIG)-Bentonite (BEN) composite (BL)	SDBS	SDBS adsorbed on LIG (80.77 g kg^{-1}) BEN (18.32 g kg^{-1})	Solińska et al., 2023
3.	ß-FeOOH-SBA-15 composites	Nonionic Surfactant P123	The triblock copolymer P123 could be efficiently removed by treatments at 40–80 °C for one–three hours,	Huang et al., 2023
4.	Eggshell-zeolite composite	Handwashing wastewater	COD removal rate = 88%, surface area = 95 mg g^{-1}, pore width = 10 nm, methylene blue number = 26 m^2g^{-1}	Turyasingura et al., 2023
5.	Magnetic carbon nanocomposite (MCNC)	CTAB	Retention≈99.99% (no effect on permeate flux) of the RO membrane with MCNC pretreatment	Ali et al., 2019
6.	Polymeric Microporous adsorbents (CAD-100 and CAD-200) using bentonite composite adsorbent (BKA)	Textile wastewater, Anionic surfactant	Reduction of COD= 65 % and concentration of surfactant=82 %,	Amonova & Ravshanov, 2019
7.	Magnetic nanocomposite sorbents (Saponite, palygorskite, and spondylite clay)	SDBS, SLS and polyphosphates	Surfactants and polyphosphate removal is 2–8 times higher than native clay.	Makarchuk et al., 2017
8.	Kaolinite clay mineral composite (KCC)	SDBS	At pH 4, adsorbent doses (0.5 g), and temperatures (30°C), KCC was able to remove 71% of SDBS in just 60 min	Kamal et al., 2017
9.	Porous membrane-based composite (PS-GO) Polysulfone (PS); graphene oxide (GO)	Triton X 100	After 4 hours treatments; removal efficiency > 90%	Zambianchi et al., 2017
10.	Fly ash TiO_2 composite	SDBS	78% of the SDBS surfactant was removed	Visa et al., 2015
11.	Chemically crosslinked composite gels - bentonite clay and nonionic polymers	CTAB and cetyl pyridinium bromide (CPB)	Surfactant adsorption causes shifts of critical micelle concentration (CMC) from 500 µl to 720 µl	Beisebekov et al., 2015
12.	Geomaterial composite formed by bentonite (mostly Ca-montmorillonite) and activated carbon.	Dodecylbenzene sulfonic acid surfactant (DBSA)	0.3 g of geomaterial was equally effective in removing LAS as activated carbon and montmorillonite at concentrations 7 and 10 times higher, respectively	Mimanne et al., 2012
13.	Commercial DL composite membrane	Chemipur CL80	Removal efficiency > 94%, at lower temp, higher removal efficiency achieved > 97 %, greatest surfactant removal attained at 20 °C temperature, pressure- 40 bar.	Kertész et al., 2008
14.	Bentonite and *Duranta erecta* fruit powder mixer embedded alginate beads	CTAB	Beads CTAB adsorption capacity qm values = 2862–2352 mg g^{-1}	Golder et al., 2021
15.	Graphene oxide (GO)-enhanced composite metal-organic frameworks (MOF)	Carwash wastewater	Effective surfactant removal ≈91% to 97%. Surfactant adsorption capacity (24.48 mg g^{-1})	Mkilima et al., 2024

