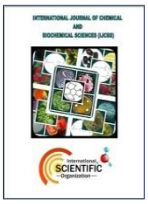
International Journal of Chemical and Biochemical Sciences
(ISSN 2226-9614)

Journal Home page: www.iscientific.org/Journal.html

© International Scientific Organization



Use of κ-Carrageenan-Based Nanocomposites for The Removal of Dyes from Wastewater: A Review

Laiba Muneer[1], Rida A. Shibli*[,2]

[1]Department of Chemistry, University of Agriculture Faisalabad, Pakistan.

[2]Plant Biotechnology Laboratory, Hamdi Mango Research Centre, The University of Jordan, Amnan, Jordan.

Abstract

Dye contamination of water is a worldwide environmental and health issue which calls for the development of efficient and environment friendly innovation. Adsorption has surpassed the others due to its great effectiveness, affordability, and ease of use. This review provides new adsorbent materials made from κ-carrageenan to remove heavy metals and dyes from wastewater bodies. The biodegradable red-seaweed polysaccharide κ-carrageenan shows enhanced mechanical strength, adsorption capacity, and chemical stability when combined with inorganic nanoparticles. It has both intrinsic gelation and a high degree of functional groups. With a focus on electrostatic forces of attraction, ion exchange, and complexation mechanisms, we critically assess preparation routes, structural features, and adsorption behaviors while highlighting advancements in field-use regenerability and readiness. Even so, operability is still constrained by a lack of field-scale or pilot experiments on real industrial wastes, regeneration efficiency, quantitative deconvolution of removal mechanisms, and long-term stability over a range of ionic strength, pH, and mixed-pollutant streams, as well as fluctuating testing procedures that make cross-study comparisons challenging. To close these crucial gaps and shift laboratory success into practical, expand wastewater treatment methods, standardized procedures, thorough mechanistic and economic studies, and field testing are required.

Keywords: Wastewater treatment, k-carrageenan base nanocomposites, dyes adsorption, k-carrageenan hydrogels

Full length article **Corresponding Author*, e-mail: r.shibli@ju.edu.jo, *Doi #* https://doi.org/10.62877/7-IJCBS-26-29-23-7
Submitted: 22-01-2026; Accepted: 10-04-2026; Published: 11-04-2026

1. Introduction

In 2022, 42% of residential water (approximately 133 billion per m^3) was not treated safely, due to which 2.2 billion people faced limited access to safely managed drinking water [1]. In the future, urbanization, population growth, and the expansion of agriculture and industry are expected to produce a 20–30% increase in the world's water consumption by 2050 [2]. Concurrently, by 2050 wastewater production is expected to increase by ~50% [3]. Industrial waste from electronic devices, mining, pharmaceuticals, chemicals, cosmetics, dyes, paints and paper printing are various sources from which waste pollutants are dumped in wide range [4]. Due to their detrimental effects on both human health and water quality, synthetic dyes and heavy metals in water sources have become a major worldwide concern. Many industries, including textiles, paper, plastics, leather, and cosmetics, heavily rely on dyes [5]. The chemicals are mostly dumped untreated into water bodies, which has detrimental consequences on the ecosystem and human health. At low quantities, synthetic dyes have strong colors that alter the water's aesthetic appeal and interfere with light penetration, which initiates aquatic photosynthesis and upsets the ecosystem's equilibrium [6]. Furthermore, dyes are frequently carcinogenic, poisonous, and mutagenic, posing grave risks to human and aquatic health [7]. A number of traditional techniques such as coagulation, precipitation, distillation, evaporation, oxidation, reverse osmosis, electrolysis, ion exchange, filtration, and adsorption can be used to eliminate toxic contaminants from wastewater [8].

Despite being widely utilized, traditional wastewater treatment techniques have a number of drawbacks that affect their sustainability and effectiveness. precipitation, which struggles with low pollutant concentrations but turns dissolved pollutants into solids, produces a lot of sludge, and requires stringent pH control [9]. Natural polymers are renewable, biodegradable, and non-toxic, so they are also very beneficial in the treatment of wastewater [10]. Polymers including κ-carrageenan, chitosan and alginate, and are non-toxic and pose little to no ecological risks. They can be obtained from readily available resources including plants, animals, and algae [11]. Moreover, natural polymers can be easily modified or combined with nanomaterials to improve their adsorption capacity & mechanical stability. Supporting sustainable water treatment and green chemistry principles, they are good substituents for synthetic materials [12]. The sulfated polysaccharide carrageenan, that originates from marine red algae, has variety of beneficial characteristics and structures [13]. Kappa (k)-carrageenan is a particular sort of carrageenan that has a structural makeup characterized by alter moieties. This type of arrangement results in the presence of one negative charge per repeating disaccharide unit, which contributes to unique physicochemical properties and functional characteristics of k-carrageenan. 3-linked b-D-galactose 4-sulfate and 4-linked 6-anhydro a-galactopyranose units within its repeating disaccharide Figure 1 [14]. Nanocomposite of κ-Carrageenan adsorbents have exhibited significant future in treatment of wastewater, especially in adsorption of heavy metals and poisonous dyes [15].

However, its native configuration will show reduced stability and mechanical qualities for industrial use [16]. κ-carrageenan is likely to combine with a broad range of nanomaterials, such as metal oxides, magnetic nanoparticles, graphene oxide and carbon nanotubes, to create physiochemically enhanced nanocomposites [17]. Because of the porosity, larger surface area and abundance of distinct active sites of hybrids, they may exhibit enhanced adsorption capacity [18]. The removal of most dyes and heavy metal ions is effective because of the synergy between the nanomaterials and κ-carrageenan, which promotes many adsorption techniques, such as ion exchange, surface complexation, hydrogen bonding and electrostatic contact [19]. Their multifunctionality, biodegradability and high efficiency make them ideal choices for environmental friendly wastewater treatment systems at a time when demand are pushing for more efficient and environmental friendly pollution clean-up solutions [20]. Even though for wastewater treatment κ-carrageenan-based nanocomposites have advanced remarkable, large-scale applications remain unattainable due to enormous gulf-like obstacles. The primary objective of this paper is to give a comprehensive overview of the synthesis, characteristics, and adsorption efficiency of κ-carrageenan-based nanocomposite materials for waste water treatment. Its purpose is to examine cooperative impact of combining κ-carrageenan with other nanomaterials in an effort to improve surface area structural stability, and adsorption capacity.

2. Synthesis of k-carrageenan nanocomposites

2.1. Preparation methods

A crucial method for creating sustainable water treatment materials is the formation of κ-carrageenan-based nanocomposites, which reveal the special physicochemical characteristics of the biopolymer. The procedure known as sol-gel is extremely flexible method for synthesizing κ-carrageenan nanocomposites, offering precise control over the material properties relevant to various applications, including effluent treatment, biomedical uses, and food packaging. To produce hybrid materials with improved thermal, functional and mechanical qualities, it combines biopolymers, such as κ-carrageenan, along with natural (like chitosan), synthetic (like polyvinyl alcohol, PVA), and inorganic nanoparticles (like ZnO and MgO) [21]. Based on the initial hydrolysis of metal oxide precursors, the sol-gel preparation kinetics comprises of three simple reaction stages. These procedures consistently manage the development of the inorganic network inside the polymer matrix; hydroxylated monomers subsequently condense to produce colloidal particles (sol) and oligomers; the gelation process, in which colloidal particles attach together through continuous condensation to form a three-dimensional gel network, reaches its peak [22].

