Environmental Chemistry Letters (2020) 18:1569–1580
https://doi.org/10.1007/s10311-020-01021-w

REVIEW

Green polymeric nanomaterials for the photocatalytic degradation of dyes: a review

Shrabana Sarkar[1] · **Nidia Torres Ponce**[2] · **Aparna Banerjee**[3] · **Rajib Bandopadhyay**[1] · **Saravanan Rajendran**[4] · **Eric Lichtfouse**[5]

Received: 18 February 2020 / Accepted: 1 June 2020 / Published online: 14 June 2020

Abstract

Pure and drinkable water will be rarer and more expensive as the result of pollution induced by industrialisation, urbanisation and population growth. Among the numerous sources of water pollution, the textile industry has become a major issue because effluents containing dyes are often released in natural water bodies. For instance, about two years are needed to biodegrade dye-derived, carcinogenic aromatic amines, in sediments. Classical remediation methods based upon physicochemical reactions are costly and still generate sludges that contain amine residues. Nonetheless, recent research shows that nanomaterials containing biopolymers are promising to degrade organic pollutants by photocatalysis. Here, we review the synthesis and applications of biopolymeric nanomaterials for photocatalytic degradation of azo dyes. We focus on conducting biopolymers incorporating metal, metal oxide, metal/metal oxide and metal sulphide for improved biodegradation. Biopolymers can be obtained from microorganisms, plants and animals. Unlike fossil-fuel-derived polymers, biopolymers are carbon neutral and thus sustainable in the context of global warming. Biopolymers are often biodegradable and biocompatible.

Keywords Biopolymer · Nanomaterial · Photocatalyst · Dye degradation

Introduction

According to the latest report of World Health Organization (WHO), approximately 844 million people worldwide lack the access to basic drinkable water (Wutich et al. 2019). Waterborne pathogens in the form of disease-causing bacteria, virus or protozoa spread many diseases including cholera, typhoid, hepatitis, giardia and COVID-19 (Sharma et al. 2020). Unsafe water causes epidemics in developing countries due to improper management of water pollution (Alhamlan et al. 2015). Organic pollutants in wastewater are potentially harmful for all living organisms. Regular consumption of untreated or poorly treated waters induces carcinogenesis or prolonged illness in humans and other animals (Sarkar et al. 2017). As a consequence, wastewater remediation and water recirculation are now the major research focus (Wen et al. 2019; Karimi-Maleh et al. 2020a). Particularly, the regulation of water contamination and recycling the wastewater should be improved in drought-affected countries (Gholami et al. 2019).

The negative health effects of water pollution are a major source of mortality worldwide (Wang and Yang 2016; Sarkar et al. 2017). In particular, water pollution has historically

✉ Aparna Banerjee
abanerjee@ucm.cl

✉ Saravanan Rajendran
saravanan3.raj@gmail.com

Eric Lichtfouse
eric.lichtfouse@gmail.com
https://cv.archives-ouvertes.fr/eric-lichtfouse

[1] UGC-Center of Advanced Study, Department of Botany, The University of Burdwan, Golapbag, Bardhaman, West Bengal 713104, India

[2] School of Biotechnology Engineering, Faculty of Agricultural and Forestry Sciences, Universidad Católica del Maule, Talca, Chile

[3] Centro de Investigación de Estudios Avanzados del Maule (CIEAM), Vicerrectoría de Investigación y Postgrado, Universidad Católica del Maule, Talca, Chile

[4] Department of Mechanical Engineering, Faculty of Engineering, University of Tarapacá, Arica, Chile

[5] Aix-Marseille Univ, CNRS, IRD, INRAE, Coll France, CEREGE, Aix-en-Provence, France

impacted food safety (Lu et al. 2015). The textile industry represents a threat when dye effluents are released into water bodies. Textile wastewater contains various contaminants such as synthetic azo dyes. Therefore, environmental legislation commonly obligates textile factories to treat effluents before discharge (Yaseen and Scholz 2019). Dye effluents are high in colour, pH, suspended solids (SS), chemical oxygen demand (COD), biochemical oxygen demand (BOD) (Yaseen and Scholz 2016), metals (Sharma et al. 2007; Sekomo et al. 2012), temperature (Dos Santos et al. 2007; Shah et al. 2013) and salts (Yaseen and Scholz 2019). Synthetic textile dyes are often recalcitrant and carcinogenic by nature due to the presence of –N=N– bond (Singh et al. 2015). Those dyes mainly consist of complex aromatic structures that are hardly biodegradable.

Wastewater treatment involves a step of physicochemical fractionation, which separates hydrophilic and hydrophobic matter (Kim and Yu 2005). Techniques and adsorbents used for wastewater treatments have been recently compared (Crini and Lichtfouse 2019; Crini et al. 2019a). Methods for the treatment of dye-contaminated waters include reverse osmosis, coagulation, flocculation, ion exchange, activated carbon adsorption, advanced oxidation, ozonation, photocatalysis, Fenton process, photo-Fenton, electrochemical oxidation (Lade et al. 2015) and filtration (Singh et al. 2015). These processes are often expensive and generate amine residues found in sludges after treatment. Alternatively, semiconductors such as titanium dioxide and zinc oxide have shown excellent photocatalytic activity due to a positive band position that develops more electrons and holes under UV light (Fujishima and Honda 1972; Mclaren et al. 2009; Xu et al. 2019). Recently, the photocatalytic capacity has been improved by modifying material surfaces using metal doped , non-metal doped and coupled systems (Gnanasekaran et al. 2017, 2018; Sulaiman et al. 2018; Kuo et al. 2019). Composite or coupled systems are now used for solar cells, opto-electronics, bio-electrochemical sensors, electro-oxidation and disinfection (Li et al. 2011; Devi and Kavitha 2013; Rokhmat et al. 2017; Karimi-Maleh et al. 2019; Karimi-Maleh and Arotiba 2020; Karimi-Maleh et al. 2020b, c). Here, we review green polymeric nanomaterials for photocatalytic dye degradation with special emphasis on recent developments, biopolymers and applications in wastewater remediation.

Synthesis of biopolymeric nanomaterials

Conventional methods to synthesise polymeric nanomaterial employ chemical compounds that may cause environmental toxicity later due to their long-term stability. By contrast, biopolymers are usually composed of safe monomers and are carbon neutral for the climate. Biopolymers facilitate the synthesis of nanomaterials because biomass morphology is often structured at the nanolevel. Biopolymers are found in various organisms such as plants, algae, fungi, bacteria and animals. Macromolecules include starch, alginate, chitosan, dextran and chitin (Fig. 1). Chitosan, starch, dextran and cellulose are polysaccharides derived from plants and microbial biofilms, and these biopolymers are common for nanomaterial synthesis (Banerjee and Bandopadhyay 2016; Farshchi et al. 2019; Kolangare et al. 2019). In particular, chitosan has been used for dye removal and wastewater treatment (Crini et al. 2019b; Lichtfouse et al. 2019).

Biopolymers are unique in composition and have various physiological properties. Biopolymeric nanomaterials can be formed by attachment of metals to biopolymers. In particular, biopolymers form molecular capsules by intramolecular hydrogen bonding. For example, starch may incorporate metals or metal oxide, thus forming polymeric nanocomposites. Chitosan is also used for nanotechnology-related applications due to its wide compatibility (Vanaamudan et al. 2018; Morin-Crini et al. 2019). Silver (Ag) can be incorporated within starch in a supramolecular way to form nanomaterials (Raveendran et al. 2003). Nanomaterials can be incorporated in biopolymers by both sorption and impregnation (Shankar and Rhim 2018). Polymeric nanomaterials are solid colloidal particles within the size range of 10 nm–1 µm.

Physical properties of nanomaterials can be drastically different from the corresponding macro-sized, bulk material because nanomaterials have much higher surface area and reactivity (Sreedharan and Rao 2019). Either nanospheres or nanocapsules can be prepared, depending on the preparation method (Sharma 2019). Biopolymeric nanomaterials are characterised by microscopy, spectroscopy and other techniques (Fig. 2). A list of green polymeric nanomaterials used for textile dye degradation is presented in Table 1.