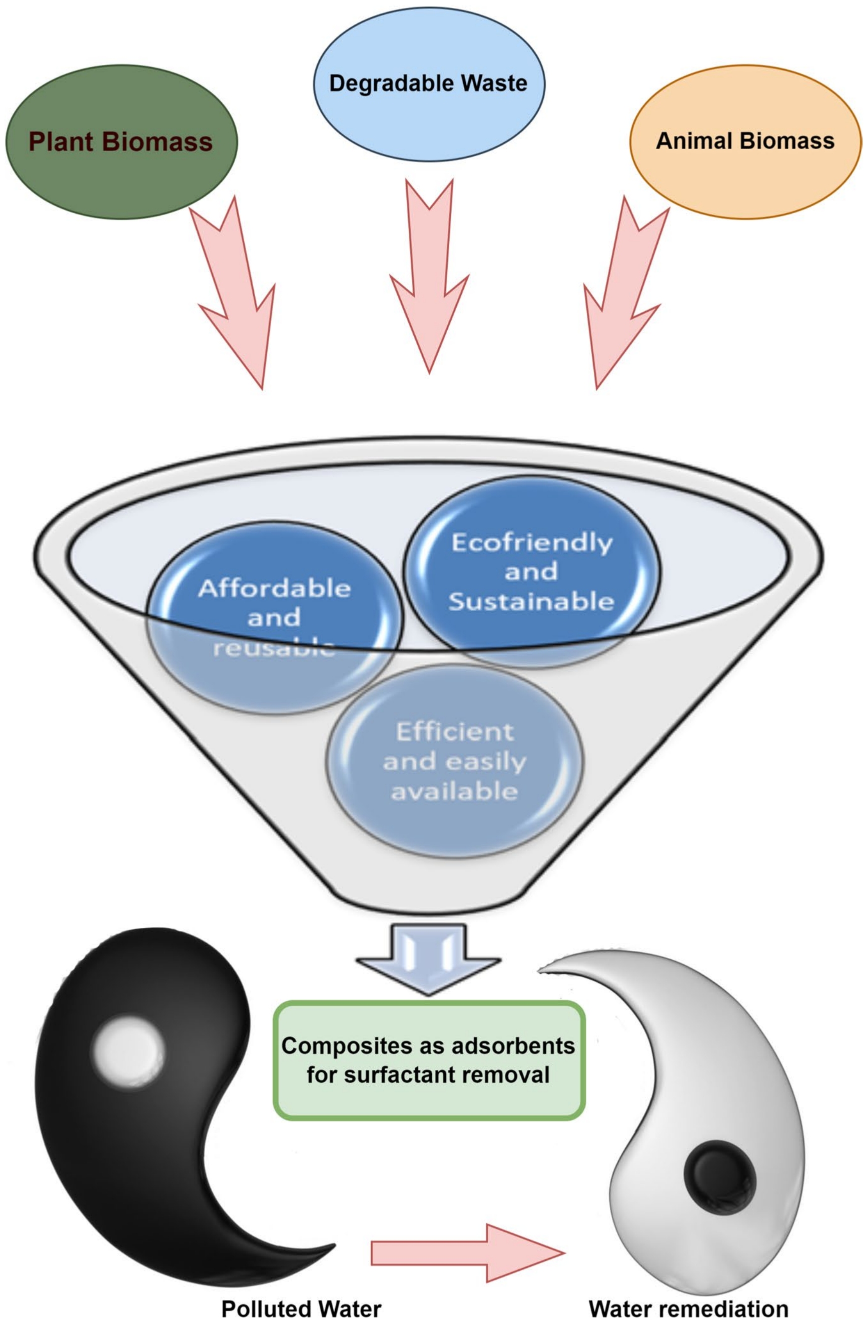

Fig. 4 Designing an ideal composite for surfactant removal

7 Conclusion

A concrete and assured surfactant removal materials and methodologies are still lacking. Efficacious commercialization and field-scale application of carbon-based adsorbents for surfactant removal in wastewater treatment require addressing several limitations. Energy-intensive synthesis restricts large-scale production, necessitating the development of low-cost technologies for activated carbon synthesis. The low conductivity, limited adsorption capacity, and low stability of raw biochar are some of its limitations, which make its modification essential. The synthesis of magnetic biochar composite can aid in the retrieval and reusability of biochar. Upcoming research should also explore the risk of secondary contamination to evaluate the sustainability of carbon-based technologies for real-world applications of surfactant removal. The utility of photocatalysts like TiO_2 combined with various adsorbents in hybrid techniques for surfactant removal needs modifications. Due to their significant band gaps, these photocatalysts can access significantly less of the solar spectrum in the photocatalytic process; hence, they need to reduce the band gap for appropriate electronic excitation. Novel yet biodegradable polymer adsorbent and some waste disposal adsorbent materials as composites need to be explored. Future studies should concentrate on combining nano adsorbent materials with bio-sorbent carriers, investigating novel functional materials, and enhancing the adsorbents'selectivity and operating expenses for surfactant mitigation. Though some composites facilitate surfactant removal, their real-time application still seems complicated. Developing hybrid surfactant removal technologies and adsorbents from composite or mixed biomass sources can be used in real-field applications, requiring further research.

Funding Details No funding was received for conducting this study.

Financial or Non-financial Interests The authors have no relevant financial or non-financial interests to disclose.

Data Availability Statement No Data Used.

Authors'Contributions Deepali Kulkarni: Conceptualisation, Literature survey, Data interpretation, Writing original draft.

Dipika Jaspal: Critical revision, Guiding, Proofreading, Supervision.

Nilisha Itankar: Guiding, Supervision.

All authors read and approved the final manuscript.

Declarations

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abd El-Lateef, H. M., Khalaf Ali, M. M., & Saleh, M. M. (2018). Adsorption and removal of cationic and anionic surfactants using zero-valent iron nanoparticles. *Journal of Molecular Liquids, 268*, 497–505. https://doi.org/10.1016/j.molliq.2018.07.093

Aboulhassan, M. A., Souabi, S., Yaacoubi, A., & Baudu, M. (2006). Removal of surfactant from industrial wastewaters by coagulation flocculation process. *International journal of Environmental Science and Technology, 3*(4), 327–332. https://doi.org/10.1007/BF03325941

Adeola, A. O., & Nomngongo, P. N. (2022). Advanced polymeric nanocomposites for water treatment applications: A holistic perspective. *Polymers, 14*(12), 2462–2485. https://doi.org/10.3390/polym14122462

Aguilar-Bolados, H., Contreras-Cid, A., Neira-Carrillo, A., Lopez-Manchado, M., & Yazdani-Pedram, M. (2019). Removal of surfactant from nanocomposites films based on thermally reduced graphene oxide and natural rubber. *Journal of Composites Science, 3*(2). https://doi.org/10.3390/jcs3020031

Ahmad, A., Priyadarshini, M., Yadav, S., Ghangrekar, M. M., & Surampalli, R. Y. (2022). The potential of biochar-based catalysts in advanced treatment technologies for efficacious removal of persistent organic pollutants from wastewater: A review. *Chemical Engineering Research and Design, 187*, 470–496. https://doi.org/10.1016/j.cherd.2022.09.024

Ahmed, T. A., Abdulhameed, A. S., Ibrahim, S., ALOthman, Z. A., Wilson, L. D., & Jawad, A. H. (2023). High surface area mesoporous activated carbon produced from Iraqi reed via pyrolysis assisted H3PO4 activation: Box-Behnken design for surfactant removal. *Diamond and Related Materials, 133*, 109756. https://doi.org/10.1016/J.DIAMOND.2023.109756

Ahtasham Iqbal, M., Akram, S., S., k., Lal, B., Hassan, S. U., Ashraf, R., Kezembayeva, G., Mushtaq, M., Chinibayeva, N., & Hosseini-Bandegharaei, A. (2024). Advanced photocatalysis as a viable and sustainable wastewater treatment process: A comprehensive review. *Environmental Research, 253*, 118947. https://doi.org/10.1016/J.ENVRES.2024.118947

Akarsu, C., & Deniz, F. (2021). Electrocoagulation/electroflotation process for removal of organics and microplastics in laundry wastewater. *Clean - Soil, Air, Water, 49*(1). https://doi.org/10.1002/clen.202000146

Ali, M., Alam, S., urRehman, N., Zahoor, M., & Khan, M. S. (2019). Adsorptive removal of cetyltrimethyl ammonium bromide (CTAB) surfactant from aqueous solution: Crossbreed pilot plant membrane studies. *Tenside, Surfactants, Detergents, 56*(6), 534–542. https://doi.org/10.3139/113.110656

Aly, M. A., Abd-Allah, & Srorr, T. (1998). Biodegradation of anionic surfactants in the presence of organic contaminants. *Water Research, 32*(3), 944–947.

Amelia, S., Rahmadani, W., Amalia, L. R., & Mufrodi, Z. (2020). Degradation of surfactant waste of leather tanning using Fe2O3/activated carbon catalyst. *Majalah Kulit, Karet, Dan Plastik, 35*(2), 49. https://doi.org/10.20543/mkkp.v35i2.5607

Amir Hossein, M., Maleki, A., & Roshani, B. (2004). Removal of Anionic Surfactants in Detergent Wastewater by Chemical Coagulation. *Pakistan Journal of Biological Sciences, 7*(12), 2222–2226.

Amirianshoja, T., Junin, R., Kamal Idris, A., & Rahmani, O. (2013). A comparative study of surfactant adsorption by clay minerals. *Journal of Petroleum Science and Engineering, 101*, 21–27. https://doi.org/10.1016/j.petrol.2012.10.002

Amonova, M. M., & Ravshanov, K. A. (2019). Polymeric composition for purification of wastewater from various impurities in textile industry. *ChemChemTech, 62*(10), 147–153. https://doi.org/10.6060/ivkkt.20196210.5963

Andrade, M. V. F., Sakamoto, I. K., de Oliveira Paranhos, A. G., Silva, E. L., & Varesche, M. B. A. (2017). Bioremoval of surfactant from laundry wastewater in optimized condition by anoxic reactors. *Water, Air, and Soil Pollution, 228*(4). https://doi.org/10.1007/s11270-017-3293-9

Aoudjit, F., Cherifi, O., & Halliche, D. (2019). Simultaneously efficient adsorption and photocatalytic degradation of sodium dodecyl sulfate surfactant by one-pot synthesized TiO 2 /layered double hydroxide materials. *Separation Science and Technology, 54*(7), 1095–1105. https://doi.org/10.1080/01496395.2018.1527352

Artemenko, S. E., Kardash, M. M., Taraskina, O. E., & Fedorchenko, A. A. (1997). Industrial ecology removal of surfactants from industrial sewage with hybrid ion-exchange composite materials. *Fibre Chemistry, 29*(4), 261–264.