The κ-carrageenan network functions as both an active substrate and a structural matrix for the inclusion of monomers in the in-situ type of polymerization synthesis of κ-carrageenan nanocomposites, which rely on the in situ commencement of the polymerization reaction within the biopolymer matrix to produce hybrid materials with synergistic characteristics [23]. This technique uses hydroxyl bonding and κ-carrageenan sulfate to initiate polymerization, stabilize nanoparticles, and regulate composite morphology in inorganic phases (such as metal oxides, silica, clay,) or artificial polymers (such as polyaniline, polyvinyl alcohol, polyacrylamide) that organize at a molecular level. Greater interfacial adhesion, improved filler dispersion, and preserved bioactivity are just a few of the benefits of in-situ polymerization over sol-gel. It may even be possible to precisely engineer mechanical, thermal, electrical, and stimulus-responsiveness by varying the crosslink density, monomer applied, and polymerization situations (e.g., UV curing, redox initiation) [24]. Due to the κ-carrageenan's biocompatibility and the regulated performance of synthetic polymer these nanocomposites function well in separation membranes [25].

The creation of κ-carrageenan nanocomposites is a significant advancement in creation of efficient adsorption substances for wastewater treatment because κ-carrageenan interacts well with both organic and inorganic pollutants, giving it high adsorption capacity for elimination of of positively charged contaminants while guaranteeing excellent balance in an aqueous medium [26]. Depending on their required qualities for elimination of particular wastes from water, a variety of nanomaterials, including clay nanoparticles (e.g., MMT, bentonite) & metal oxide nanoparticles (e.g., ZnO, Fe_3O_4, CuO, SiO_2), are present for strengthening κ-carrageenan [27]. κ-Carrageenan nanocomposites are not cheap, however they are reasonably priced when compared to the majority of high-performance adsorbent materials [28]. Red seaweed is natural source of κ-carrageenan, is abundant, renewable, & very inexpensive [29]. Preparation of these nanoparticles is exceedingly costly, particularly if tight structural control or high purity needed [30]. Conversely, κ-carrageenan nanocomposites possess biocompatibility, superior adsorption performance, and functional tunability, which has ability to counteract higher costs of material by achieving lower doses, reusability, or better contamination removal efficiency [31]. Nanomaterials' cost-competitiveness in comparison to conventional methods can be further increased by implementing less costly synthesis pathways and optimizing loadings (Figure 2).

2.2. Physical and chemical functionalization of k-carrageenan for increased adsorption

An important stage in the creation of efficient adsorbent substances for wastewater treatment is the modification of κ-carrageenan. In wastewater treatment, surface modification of κ-carrageenan is an efficient way to increase the adsorption capability for all types of contaminants. The κ-carrageenan biopolymer's hydroxyl-infused structure enables crosslinking, and chemical affixation (such as acrylic acid for enhanced dye adsorption) while its structural features, which are accompanied with negatively charged sulfate (OSO_3) groups, encourage electrostatic interactions with cations and polyelectrolytes [32]. These structural-driven changes give materials the intended stimuli-responsive, mechanical, and adsorptive qualities making the κ-Carrageenan platform for water treatment membranes. Gülcan Geyik et al. (2023) reported in their work a narrative approach to improve the functional properties of κ-carrageenan by grafting poly (2-hydroxypropyl methacrylamide) (HPMA) onto its outermost layer using a microwave-assisted technique. Associated polymers with improved hydrophilicity, pH-sensitive swelling ability and improved thermal stability were produced by the graft reaction, which was started by ACPA under microwave radiation. Additionally, κ-carrageenan limitations including brittleness, low mechanical strength, and more syneresis are satisfactorily addressed by this chemical alteration [33]. Carrageenan/natural polymer blends are becoming more popular for the creation of novel biodegradable polymers with enhanced adsorption.

Additionally, the removal of nanoparticles such as Fe_3O_4 or TiO_2 is accelerating photocatalytic degradation and magnetic separability. Hybrid materials have more than one functions i.e. large-scale platforms for sustainable wastewater treatment because they have strong reusability, environmental compatibility and pH stability. Giulia Rando et al. reported in their studies a thorough analysis of hybridized κ-carrageenan based bio-based hydrogels with specific biopolymers to improve wastewater treatment efficiency [34]. In order to improve the structure, sensitivity and selectivity of hydrogel systems, the paper also highlights the possibility of co-polymerizing or cross-linking κ-carrageenan with different biomacromolecules (cellulose, alginate, chitosan) or modification using nanoparticles (TiO_2, graphene oxide, and MOFs). These hybridization techniques greatly improve the structural stability, adsorption sensitivity, and environmental selectivity, making κ-carrageenan-based hybrid hydrogels competitive for affordable, environmentally friendly wastewater treatment methods. Furthermore, the addition of titanium dioxide and magnetite nanoparticles to κ-carrageenan matrices provides photocatalytic degradability and magnetic separability, respectively. These hybrid hydrogel systems become viable and incredibly flexible scale-up substances for wastewater purification procedures because they exhibit higher pollutant selectivity, regeneration ability, and structural stability, than virgin hydrogels [35].

3. Dyes adsorption on k-carrageenan nanocomposites

3.1. Adsorption

Adsorption is the most effective method for removing contaminants from polluted water, and it has been thoroughly studied. Due to the adsorbent's high surface energy, various molecules are pulled to it through a variety of physical or chemical interactions [36]. The literature claims that there are two types of adsorptions: chemical and physical. It differs based on the type of adsorbent or adsorbate and depends on the nature of the interaction between the two. In addition to feeble bonding like electrostatic, Vander-Waals, π-π, and hydrogen interactions, physical adsorption has lower energy demands (5–40 kJ/mol) [37]. Electron transport, redox, and ligand/ion exchange are all connected to chemical adsorption. Compared to physical interactions, these interactions require more energy (40–800 kJ/mol), making them more challenging to achieve [38]. The structural properties of adsorbates are particularly important because some dyes have molecules that differ in size and structure. The researchers have separated the different classes of nanomaterials into two groups: magnetic and non-magnetic nanoparticles. Rare earth metals from wastewater have been adsorbed using these nanoparticles. Additionally, a different group of researchers looked into zeolites, metal nano-adsorbents, polymeric nano-adsorbents, & carbon nanotubes as carbon nano-adsorbents for wastewater decontamination [39]. The disadvantage of nano-adsorbents was highlighted in relation to their toxicity and therapeutic application. However, the bio-based product has clear positive effects because it is non-toxic, biodegradable, and biocompatible. The study demonstrated the limitations and potential areas for development related to these types of adsorbents. Therefore, the removal of dyes using composite adsorbents based on κ-carrageenan is the main focus of this section.