Photocatalytic degradation of dyes by biopolymeric nanomaterials

Biopolymers such chitosan act as support material of metallic photocatalysts. Owing to strong adsorption and high surface area, chitosan reduces the amount of intermediates during photocatalytic reactions. In addition, chitosan allows quick and trouble-free recovery of the photocatalyst, which can be recycled with or without any regeneration (Adnan et al. 2020). Photocatalysis is different versus general catalysis in a way that during photocatalysis photons induce catalysis at the time of reaction (Bahal et al. 2019). In the presence of photon (λ), oxygen acts as an electron acceptor and electrons are generated photocatalytically by the breakage of complex dyes (Yang et al. 2005). In response to visible light, polymeric nanomaterials have been shown to degrade

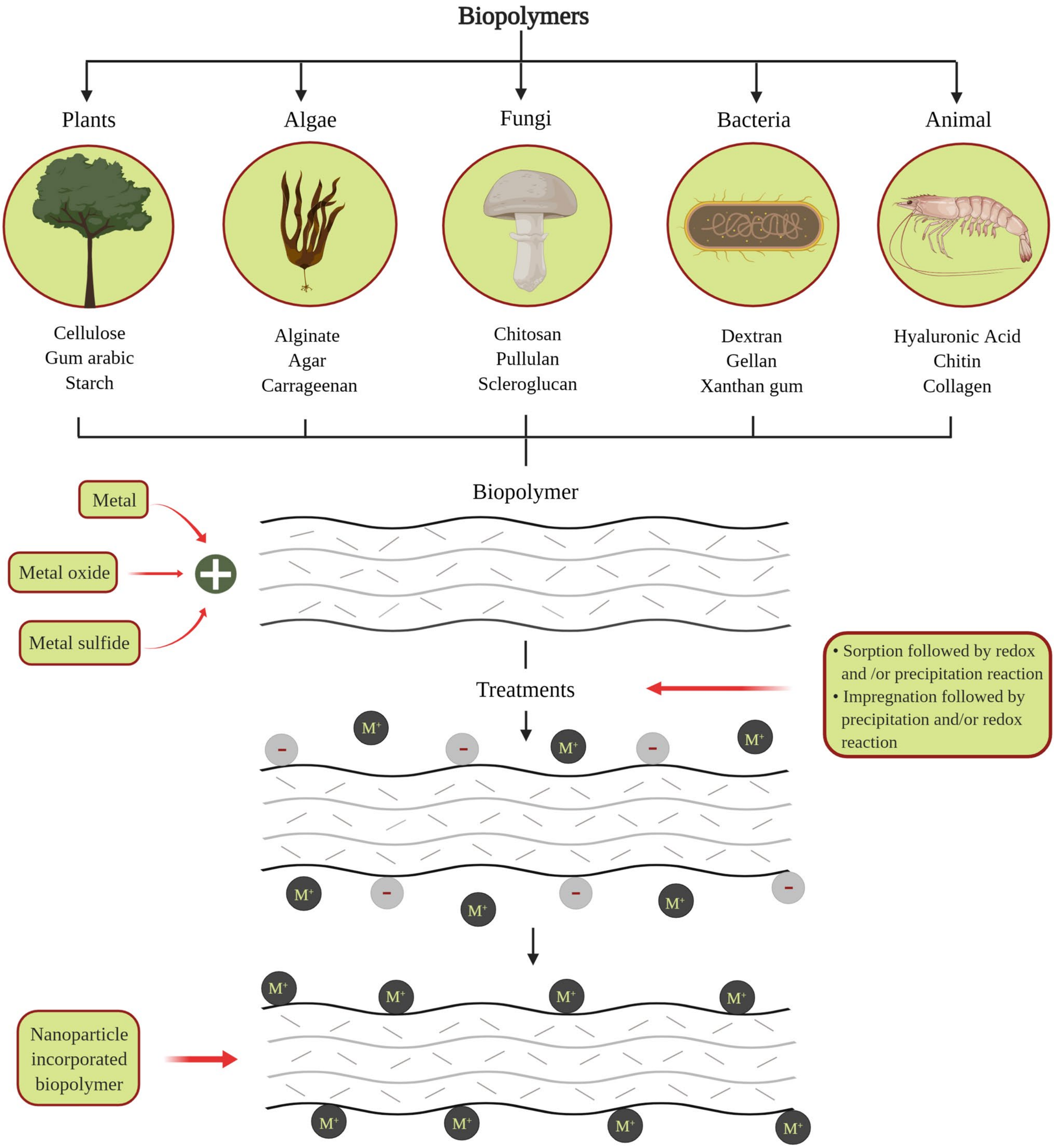

Fig. 1 Different sources of biopolymers and their usage in the synthesis of green polymeric nanomaterials. M^+: metal ions

dye-containing wastewater photocatalytically within very short period (Bahal et al. 2019), which is both eco-friendly and inexpensive.

The concept of using TiO_2 nanoparticles for photocatalytic dye degradation was developed several decades ago (Fujishima and Honda 1972). Green-synthesised silver nanomaterials have also been used as photocatalysts to treat dyes and other organic chemicals (Sharma et al. 2009). At that time, nanotechnology was not popular for wastewater remediation, but now it is due to evidence of high performances (Durgalakshmi et al. 2019).

Electron affinity is a major parameter for photocatalytic degradation of reactive textile dyes (Saravanan et al. 2013) as the ionic nature or the presence of lone pair electrons in

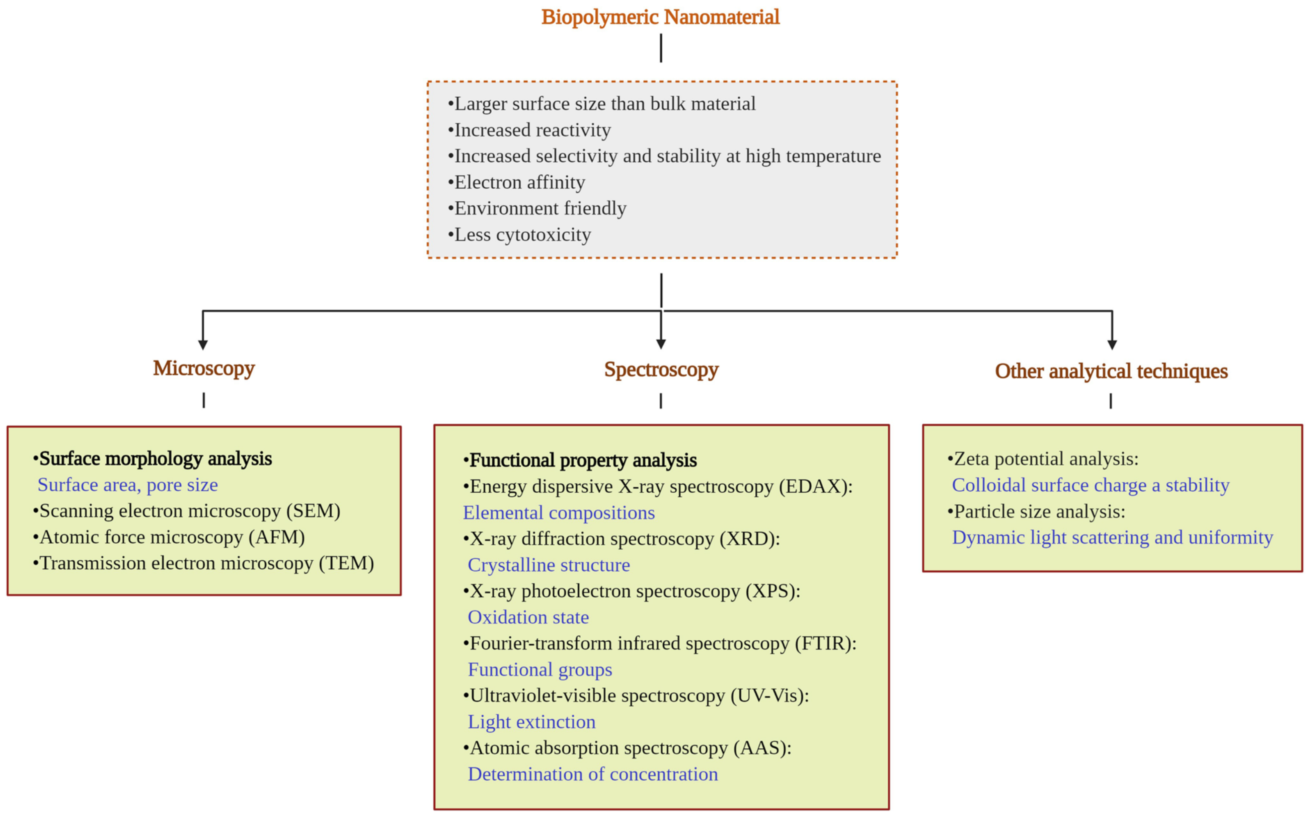

Fig. 2 Properties and analysis of biopolymeric nanomaterials

the polymeric chain backbone acts as chelating agent to stabilise the synthesised nanoparticles (Ng et al. 2013). Additionally, polymeric membrane-incorporated metal nanomaterials have increased hydrophilicity, selectivity, strength and stability at high temperature, up to 200 °C (Ng et al. 2013). Metal oxide nanomaterials incorporating gallic acid are also used in photocatalytic degradation of reactive azo dyes (Sreedharan and Rao 2019).