Ayranci, E., & Duman, O. (2007). Removal of anionic surfactants from aqueous solutions by adsorption onto high area activated carbon cloth studied by in situ UV spectroscopy. *Journal of Hazardous Materials, 148*(1–2), 75–82. https://doi.org/10.1016/j.jhazmat.2007.02.006

Azoulay, K., Bencheikh, I., Benchrifa, M., Baaziz, M. B., spsampsps Mabrouki, J. (2023). Adsorption of inorganic and organic pollutants in urban wastewater treatment using pine wood activated carbon. *Environmental Science and Engineering*. https://doi.org/10.1007/978-3-031-25662-2_18

Babaei, F., Ehrampoush, M. H., Eslami, H., Ghaneian, M. T., Fallahzadeh, H., Talebi, P., Fard, R. F., & Ebrahimi, A. A. (2019). Removal of linear alkylbenzene sulfonate and turbidity from greywater by a hybrid multi-layer slow sand filter microfiltration ultrafiltration system. *Journal of Cleaner Production, 211*, 922–931. https://doi.org/10.1016/j.jclepro.2018.11.255

Banchon, C., Castillo, A., & Posligua, P. (2017). Chemical interactions to cleanup highly polluted automobile service station wastewater by bioadsorption-coagulation-flocculation. *Journal of Ecological Engineering, 18*(1), 1–10. https://doi.org/10.12911/22998993/66252

Barambu, N. U., Peter, D., Yusoff, M. H. M., Bilad, M. R., Shamsuddin, N., Marbelia, L., Nordin, N. A. H., & Jaafar, J. (2020). Detergent and water recovery from laundry wastewater using tilted panel membrane filtration system. *Membranes, 10*(10), 1–9. https://doi.org/10.3390/membranes10100260

Basar, C. A., Karagunduz, A., Cakici, A., & Keskinler, B. (2004). Removal of surfactants by powdered activated carbon and microfiltration. *Water Research, 38*(8), 2117–2124. https://doi.org/10.1016/j.watres.2004.02.001

Bautista-Toledo, M. I., Méndez-Díaz, J. D., Sánchez-Polo, M., Rivera-Utrilla, J., & Ferro-García, M. A. (2008). Adsorption of sodium dodecylbenzenesulfonate on activated carbons: Effects of solution chemistry and presence of bacteria. *Journal of Colloid and Interface Science, 317*(1), 11–17. https://doi.org/10.1016/j.jcis.2007.09.039

Beisebekov, M. M., Serikpayeva, S. B., Zhumagalieva, S. N., Beisebekov, M. K., Abilov, Z. A., Kosmella, S., & Koetz, J. (2015). Interactions of bentonite clay in composite gels of non-ionic polymers with cationic surfactants and heavy metal ions. *Colloid and Polymer Science, 293*(2), 633–639. https://doi.org/10.1007/s00396-014-3463-x

Beltrán-Heredia, J., Sánchez-Martín, J., & Barrado-Moreno, M. (2012). Long-chain anionic surfactants in aqueous solution. Removal by Moringa oleifera coagulant. *Chemical Engineering Journal, 180*, 128–136. https://doi.org/10.1016/j.cej.2011.11.024

Berber, M. R. (2020). Current advances of polymer composites for water treatment and desalination. *Journal of Chemistry, 2020*. https://doi.org/10.1155/2020/7608423

Bilad, M. R., Mat Nawi, N. I., Subramaniam, D. D., Shamsuddin, N., Khan, A. L., Jaafar, J., & Nandiyanto, A. B. D. (2020). Low-pressure submerged membrane filtration for potential reuse of detergent and water from laundry wastewater. *Journal of Water Process Engineering, 36*. https://doi.org/10.1016/j.jwpe.2020.101264

Biswas, S., & Pal, A. (2021). Application of biopolymers as a new age sustainable material for surfactant adsorption: A brief review. *Carbohydrate Polymer Technologies and Applications, 2*. https://doi.org/10.1016/j.carpta.2021.100145

Carvalho, S., Eusébio, M., & Velizarov, S. (2025). Techno-economic and feasibility assessment of membrane-based wastewater treatment and reuse in the automotive industry. *Separations, 12*(2). https://doi.org/10.3390/separations12020030

Cheminski, T., De Figueiredo Neves, T., Silva, P. M., Guimarães, C. H., & Prediger, P. (2019). Insertion of phenyl ethyleneglycol units on graphene oxide as stabilizers and its application for surfactant removal. *Journal of Environmental Chemical Engineering, 7*(2). https://doi.org/10.1016/j.jece.2019.102976

Chu, L., Chen, L., Qian, Y., & Wang, J. (2024). Degradation of sodium dodecyl benzene sulfonate in aqueous solution by electron beam radiation and changes in surfactant micelle property. *Radiation Physics and Chemistry, 225*, 112138. https://doi.org/10.1016/J.RADPHYSCHEM.2024.112138

Cisneros-León, D. G., Espinoza-Montero, P. J., Bolaños-Mendez, D., Alvarez-Paguay, J., Fernández, L., Saavedra-Alulema, P. F., Lopez, K., Astorga, D., & Piñeiros, J. L. (2023). Electrochemical degradation of surfactants in domestic wastewater using a DiaClean® cell equipped with a boron-doped diamond electrode. *Frontiers in Chemistry, 11*. https://doi.org/10.3389/fchem.2023.900670

Dadebo, D., Atukunda, A., Ibrahim, M. G., & Nasr, M. (2023). Integrating chemical coagulation with fixed-bed column adsorption using rice husk-derived biochar for shipboard bilgewater treatment: Scale-up design and cost estimation. *Chemical Engineering Journal Advances, 16*. https://doi.org/10.1016/j.ceja.2023.100520

Dadebo, D., Nasr, M., Fujii, M., & Ibrahim, M. G. (2022). Bio-coagulation using Cicer arietinum combined with pyrolyzed residual sludge-based adsorption for carwash wastewater treatment: A techno-economic and sustainable approach. *Journal of Water Process Engineering, 49*, 103063. https://doi.org/10.1016/J.JWPE.2022.103063

De Benedicto, D. F. C., Ferreira, G. M. D., & Thomasi, S. S. (2024). β-cyclodextrin-functionalized coffee husk biochar for surfactant adsorption. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 701*, 134921. https://doi.org/10.1016/J.COLSURFA.2024.134921

de Faria, C. V., Delforno, T. P., Okada, D. Y., & Varesche, M. B. A. (2019). Evaluation of anionic surfactant removal by anaerobic degradation of commercial laundry wastewater and domestic sewage. *Environmental Technology, 40*(8), 988–996. https://doi.org/10.1080/09593330.2017.1414317