3.2. Factors influencing adsorption of carrageenan-dependent adsorbents

Carrageenan's employment as an ingredient in many different sectors is reflected in some of its most significant characteristics. Because of their many qualities, including thixotropy, high water stability, solubility, non-toxicity, biocompatibility, protein reactivity, surface modification, binding strength, gelling ability, viscosity, and compatibility with other gums, they are employed at a large scale of applications. The second distinguishing property is carrageenan's enormous propensity to swell in water [40]. Among the characteristics of κ-carrageenan are its solubility, swelling qualities, acid stability, ionicity, and surface functionalization. In terms of solubility, carrageenan dissolves slowly at room temperature (298 K) and forms pseudoplastic solutions, although it dissolves readily in solvents which are highly polar, and the most common is water [41]. Because Na ions and gelling cations mostly interact with each other on limited dissolution and hydration, it is interesting to note that both κ-carrageenan and l-carrageenan in form of sodium salt show high solubility in fact at period of gelation. In terms of acid stability, it often seems that at low pH (4.3), carrageenan solution reduces its gel strength and viscosity because of autohydrolysis, which divides molecules into 3.6 anhydrogalactose units in the form of acid. The pace of autohydrolysis is accelerated to a certain extent by availability of cations and elevated temperatures. A study found that after cooling, gels containing 0.2% KCl solutions and 0.5% κ-carrageenan lost around 25% of their original strength. Gel processing times were shown to be impacted by changes in pH and temperature [42].

Carrageenan's adsorption behavior is mostly caused by its anionic nature, which interacts with dyes of cationic nature just as crystal violet and methylene blue to synthesize balanced complexes. Strong electrostatic attractions between dyes and the substance give its high adsorption capacity to carrageenan [43]. It can be inferred that adsorbents based on l-carrageenan possess a higher adsorption capability than adsorbents based on κ-carrageenan because l-carrageenan has a higher sulfate concentration than k-carrageenan. While κ-carrageenan also generated high capacities, l-carrageenan is more anionic due to its higher sulfate concentration, which enhances its interaction with the dyes of cationic nature and produces a high adsorption capacity [44]. In recent decades, nanoparticles in particular have been thoroughly investigated as a way to remove contaminants or dyes from water. Carrageenan is a biodegradable and biocompatible polysaccharide that can be used to create a non-toxic modified nanoparticle for color removal [45]. The carrageenan coating has no effect on the nanoparticle's form. After being coated with κ-carrageenan, Fe3o4 nanoparticles remain spherical [44]. Agglomerates could be caused by a κ-carrageenan coating [43]. Following adsorption of carrageenan on nanomaterial's surface, κ-carrageenan coating changes nanoparticles' zeta potential value, increasing their negative zeta potential. Because of its strong affinity for cationic dye, coating improves the adsorption process [46].

4. K-carrageenan based adsorbents

κ-carrageenan composites can be broadly classified into numerous classes, in which magnetic nano-adsorbents have the large research investigations, according to a thorough analysis of the data from the literature. When added to nanoparticles like graphene oxide, bentonite, TiO_2, or Fe_2O_4, κ-carrageenan's due to its hydrophilic sulfate groups enable efficient adsorption of water and improve the mechanical ruggedness of hydrogel based matrix, active sites, and surface area [47]. Other studies show that due to increased contaminant penetration into the hydrogel network, higher swelling ratios will ensure more dye adsorption, mainly cationic or anionic dyes [48]. Incorporating nanoparticles into the matrix based on carrageenan can control swelling by hardness creation or crosslinking, which reduces most swelling but improves stability and selectivity in challenging circumstances [49]. For instance, κ-carrageenan/graphene oxide-based hydrogels exhibit acceptable swelling but unmatched π-π and electrostatic attachment adsorption efficiency [48]. Generally speaking, swelling is a crucial characteristic that influences how well carrageenan-derived nanocomposite hydrogels work, but its relationship to other physicochemical characteristics like porosity, strength, and surface charge should also be carefully managed for other wastewater treatment technologies [50].

To increase the adsorption capacity of κ-carrageenan nanocomposites in the elimination of dyes from aqueous solutions, a variety of nanoparticles have been added (Table 1). TiO_2, ZnO, Fe_3O, and Al_2O_3 are the most commonly used metal oxide nanoparticles because of their large surface area, active surface functional groups that can interact with the contaminants and chemical stability [47]. Fe_3O_4 magnetic nanoparticles are particularly useful because by using an external magnetic field they make it easy to separate the adsorbent from processed water. Additionally, gold (Au) and silver (Ag) nanoparticles are added to the hydrogel matrix for mechanical strengthening and antibacterial properties. Because of their increased adsorption capacity and , surface area per unit weight, carbon nanomaterials including graphene oxide (GO) and carbon nanotubes (CNTs) are used to effectively bind dye molecules [51]. The hydrogel's mechanical strength and swelling capacity are further improved by the reciprocal addition of κ-carrageenan along with the nanomaterials, which also greatly increases the hydrogel's sorption activity. This makes κ-carrageenan-based nanocomposites suitable for effective and green polluted water treatment processes [52].

4.1. k-carrageenan-based magnetic nano-adsorbents

This section covers a few κ-carrageenan nano-adsorbents based on different Fe_3O_4 magnetic nanoparticles that are utilized for the adsorption of various hues. The properties of magnetic adsorbents include superparamagnetic behavior, wide surface area, and non-toxicity. The most crucial factor in improving nano-adsorbent diffusion is recovery following adsorption. When adsorption completes, magnetic adsorbents can be easily and successfully retrieved by applying an external magnetic field with a bar magnet [52]. To remove Eriochrome Black-T dye from solutions, researchers created mCh/κ-carrageenan, a magnetic bio-adsorbent chitosan/κ-carrageenan. The magnetic bio-adsorbent was produced by the in-situ precipitation of iron ions with different molecular weights in the availability of chitosan (Ch). κ-carrageenan was used as a crosslinker with atleast two concentrations (0.2 g and 0.4 g) to synthesize the chitosan/κ-carrageenan magnetic bio-adsorbent. Samples with different concentrations were then made. According to TEM pictures, the sample with a large quantity of chitosan content had the greatest average size of Fe_3O_4 nanoparticles, measuring 52.3μm [53]. Another work detailed the development of chitosan-crosslinked magnetic carrageenan-based bio-nanoadsorbent for the in situ coprecipitation method of removing methylene blue from solution. They initially coprecipitated iron (III) or iron (II) in situ when carrageenan was available in order to produce magnetic carrageenan. Chitosan crosslinking came next SEM images of the bio-nanoadsorbent demonstrated how the various chitosan and Fe ion concentrations affected the adsorbent's form. It was believed that shapeless nanoparticles' concentration, which showed the presence of Fe_3O_4 nanoparticles on the surface of the adsorbent, was influenced by the quantity of chitosan and magnetite used [46]. A group of researchers created modified silica-coated magnetic nanoadsorbents that were incorporated with functionalized carrageenan in order to adsorb methylene blue present in water. Adsorption capabilities of Fe3O4 nanoparticles, κ-carrageenan-g-Fe_3O_4/SiO_2, Fe_3O_4/SiO_2, and κ-carrageenan-g-Fe_3O_4/SiO_2 nanoadsorbents were examined. The mean diameter of Fe_3O_4 nanoparticles was examined by XRD (X-ray diffraction) to be 9.8 nm. The coating of silica on the Fe_3O_4/SiO_2 nanoparticles was confirmed by the TEM images, which showed that their average diameter was 11.8 nm [44].