Metal-incorporated biopolymeric nanomaterials

The synthesis of metal-incorporated biopolymeric nanomaterials is outlined in Fig. 3. Metal-incorporated nanomaterials display high efficacy for the photocatalytic degradation of azo dyes. This can be attributed to their pore size, chemistry of surface plane and ideal mechanical rigidity (Opoku et al. 2017). The basics of photocatalytic degradation involve an electron transfer process coupled with a redox reaction. If the semi-conductivity is modified with metal-incorporated nanoparticles, then the system endorses the charge transport at interface and, in turn, decreases the oxidation of the metal (Subramanian et al. 2001). This process increases the lifetime of electron followed by the augmentation of the reactivity. Surface plasmon resonance (SPR) increases the co-existence of electrons due to the small particle size (Sankar et al. 2015). Polymeric nanomaterials with metal incorporation act as a stabilizer for itself. Metal nanoparticles incorporated with polymeric materials such as resin have found industrial applications as reaction catalysts (Kralik and Biffis 2001).

Metal nanoparticles can also be grafted on different polymeric materials, which increases compactness and stability (Tamayo et al. 2019) and provides a different functionality than that of the metal monomeric nanomaterials (Van Berkel and Hawker 2010). Usually, metal nanoparticles vary in size, whereas incorporation of polymer makes nanoparticle sizes more homogeneous and renders the material more stable. This has been shown during the integration of bacterial cellulose fibres with gold nanoparticles (AuNP).

Gold nanoparticles, of 74.32 nm, incorporated in biomaterials from fresh fruiting bodies of the Enoki mushroom degrade nearly 75% of the methylene blue dye in 4 h (Rabeea et al. 2020). Due to their wide substrate specificity, Au nanoparticles are able to treat diverse types of organic dyes (Tamayo et al. 2019). For lanthanum (La), the f-orbital electron of metal ions interacts with different functional groups of different biopolymers and forms complexes with greater surface areas. Lanthanum incorporation in biopolymers results in photocatalytic activity with better adsorption capacity, specifically for organic compounds such as azo dyes (Sirajudheen and Meenakshi 2019). A composite

Table 1 Biopolymeric nanomaterials used for the degradation of textile dyes degradation

Type of nanomaterial	Catalyst	Biopolymer	Degradation of dyes	References
Metal	Silver (Ag)	κ-Carrageenan gum	Mineralisation and catalytic degradation of industrially significant organic dyes such as methylene blue and rhodamine B	Pandey et al. (2020)
	Palladium (Pd)	Chitosan c-Nanotube supported	Congo red, methylene blue, methyl orange, methyl red	Sargin et al. (2020)
	Chitosan/Fe	Chitosan	Basic dye	Kasiri (2019)
	Au	Alginate beads	Discoloration of azo dye acidic orange 7 and reactive orange 5	Ahmed (2019)
	Lanthanum (La)	Chitosan	Photocatalytic degradation of azo dye (methylene blue)	Sirajudheen and Meenakshi (2019)
	Gold (Au)	Bacterial cellulosic fibre	Azo dye degradation	Tamayo et al. (2019), Vilela et al. (2018)
	Cupper (Cu)	Chitosan	Congo red	Ali et al. (2018)
	Silver (Ag)	Chitosan	Ponceau BS dye	Sultana et al. (2017)
	Palladium (Pd)	Carboxymethyl cellulose	Degradation of azo dye	Li et al. (2017a)
	Zirconium (Zr)	Gelatine	Methylene blue and fast green	Thakur et al. (2017)
	Palladium (Pd)	Glucuronoarabinogalactan polymer and gum olibanum (*Boswellia serrata*)	Coomassie brilliant blue G-250, rhodamine B, methylene blue and 4-nitrophenol	Kora and Rastogi (2016)
	Cupper (Cu)	Chitosan-coated cellulosic microfibres	Methyl orange and congo red	Kamal et al. (2016)
Metal oxide	ZnO	Chitosan in the form of hydrogel beads	Methylene blue	Taghizadeh et al. (2020)
	ZnO	Quince seed mucilage	Photocatalytic degradation of methylene blue	Moghaddas et al. (2020)
	Fe_3O_4	Chitosan	Hazardous dye X-3B	Adnan et al. (2020)
	MnO_2	Cellulose	Indigo carmine dye solution	Oliveira et al. (2020)
	Alumina (Al_2O_3)	Chitosan	sulfonated azo dye methyl orange	Kasiri (2019)
	ZnO	Chitosan	Chromium complex dye, Direct Blue 78, Acid Black 26	Kasiri (2019)
	ZnO	Cellulose	Dye-containing wastewater remediation	Bahal et al. (2019)
	TiO_2	Chitosan–acrylic acid biopolymer	Malachite green	Bahal et al. (2019)
	ZnO	Cellulose acetate polymeric sheet	Congo red, methyl orange, methylene blue	Khan et al. (2019)
	TiO_2	Bacterial cellulose	Photocatalytic dye degradation	Vilela et al. (2018)
	TiO_2	Cellulose by the fermentation of *Komagataei bacterxylinus*-immobilized laccase	Reactive red X-3B	Li et al. (2017b)
	TiO_2	Oak gall tannin	Direct yellow 86	Binaeian et al. (2016)
	TiO_2	Chitosan	Acid orange 7, acid red 18, C.I. acid blue 113, reactive yellow 17, reactive black 5, direct blue 78	Škorić et al. (2016)
	ZnO	Conducting polyalanine polymer	Methylene blue and malachite green	Riaz et al. (2015)
Metal sulphide	ZnS	Chitosan	Photodegradation of organic dyes (methyl orange)	Das et al. (2017)
	ZnS	Chitosan	Around 90% photodegradation of methylene blue under UV irradiation	Mansur and Mansur (2015)

Table 1 (continued)

Type of nanomaterial	Catalyst	Biopolymer	Degradation of dyes	References
Others	AgCl	Chitosan in the form of hydrogel beads	Methylene blue	Taghizadeh et al. (2020)
	Fe_3O_4	Immobilised laccase from *Bacillus* sp. MSK-01 conjugated with thiolated chitosan	Biocatalytic degradation of organic dyes (Reactive Blue 171 and Acid Blue 74)	Ulu et al. (2020)
	TiO_2	Chitosan–epichlorohydrin	Reactive Red 120	Jawad et al. (2020)
	$CuSO_4$	Chitosan-coated nanocomposite from *Psidium guajava* aqueous leaf extract	Congo red and methylene blue	Sathiyavimal et al. (2020)
	ZnO	Arabic gum-grafted polyacrylamide hydrogel	Complete degradation of malachite green	Mittal et al. (2020)
	ZnO/CuO	Cellulose nanocrystal from bleached bagasse pulp	Rose Bengal (RB)	Elfeky et al. (2020)
	Ag/TiO_2	Carboxymethyl cellulase and gelatine	Organic dye pollutant	Farshchi et al. (2019)
	SiO2	Chitosan/carbon nanotubes	Direct Blue 71, Reactive Blue 19	Kasiri (2019)
	$AgNO_3$	Chitosan and guar gum	Binary dye	Vanaamudan et al. (2018)
	ZnS	Chitosan	Photocatalytic degradation of organic dye	Das et al. (2017)
	$AgNO_3$	Tangerine peel containing carbohydrate polymers	Catalytic reduction of methyl orange	Alzahrani (2015)
	Pt-TiO_2	Conjugated polymer	Photocatalytic degradation of azo dye	Dong et al. (2015)