De Gisi, S., Lofrano, G., Grassi, M., & Notarnicola, M. (2016). Characteristics and adsorption capacities of low-cost sorbents for wastewater treatment: A review. *Sustainable Materials and Technologies, 9*, 10–40. https://doi.org/10.1016/j.susmat.2016.06.002

Deressa, S., Endale, H., Dadi, D., & Kitte, S. A. (2019). Removal of anionic surfactant from residential laundry wastewater using jackfruit (Artocarpus heterophyllus) seeds. *Advances in Environmental Technology, 5*(1), 47–53. https://doi.org/10.22104/aet.2020.3841.1189

Duman, O., & Ayranci, E. (2010). Adsorptive removal of cationic surfactants from aqueous solutions onto high-area activated carbon cloth monitored by in situ UV spectroscopy. *Journal of Hazardous Materials, 174*(1–3), 359–367. https://doi.org/10.1016/j.jhazmat.2009.09.058

Dutt, M. A., Hanif, M. A., Nadeem, F., & Bhatti, H. N. (2020). A review of advances in engineered composite materials popular for wastewater treatment. *Journal of Environmental Chemical Engineering, 8*(5). https://doi.org/10.1016/j.jece.2020.104073

El Feky, A. A., Shalaby, M. N., El-Shamy, O. A. A., & Selim, S. A. (2010). Adsorption of some surfactants onto polyvinyl alcohol as hydrophobic polymer surface. *Journal of Dispersion Science and Technology, 31*(8), 1091–1099. https://doi.org/10.1080/01932690903224581

El-Feky, A. A., Shalaby, M. N., & El-Shamy, O. A. A. (2009). Polymers as hydrophobic adsorbent surface for some surfactants. *Journal of Dispersion Science and Technology, 30*(4), 445–450. https://doi.org/10.1080/01932690802548536

Faccenda, H. B., Melara, F., Damini, G., Godinho, M., Manera, C., & Piccin, J. S. (2021). Greywater treatment of emerging pollutant linear alkylbenzene sulfonate by adsorption with leather shave waste activated carbon. *Environmental Science and Pollution Research International, 29*(53), 79830–79840. https://doi.org/10.21203/rs.3.rs-813084/v1

Fan, S., Chen, J., Tian, L., Fan, C., Xu, W., Zhang, Y., Gan, T., Hu, H., Huang, Z., & Qin, Y. (2023). Construction of a recyclable chitosan-based aerogel-supported TiO2 catalyst for treating high-concentration surfactants. *Composites Part B: Engineering, 251*. https://doi.org/10.1016/j.compositesb.2022.110475

Gao, Q., Wu, F., Hu, J., Chen, W., Zhang, X., Guo, X., Wang, B., & Wang, X. (2020). Chemical composition-dependent removal of cationic surfactants by carbon nanotubes. *Science of the Total Environment, 716*. https://doi.org/10.1016/j.scitotenv.2020.137017

Golder, A. K., Chauhan, S., & Ravi, R. (2021). Synthesis of low-cost bentonite/Duranta erecta's fruit powder imbedded alginate beads and its application in surfactant removal. *Environmental Science and Pollution Research, 28*(42), 58945–58957. https://doi.org/10.1007/s11356-021-14306-6

Gönder, Z. B., Vergili, I., Kaya, Y., & Barlas, H. (2010). Adsorption of cationic and anionic surfactants onto organic polymer resin Lewatit VPOC 1064 MD PH. *Environmental Geochemistry and Health, 32*(4), 267–273. https://doi.org/10.1007/s10653-010-9297-7

Gurses, A., Yalcin, M., Sozbilir, M., & Dogar, C. (2003). The investigation of adsorption thermodynamics and mechanism of a cationic surfactant, CTAB, onto powdered active carbon. *Fuel Processing Technology, 81*(1), 57–66. https://doi.org/10.1016/S0378-3820(03)00002-X

Gusain, R., Gupta, K., Joshi, P., & Khatri, O. P. (2019). Adsorptive removal and photocatalytic degradation of organic pollutants using metal oxides and their composites: A comprehensive review. *Advances in Colloid and Interface Science, 272*. https://doi.org/10.1016/j.cis.2019.102009

Han, H., Rafiq, M. K., Zhou, T., Xu, R., Mašek, O., & Li, X. (2019). A critical review of clay-based composites with enhanced adsorption performance for metal and organic pollutants. *Journal of Hazardous Materials, 369*, 780–796. https://doi.org/10.1016/j.jhazmat.2019.02.003

Harif, S., Aboulhassan, M. A., Bammou, L., Baicha, Z., & Fernández, F. J. H. (2023). Improving the Removal of Anionic Surfactant in Cardboard Industry Wastewater by Coagulation/Flocculation: Process Optimization with Response Surface Methodology. *Water, Air, and Soil Pollution, 234*(7). https://doi.org/10.1007/s11270-023-06435-0

Haruyunyan, L. R., & Pirumyan, G. P. (2015). Purification of Waters from Anionic and Cationic Surfactants by Natural Zeolites. *Chemistry and Biology, 1*, 21–28.

Herawati, I., Permadi, P., Rochliadi, A., & Marhaendrajana, T. (2022). Adsorption of anionic surfactant on sandstone reservoir containing clay minerals and its effect on wettability alteration. *Energy Reports, 8*, 11554–11568. https://doi.org/10.1016/j.egyr.2022.08.268

Huang, G., Mao, D., Zhang, Y., Chen, X. D., & Wu, Z. (2023). Postsynthesis of β-FeOOH/SBA-15 composites via mild ozone treatment: Effective surfactant removal and perfect property preservation for enhanced arsenic adsorption. *Journal of Environmental Chemical Engineering, 11*(2). https://doi.org/10.1016/j.jece.2023.109597

James, D. T. K., & Ifelebuegu, A. O. (2018). Low cost sustainable materials for grey water reclamation. *Water Science and Technology, 2017*(3), 667–678. https://doi.org/10.2166/WST.2018.225

Jangkorn, S., Kuhakaew, S., Theantanoo, S., Klinla-or, H., & Sriwiriyarat, T. (2011). Evaluation of reusing alum sludge for the coagulation of industrial wastewater containing mixed anionic surfactants. *Journal of Environmental Sciences, 23*(4), 587–594. https://doi.org/10.1016/S1001-0742(10)60451-2

Jaspal, D., Malviya, A., El Allaoui, B., Zari, N., Bouhfid, R., Kacem Qaiss, A. E., & Bhagwat, S. (2023). Emerging advances of composite membranes for seawater pre-treatment: A review. *Water Science and Technology, 88*(2), 408–429. https://doi.org/10.2166/wst.2023.220

Jennifer, Z.-A., Sonia, A.-D., Francesca, E.-B., Nadia, F.-M., & Suanny, M.-R. (2024). Advanced oxidation processes by UV/H2O2 for the removal of anionic surfactants in a decentralized wastewater treatment plant in Ecuador. *Water Science and Technology, 90*(8), 2340–2351. https://doi.org/10.2166/wst.2024.311