4.2. k-carrageenan based hydrogels

Methylene blue which is highly soluble is a model cationic pollutant because carrageenan is anionic. Researchers created κ-carrageenan-based hydrogel beads by copolymerizing κ-carrageenan and poly (glycidyl methacrylate) in which N, N-methylenebisacrylamide is used as a cross-linker. 40% κ-carrageenan content in 60% poly(glycidyl methacrylate) [54]. Malachite green (MG) is one of the hazardous and toxic hues. MG is used to dye paints, printing inks, cotton, silk, paper, and leather. The MG needs to be eliminated from the environment due of its toxicity. Pourjavadi et al. looked into the creation of a novel hydrogel nanocomposite for this reason. They created this hydrogel by graft copolymerizing kappa-CG (κC) with acrylic acid (AA) while a crosslinking material, aminosilica-functionalized TiO2 nanoparticles (κC-g-PAA/TiO_2–NH_2) and free radical initiator were present. The produced hydrogel nanocomposite could be used as an ideal effective adsorbent for the adsorption of MG with a more adsorption capacity (qm = 666–833 (mg/g)), according to the experimental results [55]. Utilizing nano-silver chloride and κ-CG, another nanocomposite hydrogel was prepared by an effective and straightforward method. Cationic dyes were eliminated using the hydrogel nanocomposite. In actuality, an effective dye absorbent was created and used in this investigation to adsorb crystal violet (CV) dye. Reusing the produced hydrogel for nine cycles won't significantly reduce its performance (it will retain more than 60% of its initial activity) (Figure 3) [56].

4.3. Comparing the effectiveness of k-carrageenan based nano-adsorbents with other materials in water treatment

κ-carrageenan-based nanocomposites offer improved potential for water purification in terms of adsorption capacity, environmental friendliness, and selectivity when compared to traditional and new adsorbent materials [57]. Because of their surface area and low cost, conventional materials including activated carbon, clay minerals, and zeolites are used; nevertheless, they usually have poor selectivity, no capacity for regeneration, and reduced effectiveness when interfering ions are present [58]. However, κ-carrageenan nanocomposites, which involves native polysaccharide (hydroxyl, sulfate) functional groups and nanomaterials such as metal oxides (ZnO , Fe_3O_4), biopolymers or carbon materials (graphene oxide) also show more interlinkage with various contaminants through surface complexation, ion exchange and electrostatic attraction [59]. In addition, κ-carrageenan's inherent biocompatibility and biodegradability make it particularly desirable for green water treatment because, in contrast to synthetic polymers, it won't cause secondary pollution [60]. κ-Carrageenan provides a more environmentally friendly option. In addition, depending on the nanoparticle being used, nanomaterials can offer functionality like magnetic separation, photocatalysis, or antimicrobiality in addition to improving adsorption capacity [61]. In conclusion, κ-carrageenan nanocomposites show a special combination of high adsorption capacity, multifunctionality, environmental friendliness, and recyclability while other materials excel in cost, removal of specific contaminants or availability. They are excellent candidates for advance polluted water treatment processes because of their high-performance characteristics in the removal of a variety of pollutants, particularly from mixed water matrices. κ-carrageenan nanocomposites are composed to become a key component in the development of high-performance, environment friendly water treatment methodologies since researchers are constantly improving their preparation process and design [61].

5. Advancement in k-carrageenan based nano-adsorbents

Because κ-carrageenan-based bionanocomposites may remove harmful elements like dyes and antibiotics from polluted water, they are increasingly sought after. Methylene blue, acidic dyes, lead, cadmium, norfloxacin, and other toxic and resistant species can be successfully removed from fluids using κ-carrageenan-based adsorbents, according to recent research published in the literature [62]. Literature show that κ-carrageenan-based compounds efficiently eliminate heavy metals and dyes from synthetic and actual polluted water. Mahdavinia et al. created magnetic composites based on κ-carrageenan for the easy and environmentally friendly removal of methylene blue (MB) from wastewater. Maximum adsorption capacities (Qmax) of 123.1 and 130.4 mg/g were demonstrated by magnetic and non-magnetic adsorbents, respectively [46]. By using gamma irradiation to create pectin/κ-carrageenan composites modified with multi-walled carbon nanotubes (MWCNTs), Aboelkhir et al. (2024) increased the particular surface area from 342.5 to 689.5 m2/g. With an elimination efficiency of 96% for the MWCNTs@PC/KC/PAAc composite at pH 11, the modified composites demonstrated higher MB removal efficiencies. When compared to pure κ-carrageenan, MWCNTs greatly increased adsorption capacity; the outcomes demonstrated the importance of surface changings to increase the adsorption capacities [63]. A biohydrogel made of κ-carrageenan and potato starch was shown by Radoor et al. (2024) for methylene blue selective adsorption (MB) among Rhodamine B (Rh B), crystal violet (CV) and acid orange (AO) with Qmax = 116.1 mg/g.

The selective adsorption of MB cationic dye in a variety of dye systems through adsorption using thin film by the novel biohydrogel has great potential for wastewater treatment. The hydrogel's exceptional recyclability—it maintains 93% efficiency after five cycles—makes it both economically viable and appropriate for long-term use [64]. Yu et al. (2024) created a polydopamine-functionalized pomelo peel powder-polyethyleneimine (PEI)-κ-carrageenan (PPEKC) nanocomposite as another biosorbent for multi-pollutant adsorption. The PPEKC biosorbent demonstrated rapid kinetics and high adsorption capabilities (2016.7 and 1176.6 mg/g for Congo red-CR and MB, respectively), making it a viable sorbent option for prolonged contaminated water treatment. It was shown that selective adsorption using hydrogen bonding, electrostatic interactions, π-π was facilitated by the pH-controlled surface charge200 [65]. According to a recent study, adding N-doped carbon dots and Fe_3O_4 magnetic nanoparticles to κ-carrageenan shown better adsorption capabilities of 114.6 and 107.6 mg/g for Pb^{2+} and Cu^{2+}, respectively. These adsorbents are good options for actual and industrial wastewater treatment systems because of the enhanced recovery and stability capabilities shown in this study [66].

6. Limitations of k-carrageenan nanocomposites

Although there is increasing curiosity in κ-carrageenan-based nanocomposites for adsorption of heavy metals and dyes from contaminated water, their large-scale applicability and wider practical uses are limited. One of biggest issues is that native κ-carrageenan has comparatively poor mechanical and thermal stability, which can cause structural failure or impair performance under harsh treatment circumstances [67]. While adding nanoparticles may improve these characteristics, incompatibility between the polymer matrix and the inorganic fillers may cause poor dispersion or agglomeration, which will negatively affect adsorption capacity [68]. Furthermore, because κ-carrageenan is extremely hydrophilic, it cannot efficiently adsorb some hydrophobic contaminants, such as certain dyes and organometallic compounds [69]. Another issue that brings up secondary pollution and environmental safety is nanoparticle leaching during processing [70]. κ-carrageenan-based adsorbents' regenerability & recyclability may also be troublesome since many cycles may result in structural fatigue or a decrease of adsorption capability, which raises operating costs. Other important issues are economic viability of producing nanocomposites at industrial scale and the scaling up of synthesis processes.