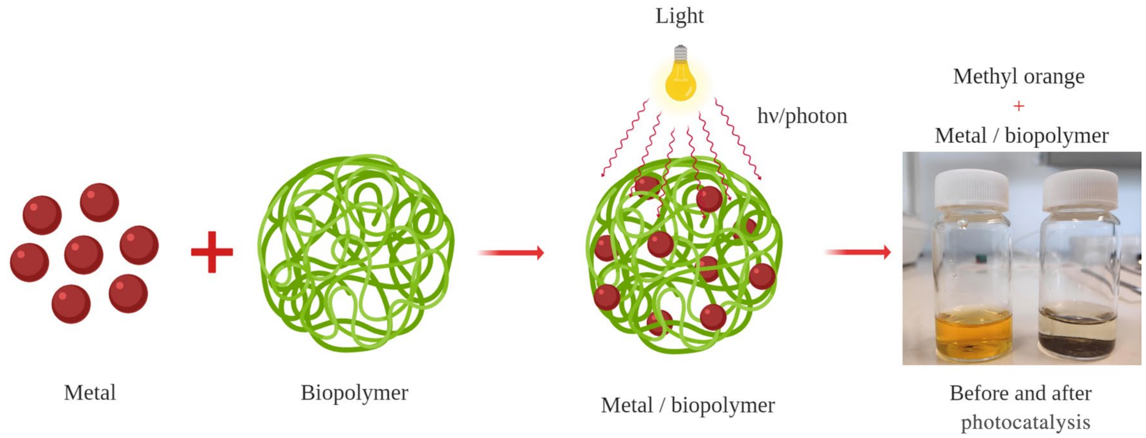

Fig. 3 Synthesis of metal-incorporated biopolymeric nanoparticles for photocatalytic dye degradation

of lanthanum (La) metal and chitosan has degraded 90% of methylene blue in 40 min (Sirajudheen and Meenakshi 2019). Here, the chemical oxygen demand (COD) decreased nearly 8 times, indicating mineralisation of methylene blue.

Metal oxide-incorporated biopolymeric nanomaterials

Synthesis of metal oxide-incorporated biopolymeric nanomaterials for photodegradation of dye is illustrated in Fig. 4. Nanomaterials made up of metal oxide and biopolymers have also extensive photocatalytic activity that can degrade complex chemical structure of azo dyes. Incorporation of biopolymer and metal oxide nanomaterials improves the physicochemical properties of the nanomaterials. Conversely, the presence of metal oxide within the biopolymeric structure enhances the properties of polymer too (Prasanna et al. 2019).

ZnO is one of the most efficient nanomaterials for photocatalytic dye degradation because of ZnO semi-conductivity,

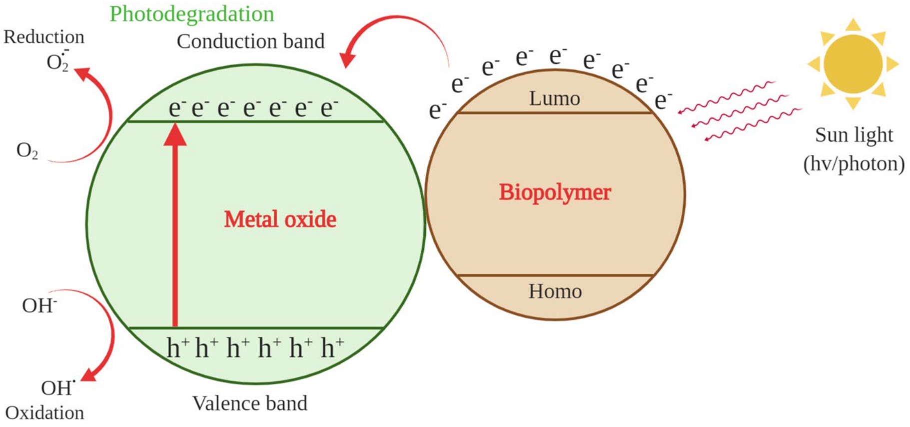

Fig. 4 Synthesis of metal oxide-incorporated biopolymeric nanoparticles for the photodegradation of dyes

stability and activity (Ravishankar et al. 2014). Starch-based ZnO nanomaterial has been reported for its improved conductive and dielectric properties, compared to pure metal oxide nanoparticles (Ravishankar et al. 2014). Cellulose-based ZnO nanomaterials display higher thermal stability than that of the pure metal oxide, and can be used for remediation of dye-containing wastewater at large scale (Ravishankar et al.2014; Azizi et al. 2013). A chitosan–acrylic acid biopolymer grafted with nano-TiO_2 was reported to degrade more than 90% of malachite green present in wastewater under neutral pH, through a visible light-mediated photocatalytic way (Bahal et al. 2019).

Chitosan incorporating nano-iron oxide (Fe_3O_4) has been used for purification of dye-containing wastewater (Prasanna et al. 2019; Ngah et al. 2011). Chitosan/nano-Fe_3O_4 nanomaterial is also increasing frictions due to magnetic dipole–dipole interactions during the degradation of the hazardous X-3B dye (Adnan et al. 2020). TiO_2 is widely used for preparing biopolymeric nanomaterials due to TiO_2 advantageous surface properties and photocatalysis under visible light (Bahal et al. 2019). Cyclodextrin, an oligosaccharide produced from enzymatic conversion of starch, has been used for wastewater treatment after modification with nano-TiO_2 (Khaoulani et al. 2015). ZnO/carbon black grafted in cellulose acetate has been used to treat azo dyes such as congo red, methyl orange and methylene blue (Khan et al. 2019).

MnO_2/cellulose nanoparticles of size lower than 100 nm degrade 90% indigo carmine within 25 min under ambient light and acidic pH (Oliveira et al. 2020). Here, the biopolymeric nanomaterials can be recovered from solution and recycled for at least 10 times without compromising the decolourisation efficiency. This provides evidence that in the presence of photons, metal oxide-incorporated biopolymeric nanomaterials degrade complex azo dyes within a very short time through an eco-friendly, recyclable process. Few bio-sourced enzymes degrade reactive azo dyes. Laccase shows good potential for bioremediation of dye-containing wastewater (Wang et al. 2013; Sarkar et al. 2020). Nano-Fe_3O_4/SiO_2 supported with immobilized laccase has achieved nearly complete degradation of the azo dye procion Red MX-5B within 20 min (Wang et al. 2013).

Metal sulphide-incorporated biopolymeric nanomaterials

Synthesis of metal sulphide-incorporated biopolymeric nanoparticles is depicted in Fig. 5. The biopolymer helps to crystallize ZnS nanoparticles (Tiwari and Dhoble 2016). ZnS-incorporated chitosan nanomaterials of 4 nm size display a photocatalytic activity and are used in photodegradation of organic dyes in wastewater (Das et al. 2017). Cadmium (Cd) and lead (Pb) are also used for the formation of metal sulphide nanomaterials. For instance, *Klebsiella pneumonia* has the ability to synthesise electron-dense nano-CdS materials on its cell membrane, which can induce photoreduction of methyl orange by subsequent electron transfer (Das et al. 2017).

Nano-chitosan has been used to remove hazardous dyes (Mansur and Mansur 2015). Chitosan-based quantum dots, a nano-photocatalyst and ZnS are able to remove methylene blue (Mansur and Mansur 2015). Here, ZnS acts as a semiconductor and thus enhances the removal. This ZnS/chitosan-based nanomaterial of nearly 3.5 nm size induces 90% photodegradation of methylene blue by oxidation under UV irradiation within 90 min.

Other biopolymeric nanomaterials

Metal/metal oxide nanoparticles are of special interest because the metal centre of the metal–metal oxide nanomaterial increases the semi-conductivity and rate of separation of electron holes, which in turn increases the photon irradiation, followed by escalation of the photocatalytic activity (Malagutti et al. 2009). For example, 0.25% Ag–TiO_2 thin film incorporation in a resin biopolymer drastically increases