Ji, G., Zhou, Y., Zhou, B., Yun, Y., Chen, Z., & Liu, H. (2019). Combined UMBAF-MBAF process treating detergent wastewater. *Water Environment Research, 91*(8), 672–678. https://doi.org/10.1002/wer.1091

Johnson, J. K., Michael Salerno, K., Schlesinger, D. R., Le, N. Q., Ko, J. S., & Xia, Z. (2022). Removing forever chemicals via amphiphilic functionalized membranes. *Clean Water, 5*(1). https://doi.org/10.1038/s41545-022-00193-y

Joseph, C. G., Taufiq-Yap, Y. H., Affandi, N. A., Nga, J. L. H., & Vijayan, V. (2022). Photocatalytic treatment of detergent contaminated wastewater: A short review on current progress. *Korean Journal of Chemical Engineering, 39*, 484–498. https://doi.org/10.1007/s11814-021-0964-4

Kahya, N., Kaygusuz, H., & Erim, F. B. (2018). Aqueous removal of sodium dodecyl benzene sulfonate (SDBS) by crosslinked chitosan films. *Journal of Polymers and the Environment, 26*(5), 2166–2172. https://doi.org/10.1007/s10924-017-1113-3

Kalam, S., Abu-Khamsin, S. A., Kamal, M. S., & Patil, S. (2021a). A review on surfactant retention on rocks: mechanisms, measurements, and influencing factors. *Fuel, 293*. https://doi.org/10.1016/j.fuel.2021.120459

Kalam, S., Abu-Khamsin, S. A., Kamal, M. S., & Patil, S. (2021b). Surfactant Adsorption Isotherms: A Review. *ACS Omega, 6*(48), 32342–32348. American Chemical Society. https://doi.org/10.1021/acsomega.1c04661

Kamal, S., Kamal, A., Shahzad, T., Rehman, S., Azeem, M., & Bibi, I. (2017). Potential of kaolinite as adsorbent to remove anionic surfactant from simulated industrial wastewater. *Desalination and Water Treatment, 88*, 85–92. https://doi.org/10.5004/dwt.2017.21342

Kertész, S., László, Z., Horváth, Z. H., & Hodúr, C. (2008). Analysis of nanofiltration parameters of removal of an anionic detergent. *Desalination, 221*(1–3), 303–311. https://doi.org/10.1016/j.desal.2007.01.087

Khan, M. N., & Zareen, U. (2004). Adsorptive removal of nonionic surfactants from water using granite sand. *Journal of the Iranian Chemical Society, 1*(2), 152–158 www.SID.ir

Klimonda, A., & Kowalska, I. (2021). Membrane technology for the treatment of industrial wastewater containing cationic surfactants. *Water Resources and Industry, 26*. https://doi.org/10.1016/j.wri.2021.100157

Koul, B., Bhat, N., Abubakar, M., Mishra, M., Arukha, A. P., & Yadav, D. (2022). Application of natural coagulants in water treatment: A sustainable alternative to chemicals. *Water, 14*(22). https://doi.org/10.3390/w14223751

Krishnan, S., Chandran, K., & Sinnathambi, C. M. (2016). Wastewater treatment technologies used for the removal of different surfactants: A comparative review. *International Journal of Applied Chemistry, 12*(4), 727–739.

Kulkarni, D., & Jaspal, D. (2023). Surfactants in waste water: Development, current status and associated challenges. *Materials Today Proceedings*. https://doi.org/10.1016/j.matpr.2023.11.022

Kumar, B., Tiyasha, S., and and Dawit, N. B. (2018). Economical approaches for the treatment and reutilization of laundry wastewater-a review. *Journal of Industrial Pollution Control, 34*(2), 2164–2178.

Li, R., Qi, X., Wang, W., Cheng, M., Wang, Y., Zhang, P., & Song, G. (2024). Floc kinetics in dual-coagulation for the treatment of high-concentration surfactant-kaolin wastewater. *Journal of Polymers and the Environment, 32*, 1706–1716. https://doi.org/10.1007/s10924-023-03079-3

Liu, W., Shi, L., Lei, X., Li, F., Li, B., Zheng, H., Zhuangzhuang, P., Weikang, L., Liwen, S., Xiaoying, L., Fuyi, L., & Bangguo, L. (2023). Effectiveness of PEI-PVA composite material for the removal of anionic surfactant from aqueous solution. *New Chemical Materials, 51*(5), 310–314. https://doi.org/10.19817/j.cnki.issn1006-3536.2023.05.058

Liu, Z., Onay, H., Guo, F., Chen, J., Poltorak, L., Hedayati, P., & Sudhölter, E. J. R. (2021). Calcium Carbonate-Modified Surfaces by Electrocrystallization to Study Anionic Surfactant Adsorption. *Energy and Fuels, 35*(2), 1358–1370. https://doi.org/10.1021/ACS.ENERGYFUELS.0C03695

López-Pérez, L., López-Martínez, M. A., Djanashvili, K., Góra-Marek, K., Tarach, K. A., Borges, M. E., & Melián-Cabrera, I. (2020). Process intensification of mesoporous material's synthesis by microwave-assisted surfactant removal. *ACS Sustainable Chemistry and Engineering, 8*(45), 16814–16822. https://doi.org/10.1021/acssuschemeng.0c05438

Luo, J., Jin, X., Wang, Y., & Jin, P. (2022). Advanced treatment of laundry wastewater by electro-hybrid ozonation–coagulation process: Surfactant and microplastic removal and mechanism. *Water, 14*(24). https://doi.org/10.3390/w14244138

Makarchuk, O., Dontsova, T., & Krymets, G. (2017). *Magnetic mineral nanocomposite sorbents for removal of surfactants*. 2017 IEEE 7th International Conference Nanomaterials: Application & Properties (NAP) (pp. 02MFPM02-1-02MFPM02-6). Odessa, UKraine. https://doi.org/10.1109/NAP.2017.8190406

Mannhardt, K., Schramm, L. L., & Novosad, J. J. (1992). Adsorption of anionic and amphoteric foam-forming surfactants on different rock types. *Colloids and Surfaces, 68*(1-2), 37–53.

Maqsood, M., Khalid, T., Kazerooni, E. G., Javed, I., & Nadeem, F. (2019). Wastewater treatment using soil composites as effective adsorbents–A comprehensive review. *International Journal of Chemical and Biochemical Sciences, 16*, 28–34.