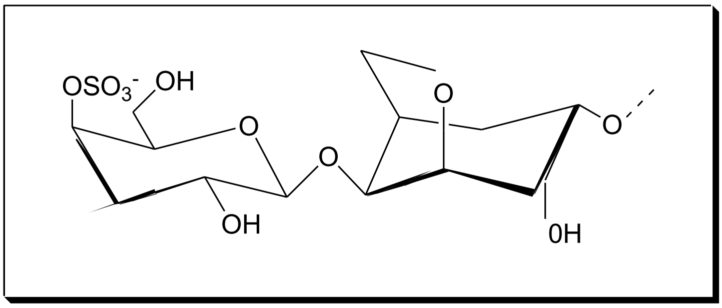


Figure 4. k-carrageenan

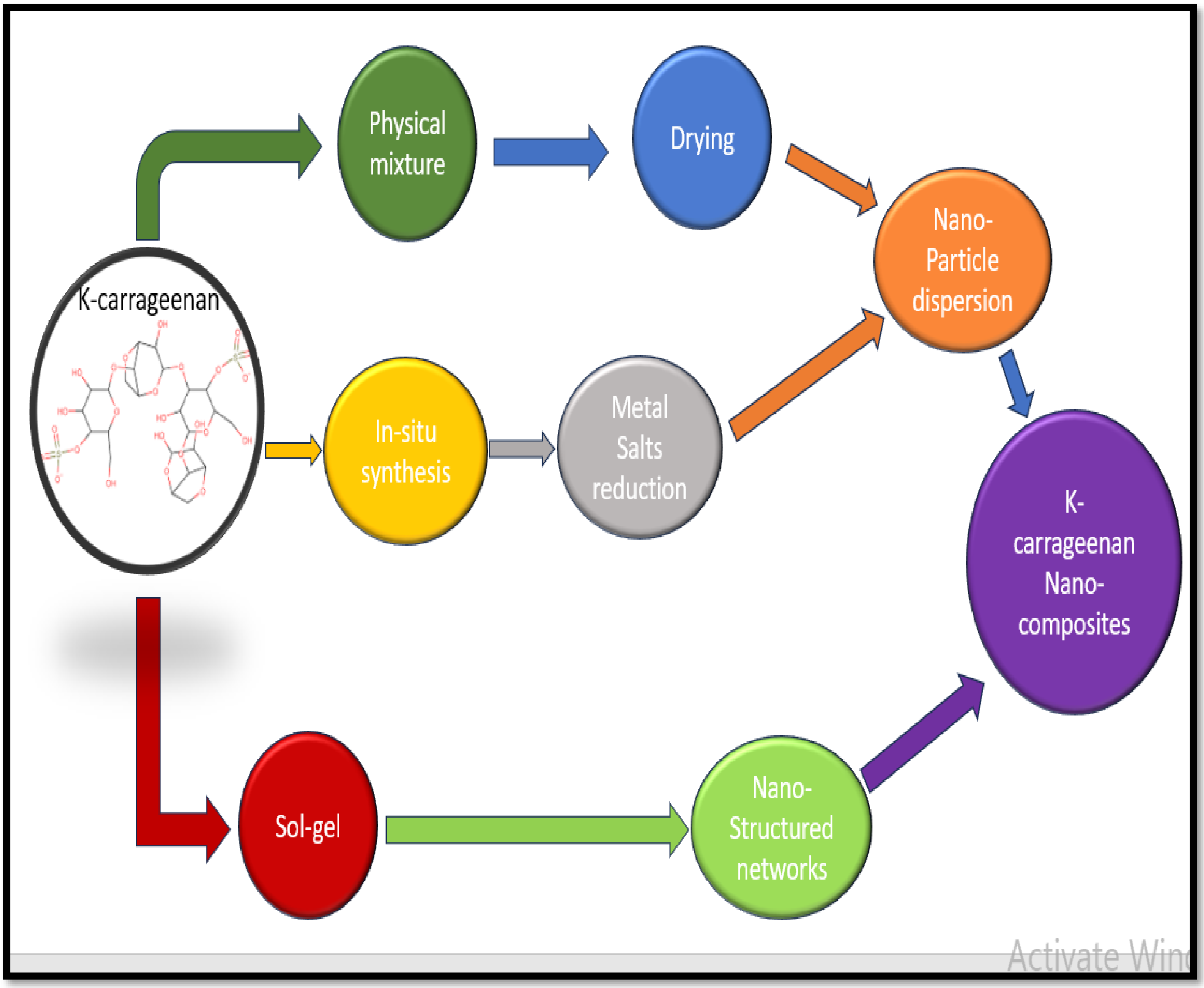


Figure 5. k-carrageenan nanocomposite's synthesis

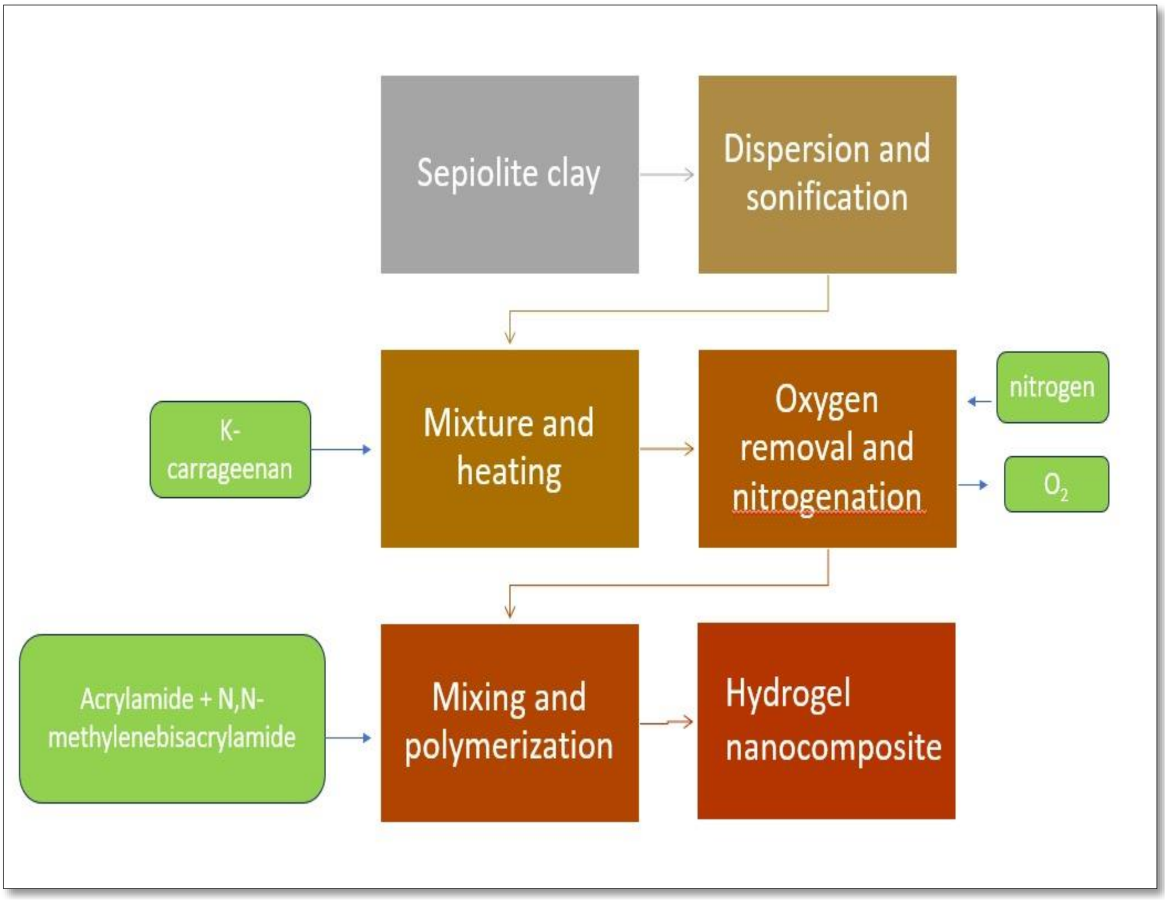


Figure 6. A simple technique for producing a carrageenan-based hydrogel nanocomposite