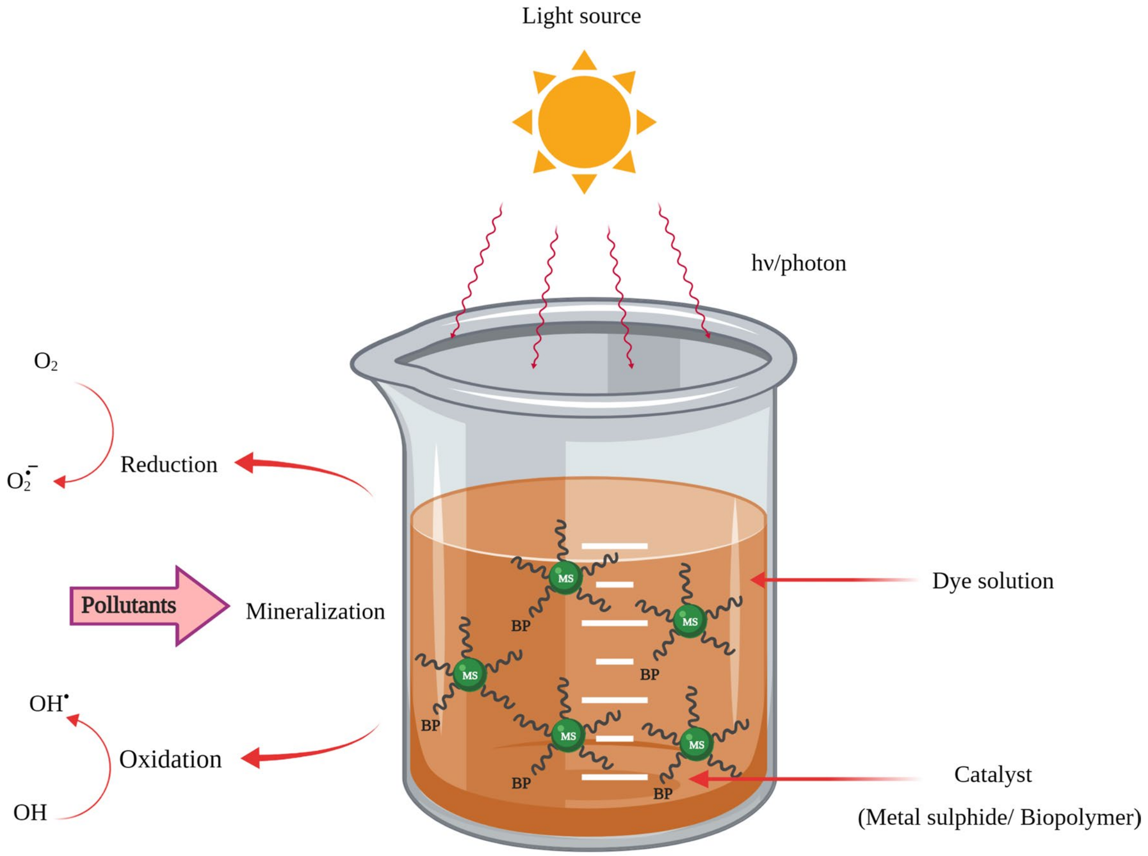

Fig. 5 Rationale behind the synthesis of metal sulphide-incorporated biopolymeric nanoparticles as photocatalysts for dye degradation. BP: biopolymer, MS: metal sulphide

the photocatalytic activity of rhodamine B, compared to sole TiO_2, as a result of reduced electron hole recombination (Malagutti et al. 2009). TiO_2/Ag hybrid, modified by the incorporation of carboxymethyl cellulase and gelatine of 50–100 nm size, has shown improved photocatalytic activity towards benzene and NH_3 present in the chemical structure of organic pollutants (Farshchi et al. 2019).

Various other chemicals are integrated with diverse polymers for the synthesis of photocatalytic nanomaterials. Several coupled systems expand the photocatalytic performances, such as metal-incorporated metal oxide and dual metal oxide systems (Gnanasekaran et al. 2017, 2018; Sulaiman et al. 2018; Kuo et al. 2019). These systems have two different band positions under sunlight or UV light exposure, which avoids electrons–holes recombination, and thus improves the photocatalytic activity (Gnanasekaran et al. 2017, 2018; Sulaiman et al. 2018; Kuo et al. 2019).

Unique properties of nanocomposites have created a revolution in the field of bioremediation (Mohanraj et al. 2020). Recently, several research groups have tried diverse biopolymeric nanocomposites such as metal/metal oxide/biopolymer or metal oxide/conducting polymer for improved degradation of synthetic azo dyes. One example of biopolymer/metal oxide nanocomposite is chitosan/ZnO/AgCl nanocomposite based on hydrogel beads, which permits complete photocatalytic degradation of methylene blue (Taghizadeh et al. 2020). The presence of chitosan in nanocomposites or other biopolymeric nanomaterials significantly increases the degradation activity, as a consequence of hydrophilic adsorption of organic pollutants (Adnan et al. 2020). Furthermore, chitosan-coated $CuSO_4$ nanocomposite, synthesised from *Psidium guajava* aqueous leaf extract, induced more than 90% oxidative photodegradation of congo red and methylene blue within 150 min (Sathiyavimal et al. 2020). Here, electrons are generated from the valance bond due to the presence of sunlight.

Cellulose nanocrystals have been prepared from bleached bagasse pulp and reacted with ZnO/CuO to synthesise biopolymeric dual metal oxide nanocomposites, which can degrade rose bengal more than 99% in 40 min (Elfeky et al. 2020). Immobilised dye-degrading enzyme laccase conjugated with thiolated chitosan–Fe_3O_4 hybrid has been reported to have magnetic properties, and it can remove more than 80% of reactive blue 171 and acid blue 74 within short periods of time (Ulu et al. 2020).

Conclusion

The long-term fate of textile dyes in river and sea sediments is not clear. A recent report suggests that aromatic amines could be naturally degraded in more than 2 years by the sediment bacterial community (Ito et al. 2016). Yet this process is slow and most probably never complete in natural anaerobic environments. Therefore, wastewater should be treated to remove all pollutants before discharge of residual waters in rivers. Here, promising techniques should be based on biosourced tools such as microorganisms and dye-degrading enzymes, e.g. laccase, azoreductase or peroxidase (Sarkar et al. 2020). The current success of photocatalytic dye degradation using biopolymers is attributed to the green process, uniform deposition of the nanoparticles, less cytotoxicity and recyclable nature.

Acknowledgements SS and RB are thankful to UGC-CAS, Department of Botany, The University of Burdwan for pursuing research activities. SS is thankful to SVMCM-Non-Net fellowship for the financial assistance. AB acknowledges the support of FONDECYT Iniciación No. 11190325 by Govt. Of Chile and Centro de Biotecnología de los Recursos Naturales (CenBio), Universidad Católica del Maule for the laboratory facilities. The author (S.R.) acknowledges the support of ANID through the project ANID/FONDAP/15110019 and FONDECYT Government of Chile (Project No.: 11170414). All the authors are thankful to biorender.com for preparation of the images.

References

Adnan MAM, Phoon BL, Julkapli NM (2020) Mitigation of pollutants by chitosan/metallic oxide photocatalyst: a review. J Clean Prod. https://doi.org/10.1016/j.jclepro.2020.121190

Ahmed HB (2019) Recruitment of various biological macromolecules in fabrication of gold nanoparticles: overview for preparation and applications. Int J Biol Macromol. https://doi.org/10.1016/j.ijbiomac.2019.08.138

Alhamlan FS, Al-Qahtani AA, Al-Ahdal MNA (2015) Recommended advanced techniques for waterborne pathogen detection in developing countries. J Infect Dev Ctries 9(02):128–135. https://doi.org/10.3855/jidc.6101

Ali N, Kamal T, Ul-Islam M, Khan A, Shah SJ, Zada A (2018) Chitosan-coated cotton cloth supported copper nanoparticles for toxic dye reduction. Int J Biol Macromol 111:832–838. https://doi.org/10.1016/j.ijbiomac.2018.01.092

Alzahrani E (2015) Eco-friendly production of silver nanoparticles from peel of tangerine for degradation of dye. http://dx.doi.org/10.4236/wjnse.2015.51002

Azizi S, Ahmad M, Hussein M, Ibrahim N (2013) Synthesis, antibacterial and thermal studies of cellulose nanocrystal stabilized ZnO–Ag heterostructure nanoparticles. Molecules 18(6):6269–6280. https://doi.org/10.3390/molecules18066269

Bahal M, Kaur N, Sharotri N, Sud D (2019) Investigations on amphoteric chitosan/TiO_2 bionanocomposites for application in visible light induced photocatalytic degradation. Adv Polym Technol. https://doi.org/10.1155/2019/2345631

Banerjee A, Bandopadhyay R (2016) Use of dextran nanoparticle: a paradigm shift in bacterial exopolysaccharide based biomedical applications. Int J Biol Macromol 87:295–301. https://doi.org/10.1016/j.ijbiomac.2016.02.059

Binaeian E, Seghatoleslami N, Chaichi MJ, Tayebi HA (2016) Preparation of titanium dioxide nanoparticles supported on hexagonal mesoporous silicate (HMS) modified by oak gall tannin and its photocatalytic performance in degradation of azo dye. Adv Powder Technol 27(4):1047–1055. https://doi.org/10.1016/j.apt.2017.05.025

Crini G, Lichtfouse E (2019) Advantages and disadvantages of techniques used in wastewater treatment. Environ Chem Lett 17:145–155. https://doi.org/10.1007/s10311-018-0785-9