Marcelo, P. R., & Alexandre, B. (2021). Evaluation of effluent post-treatment by slow filtration and adsorption with activated carbon produced from spent coffee grounds in surfactant removal in sewage treatment. *Ambiente and Água - An Interdisciplinary Journal of Applied Science, 17*(1), 1–10. https://doi.org/10.4136/1980-993X

Mascoli Junior, R., Passoni, C. M., Santos, F. M., Bernardes, F. S., Magalhães Filho, F. J. C., & Paulo, P. L. (2023). assessment of surfactant removal capacity and microbial community diversity in a greywater-treating constructed wetland. *Resources, 12*(3). https://doi.org/10.3390/resources12030038

Meconi, G. M., Ballard, N., Asua, J. M., & Zangi, R. (2016). Adsorption and desorption behavior of ionic and nonionic surfactants on polymer surfaces. *Soft Matter, 12*(48), 9692–9704. https://doi.org/10.1039/C6SM01878E

Medina, S. C., Farinha, A. S. F., Emwas, A. H., Tabatabai, A., & Leiknes, T. O. (2020). A fundamental study of adsorption kinetics of surfactants onto metal oxides using quartz crystal microbalance with dissipation (QCM-D). *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 586*. https://doi.org/10.1016/j.colsurfa.2019.124237

Merrettig-Bruns, U., & Jelen, E. (2009). Anaerobic biodegradation of detergent surfactants. *Materials, 2*(1), 181–206. https://doi.org/10.3390/ma2010181

Mimanne, G., Sennour, R., Benghalem, A., Taleb, S., & Benhabib, K. (2012). Use of the geomaterial for the elimination of surfactant dodecylbenzene sulfonic acid from aqueous solution. *Journal of Materials and Environmental Science, 3*(4), 712–725.

Mi-Na, Z., Xue-Pin, L., & Bi, S. (2006). Adsorption of Surfactants on Chromium Leather Waste. *Journal of the Society of Leather Technologists and Chemists, 90*(1), 1–6.

Mirbahoush, S. M., Chaibakhsh, N., & Moradi-Shoeili, Z. (2019). Highly efficient removal of surfactant from industrial effluents using flaxseed mucilage in coagulation/photo-Fenton oxidation process. *Chemosphere, 231*, 51–59. https://doi.org/10.1016/j.chemosphere.2019.05.118

Mkilima, T., Zharkenov, Y., Utepbergenova, L., Abduova, A., Sarypbekova, N., Smagulova, E., Abdukalikova, G., Kamidulla, F., & Zhumadilov, I. (2024). Harnessing graphene oxide-enhanced composite metal-organic frameworks for efficient wastewater treatment. *Water Cycle, 5*, 86–98. https://doi.org/10.1016/j.watcyc.2024.02.005

Mondal, B., Adak, A., & Datta, P. (2019). Degradation of anionic surfactant in municipal wastewater by UV-H2O2 : Process optimization using response surface methodology. *Journal of Photochemistry and Photobiology A: Chemistry, 375*, 237–243. https://doi.org/10.1016/j.jphotochem.2019.02.030

Mostafazadeh, K. A., Benguit, A. T., Carabin, A., Drogui, P., & Brien, E. (2019). Development of combined membrane filtration, electrochemical technologies, and adsorption processes for treatment and reuse of laundry wastewater and removal of nonylphenol ethoxylates as surfactants. *Journal of Water Process Engineering, 28*, 277–292. https://doi.org/10.1016/j.jwpe.2019.02.014

Mushtaq, W., Rafiq, M., Mushtaq, Z., Nadeem, F., & Abdul, H. (2019). Wastewater treatment and dye sequestration using potential magnetic composites–a comprehensive review. *International Journal of Chemical and Biochemical Sciences, 15*, 74–86.

Nacar, T., Ucar, D., & Şapci Ayas, Z. (2022). Removal of detergents in car wash wastewater by sub-surface flow constructed wetland. *Bitlis Eren University Journal of Science, 11*(3), 820–827. https://doi.org/10.17798/bitlisfen.1108112

Nagtode, V. S., Cardoza, C., Yasin, H. K. A., Mali, S. N., Tambe, S. M., Roy, P., Singh, K., Goel, A., Amin, P. D., Thorat, B. R., Cruz, J. N., & Pratap, A. P. (2023). Green surfactants (biosurfactants): A petroleum-free substitute for sustainability─comparison, applications, market, and future prospects. *ACS Omega, 8*(13), 11674–11699. https://doi.org/10.1021/acsomega.3c00591

Ncibi, M. C., Gaspard, S., & Sillanpää, M. (2015). As-synthesized multi-walled carbon nanotubes for the removal of ionic and non-ionic surfactants. *Journal of Hazardous Materials, 286*, 195–203. https://doi.org/10.1016/j.jhazmat.2014.12.039

Ncibi, M. C., Mahjoub, B., & Seffen, M. (2008). Adsorptive removal of anionic and non-ionic surfactants from aqueous phase using Posidonia oceanica (L.) marine biomass. *Journal of Chemical Technology and Biotechnology, 83*(1), 77–83. https://doi.org/10.1002/jctb.1787

Obaideen, K., Shehata, N., Sayed, E. T., Abdelkareem, M. A., Mahmoud, M. S., & Olabi, A. G. (2022). The role of wastewater treatment in achieving sustainable development goals (SDGs) and sustainability guideline. *Energy Nexus, 7*, 100112. https://doi.org/10.1016/j.nexus.2022.100112

Olkowska, E., Ruman, M., Kowalska, A., & Polkowska, Z. (2013). Determination of surfactants in environmental samples. part iii. non-ionic compounds4. *Ecological Chemistry and Engineering S, 20*(3), 449–461. https://doi.org/10.2478/eces-2013-0033

Önder, E., Koparal, A. S., & Öğütveren, Ü. B. (2007). An alternative method for the removal of surfactants from water: Electrochemical coagulation. *Separation and Purification Technology, 52*(3), 527–532. https://doi.org/10.1016/j.seppur.2006.06.006

Osadebe, A. U., Onyiliogwu, C. A., & Okpokwasili, G. C. (2018). Biodegradation of anionic surfactants from oilfield detergents in aquatic systems. *Universal Journal of Microbiology Research, 6*(1), 7–14. https://doi.org/10.13189/ujmr.2018.060102

Pal, A., Pan, S., & Saha, S. (2013). Synergistically improved adsorption of anionic surfactant and crystal violet on chitosan hydrogel beads. *Chemical Engineering Journal, 217*, 426–434. https://doi.org/10.1016/j.cej.2012.11.120

Palmer, M., & Hatley, H. (2018). The role of surfactants in wastewater treatment: Impact, removal and future techniques: A critical review. In *Water Research* (Vol. 147, pp. 60–72). Elsevier Ltd.. https://doi.org/10.1016/j.watres.2018.09.039

Parhizgar, F., Alishahi, A., Varasteh, H., & Rezaee, H. (2017). Removing sodium dodecyl benzene sulfonate (sdbs) from aqueous solutions using chitosan. *Journal of Polymers and the Environment, 25*(3), 836–843. https://doi.org/10.1007/s10924-016-0855-7

Pham, T. D., Kobayashi, M., & Adachi, Y. (2015). Adsorption of anionic surfactant sodium dodecyl sulfate onto alpha alumina with small surface area. *Colloid and Polymer Science, 293*(1), 217–227. https://doi.org/10.1007/s00396-014-3409-3