Table 1. Different kinds of nanoparticles employed in κ-carrageenan-based nanocomposites to remove dyes from wastewater

Type of nanoparticles	Function in nanocomposites	Target pollutants	Benefits
ZnO	Photocatalyst and adsorbent	Metal ions and dyes	Cost-effective, antibacterial, UV-active
CNTs	Improve adsorption and mechanical properties	Organic dyes Pb^{2+}, Cd^{2+}	Conductive, high surface area, porous
TiO_2	Enhances adsorption and degradation, photocatalytic activity	Organic dyes (congo red, methylene blue)	Stable, high surface area
Ag nanoparticles	Structural stabilization and antibacterial property	Microbes and dyes	Enhances durability, antibacterial
Fe_3O_4	Enhances removal efficiency, magnetic recovery	Dyes and heavy metals	Reusability, magnetic separation

Finally, more thorough long-term performance and pilot-scale research and testing under representative conditions are needed to confirm the efficacy of κ-carrageenan composites in real wastewater systems under competing ions, shifting pH, and organic load.

7. Conclusions

Increased knowledge of effective and eco-friendly remediation technology has resulted from the growing demand for dyes and the degradation of water quality caused by heavy metals. This paper critically examined new developments in κ-carrageenan-based nanocomposites as sophisticated advanced adsorbents for water filtration. κ-carrageenan is an ideal component for creating advanced nanocomposites due to its hydrophilicity, biocompatibility, renewability, and abundance of active sulfate functional groups. κ-carrageenan shows remarkable improvements in surface area, adsorptivity and chemical stability when combined with nanoparticles such metal oxides, carbon nanotubes, graphene derivatives, and magnetic materials. Through ion exchange, hydrogen bonding, and electrostatic attraction, hybrid materials effectively desorb a variety of colors and hazardous metal ions. Even while the results are encouraging, a lot of work has only done at laboratory scale thus far, using ideal synthetic wastewaters in a closed system. A few suggestions are made in order to move forward with practical applications. To endure competing ions and matrix complexities, the performance should first be validated against actual industrial effluents. Second, the rate-controlling adsorption processes should be the focus of additional mechanistic studies, such as kinetic and thermodynamic modeling. Third, in order to be economically justified, regeneration and reusability effectiveness over long periods of time must be enhanced. Such a composite should be thoroughly examined for stability under various environmental conditions. In comparison with traditional adsorbents like activated carbon, life-cycle assessment and cost accounting ought to be required. Finally, combining adsorption with complementary technologies such as membrane filtration or photocatalysis can provide multifunctional treatment systems and increase removal efficiency. All things considered, κ-carrageenan-based nanocomposites offer a high-performance, multifunctional, and environmentally friendly wastewater washing solution—as long as current limitations are systematically addressed by substantial research and technological advancement.

References

[1] J. Nyika, M.O. Dinka, The Global Challenge of Wastewater and Its Mismanagement. In *The Silent Wastewater Problem in Sub-Saharan Africa*, Springer Nature Switzerland: Cham, 2025; pp 1-26.

[2] A. Boretti, L. Rosa. (2019). Reassessing the projections of the World Water Development Report. npj Clean Water. 2(1): 15.

[3] A.E. Ercin, A.Y. Hoekstra. (2014). Water footprint scenarios for 2050: A global analysis. Environment International. 64: 71-82.

[4] P. Samanta, A.V. Desai, S. Let, S.K. Ghosh. (2019). Advanced Porous Materials for Sensing, Capture and Detoxification of Organic Pollutants toward Water Remediation. ACS Sustainable Chemistry & Engineering. 7(8): 7456-7478.

[5] R. Al-Tohamy, S.S. Ali, F. Li, K.M. Okasha, Y.A.G. Mahmoud, T. Elsamahy, H. Jiao, Y. Fu, J. Sun. (2022). A critical review on the treatment of dye-containing wastewater: Ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety. Ecotoxicology and Environmental Safety. 231: 113160.

[6] S. Khan, D. Borah. (2024). Microbial cell factories in the degradation of azo-dye and their limiting factors: An insight. Cleaner Water. 2: 100034.

[7] B. Lellis, C.Z. Fávaro-Polonio, J.A. Pamphile, J.C. Polonio. (2019). Effects of textile dyes on health and the environment and bioremediation potential of living organisms. Biotechnology Research and Innovation. 3(2): 275-290.

[8] S. Bolisetty, M. Peydayesh, R. Mezzenga. (2019). Sustainable technologies for water purification from heavy metals: review and analysis. Chemical Society Reviews. 48(2): 463-487.

[9] T.A. Kurniawan, P.-S. Yap, Z. Chen. (2025). Techniques for pollutant removal, nutrient recovery, and energy production from landfill leachates: a review. Environmental Chemistry Letters. 23(2): 517-577.

[10] A. Saravanan, P. Thamarai, P.S. Kumar, G. Rangasamy. (2022). Recent advances in polymer composite, extraction, and their application for wastewater treatment: A review. Chemosphere. 308: 136368.

[11] J. Kurczewska, M. Cegłowski. (2025). Alginate vs chitosan composites loaded with halloysite/molecularly imprinted polymer hybrids for tetracycline removal: Comparative studies of adsorption behaviour. International Journal of Biological Macromolecules. 307: 142000.

[12] H. Alkhaldi, S. Alharthi, S. Alharthi, H.A. AlGhamdi, Y.M. AlZahrani, S.A. Mahmoud, L.G. Amin, N.H. Al-Shaalan, W.E. Boraie, M.S. Attia, S.A. Al-Gahtany, N. Aldaleeli, M.M. Ghobashy, A.I. Sharshir, M. Madani, R. Darwesh, S.F. Abaza. (2024). Sustainable polymeric adsorbents for adsorption-based water remediation and pathogen deactivation: a review. RSC Advances. 14(45): 33143-33190.

[13] A. P, A. P, R.J. M, J.M. Joy, S. Mathew. (2024). Developmental prospects of carrageenan-based wound dressing films: Unveiling techno-functional properties and freeze-drying technology for the development of absorbent films — A review. International Journal of Biological Macromolecules. 276: 133668.

[14] F. van de Velde, S.H. Knutsen, A.I. Usov, H.S. Rollema, A.S. Cerezo. (2002). 1H and 13C high resolution NMR spectroscopy of carrageenans: application in research and industry. Trends in Food Science & Technology. 13(3): 73-92.

[15] P. Kulal, V. Badalamoole. (2020). Hybrid nanocomposite of kappa-carrageenan and magnetite as adsorbent material for water purification. International Journal of Biological Macromolecules. 165: 542-553.

[16] H. Pourramezan, M. Labbafi, F. Khodaiyan, M. Mousavi, M. Gharaghani, M. Saadatvand, A. Mahmoudi. (2022). Preparation of octenyl succinylated kappa-carrageenan; reaction optimization, characterization, and application in low-fat vegan mayonnaise. International Journal of Biological Macromolecules. 223: 882-898.