Crini G, Lichtfouse E, Wilson LD, Morin-Crini N (2019a) Conventional and non-conventional adsorbents for wastewater treatment. Environ Chem Lett 17:195–213. https://doi.org/10.1007/s10311-018-0786-8

Crini G, Torri G, Lichtfouse E, Kyzas GZ, Wilson LD, Morin-Crini N (2019b) Dye removal by biosorption using cross-linked chitosan-based hydrogels. Environ Chem Lett 17:1645–1666. https://doi.org/10.1007/s10311-019-00903-y

Das RK, Pachapur VL, Lonappan L, Naghdi M, Pulicharla R, Maiti S, Cledon M, Dalila LM, Sarma SJ, Brar SK (2017) Biological synthesis of metallic nanoparticles: plants, animals and microbial aspects. Nanotechnol Environ Eng 2(1):18. https://doi.org/10.1007/s41204-017-0029-4

Devi LG, Kavitha R (2013) A review on non metal ion doped titania for the photocatalytic degradation of organic pollutants under UV/solar light: role of photogenerated charge carrier dynamics in enhancing the activity. Appl Catal B 140:559–587. https://doi.org/10.1016/j.apcatb.2013.04.035

Dong S, Feng J, Fan M, Pi Y, Hu L, Han X, Liu M, Sun J, Sun J (2015) Recent developments in heterogeneous photocatalytic water treatment using visible light-responsive photocatalysts: a review. RSC Adv 5(19):14610–14630. https://doi.org/10.1039/C4RA13734E

Dos Santos AB, Cervantes FJ, Van Lier JB (2007) Review paper on current technologies for decolourisation of textile wastewaters: perspectives for anaerobic biotechnology. Biores Technol 98(12):2369–2385. https://doi.org/10.1016/j.biortech.2006.11.013

Durgalakshmi D, Rajendran S, Naushad M (2019) Current role of nanomaterials in environmental remediation. In: Advanced nanostructured materials for environmental remediation. Springer, Cham, pp 1–20. https://doi.org/10.1007/978-3-030-04477-0_1

Elfeky AS, Salem SS, Elzaref AS, Owda ME, Eladawy HA, Saeed AM, Fouda A (2020) Multifunctional cellulose nanocrystal/metal oxide hybrid, photo-degradation, antibacterial and larvicidal activities. Carbohydr Polym 230:115711. https://doi.org/10.1016/j.carbpol.2019.115711

Farshchi E, Pirsa S, Roufegarinejad L, Alizadeh M, Rezazad M (2019) Photocatalytic/biodegradable film based on carboxymethyl cellulose, modified by gelatin and TiO_2–Ag nanoparticles. Carbohydr Polym 216:189–196. https://doi.org/10.1016/j.carbpol.2019.03.094

Fujishima A, Honda K (1972) Electrochemical photolysis of water at a semiconductor electrode. Nature 238(5358):37. https://doi.org/10.1038/238037a0

Gholami S, Naderi M, Yousefi M, Arjmand MM (2019) The electrochemical removal of bacteria from drinking water. Desalin Water Treat 160:110–115. https://doi.org/10.5004/dwt.2019.24181

Gnanasekaran L, Hemamalini R, Saravanan R, Ravichandran K, Gracia F, Agarwal S, Gupta VK (2017) Synthesis and characterization of metal oxides (CeO_2, CuO, NiO, Mn_3O_4, SnO_2 and ZnO) nanoparticles as photo catalysts for degradation of textile dyes. J Photochem Photobiol, B 173:43–49. https://doi.org/10.1016/j.jphotobiol.2017.05.027

Gnanasekaran L, Hemamalini R, Naushad M (2018) Efficient photocatalytic degradation of toxic dyes using nanostructured TiO_2/

polyaniline nanocomposite. Desalin Water Treat 108:322–328. https://doi.org/10.5004/dwt.2018.21967

Ito T, Adachi Y, Yamanashi Y, Shimada Y (2016) Long–term natural remediation process in textile dye–polluted river sediment driven by bacterial community changes. Water Res 100:458–465. https://doi.org/10.1016/j.watres.2016.05.050

Jawad AH, Mubarak NSA, Abdulhameed AS (2020) Hybrid crosslinked chitosan–epichlorohydrin/TiO_2 nanocomposite for reactive red 120 dye adsorption: kinetic, isotherm, thermodynamic, and mechanism study. J Polym Environ 28(2):624–637. https://doi.org/10.1007/s10924-019-01631-8

Kamal T, Khan SB, Asiri AM (2016) Synthesis of zero-valent Cu nanoparticles in the chitosan coating layer on cellulose microfibers: evaluation of azo dyes catalytic reduction. Cellulose 23(3):1911–1923. https://doi.org/10.1007/s10570-016-0919-9

Karimi-Maleh H, Arotiba OA (2020) Simultaneous determination of cholesterol, ascorbic acid and uric acid as three essential biological compounds at a carbon paste electrode modified with copper oxide decorated reduced graphene oxide nanocomposite and ionic liquid. J Colloid Interface Sci 560:208–212. https://doi.org/10.1016/j.jcis.2019.10.007

Karimi-Maleh H, Karimi F, Alizadeh M, Sanati AL (2019) Electrochemical sensors, a bright future in the fabrication of portable kits in analytical systems. Chem Rec. https://doi.org/10.1002/tcr.201900092

Karimi-Maleh H, Cellat K, Arıkan K, Savk A, Karimi F, Şen F (2020a) Palladium–nickel nanoparticles decorated on functionalized-MWCNT for high precision non-enzymatic glucose sensing. Mater Chem Phys 250:123042. https://doi.org/10.1016/j.matchemphys.2020.123042

Karimi-Maleh H, Karimi F, Malekmohammadi S, Zakariae N, Esmaeili R, Rostamnia S, Razmjou A (2020b) An amplified voltammetric sensor based on platinum nanoparticle/polyoxometalate/two-dimensional hexagonal boron nitride nanosheets composite and ionic liquid for determination of *N*-hydroxysuccinimide in water samples. J Mol Liq. https://doi.org/10.1016/j.molliq.2020.113185

Karimi-Maleh H, Shafieizadeh M, Taher MA, Opoku F, Kiarii EM, Govender PP, Orooji Y (2020c) The role of magnetite/graphene oxide nano-composite as a high-efficiency adsorbent for removal of phenazopyridine residues from water samples, an experimental/theoretical investigation. J Mol Liq 298:112040. https://doi.org/10.1016/j.molliq.2019.112040

Kasiri MB (2019) Application of chitosan derivatives as promising adsorbents for treatment of textile wastewater. In: The impact and prospects of green chemistry for textile technology. Woodhead Publishing, pp 417–469. https://doi.org/10.1016/B978-0-08-102491-1.00014-9

Khan SA, Khan SB, Farooq A, Asiri AM (2019) A facile synthesis of CuAg nanoparticles on highly porous ZnO/carbon black-cellulose acetate sheets for nitroarene and azo dyes reduction/degradation. Int J Biol Macromol 130:288–299. https://doi.org/10.1016/j.ijbiomac.2019.02.114

Khaoulani S, Chaker H, Cadet C, Bychkov E, Cherif L, Bengueddach A, Fourmentin S (2015) Wastewater treatment by cyclodextrin polymers and noble metal/mesoporous TiO_2 photocatalysts. C R Chim 18(1):23–31. https://doi.org/10.1016/j.crci.2014.07.004

Kim HC, Yu MJ (2005) Characterization of natural organic matter in conventional water treatment processes for selection of treatment processes focused on DBPs control. Water Res 39(19):4779–4789. https://doi.org/10.1016/j.watres.2005.09.021

Kolangare IM, Isloor AM, Karim ZA, Kulal A, Ismail AF, Asiri AM (2019) Antibiofouling hollow-fiber membranes for dye rejection by embedding chitosan and silver-loaded chitosan nanoparticles. Environ Chem Lett 17:581–587. https://doi.org/10.1007/s10311-018-0799-3

Kora AJ, Rastogi L (2016) Catalytic degradation of anthropogenic dye pollutants using palladium nanoparticles synthesized by gum olibanum, a glucuronoarabinogalactan biopolymer. Ind Crops Prod 81:1–10. https://doi.org/10.1016/j.indcrop.2015.11.055

Kralik M, Biffis A (2001) Catalysis by metal nanoparticles supported on functional organic polymers. J Mol Catal A: Chem 177(1):113–138. https://doi.org/10.1016/S1381-1169(01)00313-2

Kuo CY, Jheng HK, Syu SE (2019) Effect of non-metal doping on the photocatalytic activity of titanium dioxide on the photodegradation of aqueous bisphenol A. Environ Technol. https://doi.org/10.1080/09593330.2019.1674930