Prediger, P., Cheminski, T., de Figueiredo Neves, T., Nunes, W. B., Sabino, L., Picone, C. S. F., Oliveira, R. L., & Correia, C. R. D. (2018). Graphene oxide nanomaterials for the removal of non-ionic surfactant from water. *Journal of Environmental Chemical Engineering, 6*(1), 1536–1545. https://doi.org/10.1016/j.jece.2018.01.072

Priyanka, K., Behera, M., & Neelancherry, R. (2020). Graywater treatment in sequencing batch reactor using simultaneous nitrification, denitrification, and phosphorus removal, with kinetic studies of phosphate adsorption onto corncob. *Journal of Hazardous, Toxic, and Radioactive Waste, 24*(3), 04020017. https://doi.org/10.1061/(ASCE)

Rahman, R. O. A., El-Kamash, A. M., & Hung, Y. T. (2022). Applications of nano-zeolite in wastewater treatment: an overview. *Water MDPI, 14*(2). https://doi.org/10.3390/w14020137

Ramírez-Arias, A. M., Moreno-Piraján, J. C., & Giraldo, L. (2020). Adsorption of Triton X-100 in aqueous solution on activated carbon obtained from waste tires for wastewater decontamination. *Adsorption, 26*(2), 303–316. https://doi.org/10.1007/s10450-019-00157-8

Roy, H., Prantika, T. R., Riyad, M. H., Paul, S., & Islam, M. S. (2022). Synthesis, characterizations, and RSM analysis of Citrus macroptera peel derived biochar for textile dye treatment. *South African Journal of Chemical Engineering, 41*, 129–139. https://doi.org/10.1016/j.sajce.2022.05.008

Sathe, S. M., Bhowmick, G. D., Dubey, B. K., & Ghangrekar, M. M. (2020). Surfactant removal from wastewater using photo-cathode microbial fuel cell and laterite-based hybrid treatment system. *Bioprocess and Biosystems Engineering, 43*(11), 2075–2084. https://doi.org/10.1007/s00449-020-02396-4

Schuricht, F., Borovinskaya, E. S., & Reschetilowski, W. (2017). Removal of perfluorinated surfactants from wastewater by adsorption and ion exchange — Influence of material properties, sorption mechanism and modeling. *Journal of Environmental Sciences, 54*, 160–170. https://doi.org/10.1016/j.jes.2016.06.011

Scott, M. J., & Jones, M. N. (2000). The biodegradation of surfactants in the environment. *Biochimica et Biophysica Acta (BBA) - Biomembranes, 1508*(1-2), 235–251.

Sen, T. K., Thi, M. T., Afroze, S., Phan, C., & Ang, M. (2012). Removal of anionic surfactant sodium dodecyl sulphate from aqueous solution by adsorption onto pine cone biomass of pinus radiate: Equilibrium, thermodynamic, kinetics, mechanism and process design. *Desalination and Water Treatment, 45*(1–3), 263–275. https://doi.org/10.1080/19443994.2012.692036

Serejo, M. L., Farias, S. L., Ruas, G., Paulo, P. L., & Boncz, M. A. (2020). Surfactant removal and biomass production in a microalgal-bacterial process: Effect of feeding regime. *Water Science and Technology, 82*(6), 1176–1183. https://doi.org/10.2166/wst.2020.276

Shami, S., Dash, R. R., Verma, A. K., Dash, A. K., & Pradhan, A. (2020). Adsorptive removal of surfactant using dolochar: A kinetic and statistical modeling approach. *Water Environment Research, 92*(2), 222–235. https://doi.org/10.1002/wer.1193

Singh, N., Hu, X. H., Kumar, V., Solanki, M. K., Kaushik, A., Singh, V. K., Singh, S. K., Yadav, P., Singh, R. P., Bhardwaj, N., Wang, Z., & Kumar, A. (2024). Microbially derived surfactants: an ecofriendly, innovative, and effective approach for managing environmental contaminants. *Frontiers in Bioengineering and Biotechnology, 12*. https://doi.org/10.3389/fbioe.2024.1398210

Siyal, A. A., Rashid Shamsuddin, M., Rabat, N. E., Zulfiqar, M., Ayoub, M., & Azizli, K. A. (2018). Removal of anionic surfactant sodium dodecylbenzenesulfonate from water using fly ash adsorbent. *IOP Conference Series: Materials Science and Engineering, 458*(1). https://doi.org/10.1088/1757-899X/458/1/012043

Siyal, A. A., Shamsuddin, M. R., Low, A., & Rabat, N. E. (2020). A review on recent developments in the adsorption of surfactants from wastewater. *Journal of Environmental Management, 254*. https://doi.org/10.1016/j.jenvman.2019.109797

Siyal, A. A., Shamsuddin, M. R., Rabat, N. E., Zulfiqar, M., Man, Z., & Low, A. (2019). Fly ash based geopolymer for the adsorption of anionic surfactant from aqueous solution. *Journal of Cleaner Production, 229*, 232–243. https://doi.org/10.1016/j.jclepro.2019.04.384

Solińska, A., Marchewka, J., Sitarz, M., & Bajda, T. (2023). Infrared spectroscopy: the key to elucidating the sorption mechanism of surfactants, dyes and pharmaceuticals on mineral composite material. *Spectrochimica Acta - Part A: Molecular and Biomolecular Spectroscopy, 299*. https://doi.org/10.1016/j.saa.2023.122758

Sophia, A., & C., and Lima, E. C. (2018). Removal of emerging contaminants from the environment by adsorption. *Ecotoxicology and Environmental Safety, 150*, 1–17. https://doi.org/10.1016/j.ecoenv.2017.12.026

Šostar-Turk, S., Petrinić, I., & Simonič, M. (2005). Laundry wastewater treatment using coagulation and membrane filtration. *Resources, Conservation and Recycling, 44*(2), 185–196. https://doi.org/10.1016/j.resconrec.2004.11.002

Sriram, A. (2019). Removal of solids from surfactant wastewater through synergetic utilization of strychnos potatorum and colocasia esculenta. *Desalination and Water Treatment, 156*, 357–369. https://doi.org/10.5004/dwt.2019.24142

Stubbs, S., Yousaf, S., & Khan, I. (2022). A review on the synthesis of bio-based surfactants using green chemistry principles. *DARU Journal of Pharmaceutical Sciences, 30*(2), 407–426. https://doi.org/10.1007/s40199-022-00450-y

Suárez, L., Díez, M. A., García, R., & Riera, F. A. (2012). Membrane technology for the recovery of detergent compounds: A review. *Journal of Industrial and Engineering Chemistry, 18*(6), 1859–1873. https://doi.org/10.1016/j.jiec.2012.05.015

Szabó-Bárdos, E., Zsilák, Z., & Horváth, O. (2008). Photocatalytic degradation of anionic surfactant in titanium dioxide suspension. Colloids for nano- and biotechnology. *Progress in Colloid and Polymer Science, 135*, 21–28. https://doi.org/10.1007/2882_2008_096