[17] W. Li, S.A. Qamar, M. Qamar, A. Basharat, M. Bilal, H.M.N. Iqbal. (2021). Carrageenan-based nano-hybrid materials for the mitigation of hazardous environmental pollutants. International Journal of Biological Macromolecules. 190: 700-712.

[18] R. Priyadharshini, S.S. Elanchezhiyan, S.M. Prabhu, S. Meenakshi. (2025). Bimetallic oxide integrated chitosan matrix for adsorption coupled reduction of Cr(VI) from aqueous solution. Separation and Purification Technology. 370: 133158.

[19] O. Duman, T.G. Polat, C.Ö. Diker, S. Tunç. (2020). Agar/κ-carrageenan composite hydrogel adsorbent for the removal of Methylene Blue from water. International Journal of Biological Macromolecules. 160: 823-835.

[20] Annu, M. Mittal, S. Tripathi, D.K. Shin. (2024). Biopolymeric Nanocomposites for Wastewater Remediation: An Overview on Recent Progress and Challenges. Polymers. 16(2): 294.

[21] Q. Qin Zhang, J. Tang, Y. Feng Wu, C. Yu Qian, S. Qin, Z. Hang Cai, H. Wang, H. Mei Xiao. (2024). Gelation of crocodile myofibrillar protein – κ-carrageenan mixtures in two low-NaCl solution. Food Chemistry. 445: 138753.

[22] X. Yang, M. Zhang, B. Zhao, X. Zou, R. Song. (2024). Development, characteristics and biological activities of bilayer composite film based on gelatin/κ-carrageenan loading curcumin and ε-polylysine. Food Hydrocolloids. 150: 109646.

[23] G.R. Mahdavinia, H. Aghaie, H. Sheykhloie, M.T. Vardini, H. Etemadi. (2013). Synthesis of CarAlg/MMt nanocomposite hydrogels and adsorption of cationic crystal violet. Carbohydrate polymers. 98(1): 358-365.

[24] J.C.M. da Costa, A.R.S. Bruni, G.A.M. Jesus, E.S. Alves, O. de Oliveira S. Júnior, A.F. Martins, E.G. Bonafe. (2024). Enhancing fresh pear preservation with UV-blocking film coatings based on κ-carrageenan, cassava starch, and copper oxide particles. Journal of Food Engineering. 368: 111853.

[25] S. Pavlidou, C.D. Papaspyrides. (2008). A review on polymer–layered silicate nanocomposites. Progress in Polymer Science. 33(12): 1119-1198.

[26] M.H. Maleki, M. Rezaie, M. Dinari. (2022). Facile synthesis of green and efficient magnetic nanocomposites of carrageenan/copper for the reduction of nitrophenol derivatives. International Journal of Biological Macromolecules. 220: 954-963.

[27] F. Sabbagh, N.M. Khatir, K. Kiarostami. (2023). Synthesis and Characterization of k-Carrageenan/PVA Nanocomposite Hydrogels in Combination with MgZnO Nanoparticles to Evaluate the Catechin Release. Polymers. 15(2): 272.

[28] A. Ulu, M. Alpaslan, A. Gultek, B. Ates. (2022). Eco-friendly chitosan/κ-carrageenan membranes reinforced with activated bentonite for adsorption of methylene blue. Materials Chemistry and Physics. 278: 125611.

[29] M.H. Shafie, M.L. Kamal, F.F. Zulkiflee, S. Hasan, N.H. Uyup, S. Abdullah, N.A. Mohamed Hussin, Y.C. Tan, Z. Zafarina. (2022). Application of Carrageenan extract from red seaweed (Rhodophyta) in cosmetic products: A review. Journal of the Indian Chemical Society. 99(9): 100613.

[30] Z. Hashmi, I.M. Idriss, F. Gapsari, N. Samsuddin, M.R. Bilad. (2025). The role of nanomaterials in enhancing membrane-based treatment for emerging contaminants: A review. Sustainable Chemistry for Climate Action. 7: 100092.

[31] F. Jabeen, A. Zil e, R. Ahmad, S. Mir, N.S. Awwad, H.A. Ibrahium. (2025). Carrageenan: structure, properties and applications with special emphasis on food science. RSC Advances. 15(27): 22035-22062.

[32] P. Yang, F. Yu, Z. Yang, X. Zhang, J. Ma. (2022). Graphene oxide modified κ-carrageenan/sodium alginate double-network hydrogel for effective adsorption of antibiotics in a batch and fixed-bed column system. Science of The Total Environment. 837: 155662.

[33] G. Geyik, N. Işıklan. (2023). Chemical modification of κ-carrageenan with poly(2-hydroxypropylmethacrylamide) through microwave induced graft copolymerization: Characterization and swelling features. International Journal of Biological Macromolecules. 235: 123888.

[34] G. Rando, E. Scalone, S. Sfameni, M.R. Plutino. (2024). Functional Bio-Based Polymeric Hydrogels for Wastewater Treatment: From Remediation to Sensing Applications. Gels. 10(8): 498.

[35] L. Alsaka, L. Alsaka, A. Altaee, S.J. Zaidi, J. Zhou, T. Kazwini. (2025). A Review of Hydrogel Application in Wastewater Purification. Separations. 12(2): 51.

[36] T. Kegl, A. Košak, A. Lobnik, Z. Novak, A.K. Kralj, I. Ban. (2020). Adsorption of rare earth metals from wastewater by nanomaterials: A review. Journal of Hazardous Materials. 386: 121632.

[37] A.R. Bagheri, M. Ghaedi, A. Asfaram, A.A. Bazrafshan, R. Jannesar. (2017). Comparative study on ultrasonic assisted adsorption of dyes from single system onto Fe3O4 magnetite nanoparticles loaded on activated carbon: Experimental design methodology. Ultrasonics Sonochemistry. 34: 294-304.

[38] S. Khanjani, A. Morsali. (2014). Ultrasound-promoted coating of MOF-5 on silk fiber and study of adsorptive removal and recovery of hazardous anionic dye “congo red”. Ultrasonics Sonochemistry. 21(4): 1424-1429.

[39] M.E.A. El-sayed. (2020). Nanoadsorbents for water and wastewater remediation. Science of The Total Environment. 739: 139903.

[40] M. Takemasa, A. Chiba, M. Date. (2002). Counterion Dynamics of κ- and ι-Carrageenan Aqueous Solutions Investigated by the Dielectric Properties. Macromolecules. 35(14): 5595-5600.

[41] A.C. Pinheiro, A.I. Bourbon, B.G.d.S. Medeiros, L.H.M. da Silva, M.C.H. da Silva, M.G. Carneiro-da-Cunha, M.A. Coimbra, A.A. Vicente. (2012). Interactions between κ-carrageenan and chitosan in nanolayered coatings—Structural and transport properties. Carbohydrate polymers. 87(2): 1081-1090.

[42] G. Sharma, A. Khosla, A. Kumar, N. Kaushal, S. Sharma, M. Naushad, D.-V.N. Vo, J. Iqbal, F.J. Stadler. (2022). A comprehensive review on the removal of noxious pollutants using carrageenan based advanced adsorbents. Chemosphere. 289: 133100.

[43] A.M. Salgueiro, A.L. Daniel-da-Silva, A.V. Girão, P.C. Pinheiro, T. Trindade. (2013). Unusual dye adsorption behavior of κ-carrageenan coated superparamagnetic nanoparticles. Chemical Engineering Journal. 229: 276-284.