Lade H, Kadam A, Paul D, Govindwar S (2015) Biodegradation and detoxification of textile azo dyes by bacterial consortium under sequential microaerophilic/aerobic processes. EXCLI J 14:158. https://doi.org/10.17179/excli2014-642

Li M, Noriega-Trevino ME, Nino-Martinez N, Marambio-Jones C, Wang J, Damoiseaux R, Hoek EM (2011) Synergistic bactericidal activity of Ag–TiO_2 nanoparticles in both light and dark conditions. Environ Sci Technol 45(20):8989–8995. https://doi.org/10.1021/es201675m

Li G, Li Y, Wang Z, Liu H (2017a) Green synthesis of palladium nanoparticles with carboxymethyl cellulose for degradation of azo-dyes. Mater Chem Phys 187:133–140. https://doi.org/10.1016/j.matchemphys.2016.11.057

Li G, Nandgaonkar AG, Wang Q, Zhang J, Krause WE, Wei Q, Lucia LA (2017b) Laccase-immobilized bacterial cellulose/TiO_2 functionalized composite membranes: evaluation for photo-and biocatalytic dye degradation. J Membr Sci 525:89–98. https://doi.org/10.1016/j.memsci.2016.10.033

Lichtfouse E, Morin-Crini N, Fourmentin M, Zemmouri H, Oliveira Carmo do Nascimento I, Queiroz LM, Tadza MYM, Picos-Corrales LA, Pei H, Wilson LD, Crini G (2019) Chitosan for direct bioflocculation of wastewater. Environ Chem Lett 17:1603–1621. https://doi.org/10.1007/s10311-019-00900-1

Lu Y, Song S, Wang R, Liu Z, Meng J, Sweetman AJ, Jenkins A, Ferrier RC, Li H, Luo W, Wang T (2015) Impacts of soil and water pollution on food safety and health risks in China. Environ Int 77:5–15. https://doi.org/10.1016/j.envint.2014.12.010

Malagutti AR, Mourao HA, Garbin JR, Ribeiro C (2009) Deposition of TiO_2 and Ag: TiO_2 thin films by the polymeric precursor method and their application in the photodegradation of textile dyes. Appl Catal B 90(1–2):205–212. https://doi.org/10.1016/j.apcatb.2009.03.014

Mansur HS, Mansur AAP (2015) Nano-photocatalysts based on ZnS quantum dots/chitosan for the photodegradation of dye pollutants. In: IOP conference series: materials science and engineering, vol 76, no. 1, p 012003. https://doi.org/10.1088/1757-899X/76/1/012003

Mclaren A, Valdes-Solis T, Li G, Tsang SC (2009) Shape and size effects of ZnO nanocrystals on photocatalytic activity. J Am Chem Soc 131(35):12540–12541. https://doi.org/10.1021/ja9052703

Mittal H, Morajkar PP, Al Alili A, Alhassan SM (2020) In-situ synthesis of ZnO nanoparticles using gum arabic based hydrogels as a self-template for effective malachite green dye adsorption. J Polym Environ. https://doi.org/10.1007/s10924-020-01713-y

Moghaddas SMTH, Elahi B, Javanbakht V (2020) Biosynthesis of pure zinc oxide nanoparticles using Quince seed mucilage for photocatalytic dye degradation. J Alloys Compd 821:153519. https://doi.org/10.1016/j.jallcom.2019.153519

Mohanraj J, Durgalakshmi D, Rakkesh RA, Balakumar S, Rajendran S, Karimi-Maleh H (2020) Facile synthesis of paper based graphene electrodes for point of care devices: a double stranded DNA (dsDNA) biosensor. J Colloid Interface Sci 566:463–472. https://doi.org/10.1016/j.jcis.2020.01.089

Morin-Crini N, Lichtfouse E, Torri G, Crini G (2019) Applications of chitosan in food, pharmaceuticals, medicine, cosmetics, agriculture, textiles, pulp and paper, biotechnology, and environmental chemistry. Environ Chem Lett 17:1667–1692. https://doi.org/10.1007/s10311-019-00904-x

Ng LY, Mohammad AW, Leo CP, Hilal N (2013) Polymeric membranes incorporated with metal/metal oxide nanoparticles: a comprehensive review. Desalination 308:15–33. https://doi.org/10.1016/j.desal.2010.11.033

Ngah WW, Teong LC, Hanafiah MAKM (2011) Adsorption of dyes and heavy metal ions by chitosan composites: a review. Carbohydr Polym 83(4):1446–1456. https://doi.org/10.1016/j.carbpol.2010.11.004

Oliveira LV, Bennici S, Josien L, Limousy L, Bizeto MA, Camilo FF (2020) Free-standing cellulose film containing manganese dioxide nanoparticles and its use in discoloration of indigo carmine dye. Carbohydr Polym 230:115621. https://doi.org/10.1016/j.carbpol.2019.115621

Opoku F, Kiarii EM, Govender PP, Mamo MA (2017) Metal oxide polymer nanocomposites in water treatments. Descriptive inorganic chemistry researches of metal compounds. In: IntechOpen, vol 173. https://doi.org/10.5772/67835

Pandey S, Do JY, Kim J, Kang M (2020) Fast and highly efficient catalytic degradation of dyes using κ-carrageenan stabilized silver nanoparticles nanocatalyst. Carbohydr Polym 230:115597. https://doi.org/10.1016/j.carbpol.2019.115597

Prasanna SS, Balaji K, Pandey S, Rana S (2019) Metal oxide based nanomaterials and their polymer nanocomposites. In: Nanomaterials and polymer nanocomposites. Elsevier, pp 123–144. https://doi.org/10.1016/B978-0-12-814615-6.00004-7

Rabeea MA, Owaid MN, Aziz AA, Jameel MS, Dheyab MA (2020) Mycosynthesis of gold nanoparticles using the extract of *Flammulina velutipes*, Physalacriaceae, and their efficacy for decolorization of methylene blue. J Environ Chem Eng. https://doi.org/10.1016/j.jece.2020.103841

Raveendran P, Fu J, Wallen SL (2003) Completely "green" synthesis and stabilization of metal nanoparticles. J Am Chem Soc 125(46):13940–13941. https://doi.org/10.1021/ja029267j

Ravishankar TN, Manjunatha K, Ramakrishnappa T, Nagaraju G, Kumar D, Sarakar S, Anandakumar BS, Chandrappa GT, Reddy V, Dupont J (2014) Comparison of the photocatalytic degradation of trypan blue by undoped and silver-doped zinc oxide nanoparticles. Mater Sci Semicond Process 26:7–17. https://doi.org/10.1016/j.mssp.2014.03.027

Riaz U, Ashraf SM, Kashyap J (2015) Enhancement of photocatalytic properties of transitional metal oxides using conducting polymers: a mini review. Mater Res Bull 71:75–90. https://doi.org/10.1016/j.materresbull.2015.06.035

Rokhmat M, Wibowo E, Sutisna K, Abdullah M (2017) Performance improvement of TiO_2/CuO solar cell by growing copper particle using fix current electroplating method. Procedia Eng 170:72–77. https://doi.org/10.1016/j.proeng.2017.03.014

Sankar R, Rizwana K, Shivashangari KS, Ravikumar V (2015) Ultrarapid photocatalytic activity of *Azadirachta indica* engineered colloidal titanium dioxide nanoparticles. Appl Nanosci 5(6):731–736. https://doi.org/10.1007/s13204-

Saravanan R, Karthikeyan S, Gupta VK, Sekaran G, Narayanan V, Stephen AJMS (2013) Enhanced photocatalytic activity of ZnO/CuO nanocomposite for the degradation of textile dye on visible light illumination. Mater Sci Eng, C 33(1):91–98. https://doi.org/10.1016/j.msec.2012.08.011

Sargin I, Baran T, Arslan G (2020) Environmental remediation by chitosan–carbon nanotube supported palladium nanoparticles: conversion of toxic nitroarenes into aromatic amines, degradation of dye pollutants and green synthesis of biaryls. Sep Purif Technol. https://doi.org/10.1016/j.seppur.2020.116987

Sarkar S, Banerjee A, Halder U, Biswas R, Bandopadhyay R (2017) Degradation of synthetic azo dyes of textile industry: a sustainable approach using microbial enzymes. Water Conserv Sci Eng 2(4):121–131. https://doi.org/10.1007/s41101-017-0031-5