Taffarel, S. R., & Rubio, J. (2010). Adsorption of sodium dodecyl benzene sulfonate from aqueous solution using a modified natural zeolite with CTAB. *Minerals*

Engineering, 23(10), 771–779. https://doi.org/10.1016/j.mineng.2010.05.018
Touny, A. H., Abd El-Lateef, H. M., & Saleh, M. M. (2019). Removal of cationic surfactants from dilute solutions using nanoporous nickel phosphate: A structural, kinetic and thermodynamic study. *Journal of Molecular Liquids, 283*, 30–38. https://doi.org/10.1016/j.molliq.2019.03.032
Tripathi, S. K., Tyagi, R., & Nandi, B. K. (2013). Removal of residual surfactants from laundry wastewater: A review. *Journal of Dispersion Science and Technology, 34*(11), 1526–1534. https://doi.org/10.1080/01932691.2012.752328
Turk, S. Š., Petrinić, I., & Simonič, M. (2005). Laundry wastewater treatment using coagulation and membrane filtration. *Resources, Conservation and Recycling, 44*(2), 185–196. https://doi.org/10.1016/j.resconrec.2004.11.002
Turyasingura, M., Wakatuntu, J., Lubwama, M., Jjagwe, J., Hensel, O., & Olupot, P. W. (2023). Optimisation of eggshell-zeolite composite as a potential surfactant adsorbent for hand-washing wastewater. *Case Studies in Chemical and Environmental Engineering, 7*. https://doi.org/10.1016/j.cscee.2022.100284
Valizadeh, S., Younesi, H., & Bahramifar, N. (2016). Highly mesoporous K2CO3 and KOH/activated carbon for SDBS removal from water samples: Batch and fixed-bed column adsorption process. *Environmental Nanotechnology, Monitoring & Management, 6*, 1–13. https://doi.org/10.1016/j.enmm.2016.06.005
Vinardell, S., Astals, S., Mata-Alvarez, J., & Dosta, J. (2020). Techno economic analysis of combining forward osmosis reverse osmosis and anaerobic membrane bioreactor technologies for municipal wastewater treatment and water production. *Bioresource Technology, 297*, 122395. https://doi.org/10.1016/J.BIORTECH.2019.122395
Visa, M., & Duta, A. (2013). TiO2/fly ash novel substrate for simultaneous removal of heavy metals and surfactants. *Chemical Engineering Journal, 223*, 860–868. https://doi.org/10.1016/j.cej.2013.03.062
Visa, M., Isac, L., & Duta, A. (2015). New fly ash TiO2 composite for the sustainable treatment of wastewater with complex pollutants load. *Applied Surface Science, 339*(1), 62–68. https://doi.org/10.1016/j.apsusc.2015.02.159
Wang, S., & Wang, J. (2019). Activation of peroxymonosulfate by sludge-derived biochar for the degradation of triclosan in water and wastewater. *Chemical Engineering Journal, 356*, 350–358. https://doi.org/10.1016/j.cej.2018.09.062
Wu, S. H., & Pendleton, P. (2001). Adsorption of anionic surfactant by activated carbon: Effect of surface chemistry, ionic strength, and hydrophobicity. *Journal of Colloid and Interface Science, 243*(2), 306–315. https://doi.org/10.1006/jcis.2001.7905
Wysokowska, K., Cupiał, Z., Staszak, M., Zgoła-Grześkowiak, A., Koziolek, J., Ławniczak, Ł., Wysokowski, M., & Wyrwas, B. (2024). Photocatalytic degradation of non-ionic, anionic, and cationic surfactants: From batch experiments through equilibrium/kinetic study to ecotoxicology analysis. *Chemical Papers, 78*(2), 761–777. https://doi.org/10.1007/s11696-023-03117-3
Xiao, J. X., Zhang, Y., Wang, C., Zhang, J., Wang, C. M., Bao, Y. X., & Zhao, Z. G. (2005). Adsorption of cationic-anionic surfactant mixtures on activated carbon. *Carbon, 43*(5), 1032–1038. https://doi.org/10.1016/j.carbon.2004.11.039
Xiarchos, I., Doulia, D., Gekas, V., & Trägårdh, G. (2003). Polymeric ultrafiltration membranes and surfactants. *Separation and Purification Reviews, 32*(2), 215–278. https://doi.org/10.1081/SPM-120026628
Zakaria, N. A. S., Goh, P. S., Lau, W. J., Ismail, A. F., & Samavati, Z. (2025). Membrane technology for laundry wastewater treatment: Recent progresses and future outlook. *Separation and Purification Reviews, 1–20*. https://doi.org/10.1080/15422119.2025.2451984
Zambianchi, M., Durso, M., Liscio, A., Treossi, E., Bettini, C., Capobianco, M. L., Aluigi, A., Kovtun, A., Ruani, G., Corticelli, F., Brucale, M., Palermo, V., Navacchia, M. L., & Melucci, M. (2017). Graphene oxide doped polysulfone membrane adsorbers for the removal of organic contaminants from water. *Chemical Engineering Journal, 326*, 130–140. https://doi.org/10.1016/j.cej.2017.05.143
Zanoletti, A., Federici, S., Borgese, L., Bergese, P., Ferroni, M., Depero, L. E., & Bontempi, E. (2017). Embodied energy as key parameter for sustainable materials selection: The case of reusing coal fly ash for removing anionic surfactants. *Journal of Cleaner Production, 141*, 230–236. https://doi.org/10.1016/j.jclepro.2016.09.070
Zhang, C., Wen, H., Huang, Y., & Shi, W. (2017). Adsorption of anionic surfactants from aqueous solution by high content of primary amino crosslinked chitosan microspheres. *International Journal of Biological Macromolecules, 97*, 635–641. https://doi.org/10.1016/j.ijbiomac.2017.01.088
Zhang, H., Quan, X., Chen, S., Zhao, H., & Zhao, Y. (2006). The removal of sodium dodecylbenzene sulfonate surfactant from water using silica/titania nanorods/nanotubes composite membrane with photocatalytic capability. *Applied Surface Science, 252*(24), 8598–8604. https://doi.org/10.1016/j.apsusc.2005.11.090
Zhao, H., Helgason, A., Leng, R., Chowdhury, S., Clermont, N., Dinh, J., Aldebasi, R., Zhang, X., Gattrell, M., Lockhart, J., & Hamza, H. (2024). Removal of microplastics/microfibers and detergents from laundry wastewater by microbubble flotation. *ACS ES&T Water, 4*(4), 1819–1833. https://doi.org/10.1021/acsestwater.3c00802
Zhou, X., Liang, J. T., Andersen, C. D., Cai, J., & Lin, Y. Y. (2018). Enhanced adsorption of anionic surfactants on negatively charged quartz sand grains treated with cationic polyelectrolyte complex nanoparticles. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 553*, 397–405. https://doi.org/10.1016/J.COLSURFA.2018.05.079

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.