[44] A.L. Daniel-da-Silva, A.M. Salgueiro, B. Creaney, R. Oliveira-Silva, N.J.O. Silva, T. Trindade. (2015). Carrageenan-grafted magnetite nanoparticles as recyclable sorbents for dye removal. Journal of Nanoparticle Research. 17(7): 302.

[45] S. Mola Ali Abasiyan, F. Dashbolaghi, G.R. Mahdavinia. (2019). Chitosan cross-linked with κ-carrageenan to remove cadmium from water and soil systems. Environmental Science and Pollution Research. 26(25): 26254-26264.

[46] G.R. Mahdavinia, A. Mosallanezhad. (2016). Facile and green rout to prepare magnetic and chitosan-

crosslinked κ-carrageenan bionanocomposites for removal of methylene blue. Journal of Water Process Engineering. 10: 143-155.

[47] A.K. Sharma, A. Gupta, A. Dhiman, M. Garg, R. Mishra, G. Agrawal. (2022). Fe3O4 embedded κ-carrageenan/sodium alginate hydrogels for the removal of basic dyes. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 654: 130155.

[48] M. Yang, X. Liu, Y. Qi, W. Sun, Y. Men. (2017). Preparation of κ-carrageenan/graphene oxide gel beads and their efficient adsorption for methylene blue. Journal of Colloid and Interface Science. 506: 669-677.

[49] Y. Majooni, K. Fayazbakhsh, N. Yousefi. (2024). Toward mechanically robust and highly recyclable adsorbents using 3D printed scaffolds: A case study of encapsulated carrageenan hydrogel. Chemical Engineering Journal. 494: 152672.

[50] F. Yu, T. Cui, C. Yang, X. Dai, J. Ma. (2019). κ-Carrageenan/Sodium alginate double-network hydrogel with enhanced mechanical properties, anti-swelling, and adsorption capacity. Chemosphere. 237: 124417.

[51] R.H. Krishna, M.N. Chandraprabha, K. Samrat, T.P. Krishna Murthy, C. Manjunatha, S.G. Kumar. (2023). Carbon nanotubes and graphene-based materials for adsorptive removal of metal ions – A review on surface functionalization and related adsorption mechanism. Applied Surface Science Advances. 16: 100431.

[52] S. Radoor, D.R. Kandel, S. Chang, J. Karayil, J. Lee. (2024). Carrageenan/calcium alginate composite hydrogel filtration membranes for efficient cationic dye separation. International Journal of Biological Macromolecules. 270: 132309.

[53] M.H. Karimi, G.R. Mahdavinia, B. Massoumi, A. Baghban, M. Saraei. (2018). Ionically crosslinked magnetic chitosan/κ-carrageenan bioadsorbents for removal of anionic eriochrome black-T. International Journal of Biological Macromolecules. 113: 361-375.

[54] S. Lapwanit, T. Sooksimuang, T. Trakulsujaritchok. (2018). Adsorptive removal of cationic methylene blue dye by kappa-carrageenan/poly(glycidyl methacrylate) hydrogel beads: Preparation and characterization. Journal of Environmental Chemical Engineering. 6(5): 6221-6230.

[55] V. Vaid, Khushbu, M. Sharma, Parul, N. Maurya, R. Jindal. (2025). β-Cyclodextrin modified chitosan and κ-carrageenan composites for acid fuchsin dye removal: mechanism insight and adsorption performance. Biomass Conversion and Biorefinery. 15(7): 10567-10584.

[56] (2024). Kinetic Study of Pb(II) Adsorption on Food-grade κ-Carrageenan Beads. Jurnal Serambi Engineering. 9(3): 10193 - 10200.

[57] S. Satyam, S. Patra. (2024). Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review. Heliyon. 10(9).

[58] S. De Gisi, G. Lofrano, M. Grassi, M. Notarnicola. (2016). Characteristics and adsorption capacities of low-cost sorbents for wastewater treatment: A review. Sustainable Materials and Technologies. 9: 10-40.

[59] A. Naseer. (2024). Role of nanocomposites and nano adsorbents for heavy metals removal and dyes. An overview. Desalination and Water Treatment. 320: 100662.

[60] V.S. Garcia, L.M. Gugliotta, C.G. Gutierrez, V.D.G. Gonzalez. (2024). κ-Carrageenan Hydrogels as a Sustainable Alternative for Controlled Release of New Biodegradable Molecules with Antimicrobial Activities. Journal of Polymers and the Environment. 32(8): 3795-3809.

[61] A. Akbari, H. Abbasi, M. Shafiee, H. Baniasadi. (2024). Synergistic adsorption of methylene blue with carrageenan/hydrochar-derived activated carbon hydrogel composites: Insights and optimization strategies. International Journal of Biological Macromolecules. 265: 130750.

[62] P. Sharma, M. Sharma, H. Laddha, R. Gupta, M. Agarwal. (2023). Non-toxic and biodegradable κ-carrageenan/ZnO hydrogel for adsorptive removal of norfloxacin: Optimization using response surface methodology. International Journal of Biological Macromolecules. 238: 124145.

[63] D.M. Aboelkhir, A. Sayed, L.S. Eldondaity, V. Joseph, A. Amin, G.A. Mahmoud. (2024). Multiwalled carbon nanotubes@ pectin/κ-carrageenan-based nanocomposite biohydrogel prepared by gamma irradiation for efficient methylene blue dye sequestration. Journal of applied polymer science. 141(22): e55452.

[64] S. Radoor, S.K. Kassahun, H. Kim. (2024). Selective adsorption of cationic dye by κ-carrageenan-potato starch bio-hydrogel: Kinetics, isotherm, and thermodynamic studies. International Journal of Biological Macromolecules. 281: 136377.

[65] J. Yu, S. Tian, A. Yao, H. Hu, J. Lan, L. Yang, X. Du, S. Lin. (2024). Compressible polydopamine modified pomelo peel powder/poly (ethyleneimine)/κ-carrageenan aerogel with pH-tunable charge for selective removal of anionic and cationic dyes. Carbohydrate polymers. 323: 121377.

[66] Z. Rahmani, M. Ghaemy, A. Olad. (2022). Removal of heavy metals from polluted water using magnetic adsorbent based on κ-carrageenan and N-doped carbon dots. Hydrometallurgy. 213: 105915.

[67] M.I. Wahba. (2021). Carrageenan stabilized calcium pectinate beads and their utilization as immobilization matrices. Biocatalysis and Agricultural Biotechnology. 35: 102078.

[68] S. Fu, Z. Sun, P. Huang, Y. Li, N. Hu. (2019). Some basic aspects of polymer nanocomposites: A critical review. Nano Materials Science. 1(1): 2-30.

[69] F. Yu, Z. Yang, X. Zhang, P. Yang, J. Ma. (2021). Lanthanum modification κ-carrageenan/sodium alginate dual-network aerogels for efficient adsorption of ciprofloxacin hydrochloride. Environmental Technology & Innovation. 24: 102052.

[70] O.T. Mahlangu, M.M. Motsa, H. Richards, B.B. Mamba, M.J. George, L.N. Nthunya. (2024). The impact of nanoparticle leach on sustainable performance of the membranes–A critical review. Environmental Nanotechnology, Monitoring & Management. 22: 100984.