Sarkar S, Banerjee A, Chakraborty N, Soren K, Chakraborty P, Bandopadhyay R (2020) Structural-functional analyses of textile dye degrading azoreductase, laccase and peroxidase: a comparative in silico study. Electron J Biotechnol 43:48–54. https://doi.org/10.1016/j.ejbt.2019.12.004

Sathiyavimal S, Vasantharaj S, Kaliannan T, Pugazhendhi A (2020) Eco-biocompatibility of chitosan coated biosynthesized copper oxide nanocomposite for enhanced industrial (Azo) dye removal from aqueous solution and antibacterial properties. Carbohydr Polym. https://doi.org/10.1016/j.carbpol.2020.116243

Sekomo CB, Rousseau DP, Saleh SA, Lens PN (2012) Heavy metal removal in duckweed and algae ponds as a polishing step for textile wastewater treatment. Ecol Eng 44:102–110. https://doi.org/10.1016/j.ecoleng.2012.03.003

Shah AH, Manikandan E, Ahmed MB, Ganesan V (2013) Enhanced bioactivity of Ag/ZnO nanorods—a comparative antibacterial study. J Nanomed Nanotechol. https://doi.org/10.1016/j.mssp.2014.03.027

Shankar S, Rhim JW (2018) Bionanocomposite films for food packaging applications. Ref Modul Food Sci. https://doi.org/10.1016/B978-0-08-100596-5.21875-1

Sharma M (2019) Transdermal and intravenous nano drug delivery systems: present and future. In: Applications of targeted nano drugs and delivery systems. Elsevier, pp 499–550. https://doi.org/10.1016/B978-0-12-814029-1.00018-1

Sharma KP, Sharma S, Sharma S, Singh PK, Kumar S, Grover R, Sharma PK (2007) A comparative study on characterization of textile wastewaters (untreated and treated) toxicity by chemical and biological tests. Chemosphere 69(1):48–54. https://doi.org/10.1016/j.chemosphere.2007.04.086

Sharma VK, Yngard RA, Lin Y (2009) Silver nanoparticles: green synthesis and their antimicrobial activities. Adv Coll Interface Sci 145(1–2):83–96. https://doi.org/10.1016/j.cis.2008.09.002

Sharma VK, Jinadatha C, Lichtfouse E (2020) Environmental chemistry is most relevant to study coronavirus pandemics. Environ Chem Lett. https://doi.org/10.1007/s10311-020-01017-6

Singh RL, Singh PK, Singh RP (2015) Enzymatic decolorization and degradation of azo dyes—a review. Int Biodeterior Biodegrad 104:21–31. https://doi.org/10.1016/j.ibiod.2015.04.027

Sirajudheen P, Meenakshi S (2019) Facile synthesis of chitosan–La^{3+}-graphite composite and its influence in photocatalytic degradation of methylene blue. Int J Biol Macromol 133:253–261. https://doi.org/10.1016/j.ijbiomac.2019.04.073

Škorić ML, Terzić I, Milosavljević N, Radetić M, Šaponjić Z, Radoičić M, Krušić MK (2016) Chitosan-based microparticles for immobilization of TiO_2 nanoparticles and their application for photodegradation of textile dyes. Eur Polym J 82:57–70. https://doi.org/10.1016/j.eurpolymj.2016.06.026

Sreedharan V, Rao KVB (2019) Biodegradation of Textile Azo Dyes. In: Nanoscience and biotechnology for environmental applications. Springer, Cham, pp 115–139. https://doi.org/10.1007/978-3-319-97922-9_5

Subramanian V, Wolf E, Kamat PV (2001) Semiconductor–metal composite nanostructures To what extent do metal nanoparticles improve the photocatalytic activity of TiO_2 films? J Phys Chem B 105(46):11439–11446. https://doi.org/10.1021/jp011118k

Sulaiman SN, Noh MZ, Adnan NN, Bidin N, Ab Razak SN (2018) Effects of photocatalytic activity of metal and non-metal doped TiO_2 for hydrogen production enhancement—a review. J Phys: Conf Ser 1027(1):012006. https://doi.org/10.1088/1742-6596/1027/1/012006

Sultana S, Ahmad N, Faisal SM, Owais M, Sabir S (2017) Synthesis, characterisation and potential applications of polyaniline/

chitosan–Ag-nano-biocomposite. IET Nanobiotechnol 11(7):835–842. https://doi.org/10.1049/iet-nbt.2016.0215

Taghizadeh MT, Siyahi V, Ashassi-Sorkhabi H, Zarrini G (2020) ZnO, AgCl and AgCl/ZnO nanocomposites incorporated chitosan in the form of hydrogel beads for photocatalytic degradation of MB, *E. coli* and *S. aureus*. Int J Biol Macromol 147:1018–1028. https://doi.org/10.1016/j.ijbiomac.2019.10.070

Tamayo L, Palza H, Bejarano J, Zapata PA (2019) Polymer composites with metal nanoparticles: synthesis, properties, and applications. In: Polymer composites with functionalized nanoparticles. Elsevier, pp 249–286. https://doi.org/10.1016/B978-0-12-814064-2.00008-1

Thakur M, Sharma G, Ahamad T, Ghfar AA, Pathania D, Naushad M (2017) Efficient photocatalytic degradation of toxic dyes from aqueous environment using gelatin-Zr (IV) phosphate nanocomposite and its antimicrobial activity. Colloids Surf B 157:456–463. https://doi.org/10.1016/j.colsurfb.2017.06.018

Tiwari A, Dhoble SJ (2016) Stabilization of ZnS nanoparticles by polymeric matrices: syntheses, optical properties and recent applications. RSC Adv 6(69):64400–64420. https://doi.org/10.1039/C6RA13108E

Ulu A, Birhanli E, Boran F, Köytepe S, Yesilada O, Ateş B (2020) Laccase-conjugated thiolated chitosan–Fe_3O_4 hybrid composite for biocatalytic degradation of organic dyes. Int J Biol Macromol 150:871–884. https://doi.org/10.1016/j.ijbiomac.2020.02.006

Van Berkel KY, Hawker CJ (2010) Tailored composite polymer–metal nanoparticles by miniemulsion polymerization and thiol-ene functionalization. J Polym Sci, Part A: Polym Chem 48(7):1594–1606. https://doi.org/10.1002/pola.23917

Vanaamudan A, Sadhu M, Pamidimukkala P (2018) Chitosan-Guar gum blend silver nanoparticle bionanocomposite with potential for catalytic degradation of dyes and catalytic reduction of nitrophenol. J Mol Liq 271:202–208. https://doi.org/10.1016/j.molliq.2018.08.136

Vilela C, Pinto RJB, Pinto S, Marques P, Silvestre A, Barros CSDRF (2018) Polysaccharides-based hybrids with metal oxide nanoparticles. In: Polysaccharide based hybrid materials. Springer, Cham, pp 31–68. https://doi.org/10.1007/978-3-030-00347-0_3

Wang Q, Yang Z (2016) Industrial water pollution, water environment treatment, and health risks in China. Environ Pollut 218:358–365. https://doi.org/10.1016/j.envpol.2016.07.011

Wang H, Zhang W, Zhao J, Xu L, Zhou C, Chang L, Wang L (2013) Rapid decolorization of phenolic azo dyes by immobilized laccase with Fe_3O_4/SiO_2 nanoparticles as support. Ind Eng Chem Res 52(12):4401–4407. https://doi.org/10.1021/ie302627c

Wen Y, Yuan J, Ma X, Wang S, Liu Y (2019) Polymeric nanocomposite membranes for water treatment: a review. Environ Chem Lett. https://doi.org/10.1007/s10311-019-00895-9

Wutich A, Rosinger AY, Stoler J, Jepson W, Brewis A (2019) Measuring human water needs. Am J Hum Biol 3:e23350. https://doi.org/10.1002/ajhb.23350

Xu C, Anusuyadevi PR, Aymonier C, Luque R, Marre S (2019) Nanostructured materials for photocatalysis. Chem Soc Rev 48(14):3868–3902. https://doi.org/10.1039/C9CS00102F

Yang J, Chen C, Ji H, Ma W, Zhao J (2005) Mechanism of TiO_2-assisted photocatalytic degradation of dyes under visible irradiation: photoelectrocatalytic study by TiO_2-film electrodes. J Phys Chem B 109(46):21900–21907. https://doi.org/10.1021/jp0540914

Yaseen DA, Scholz M (2016) Shallow pond systems planted with Lemna minor treating azo dyes. Ecol Eng 94:295–305. https://doi.org/10.1016/j.ecoleng.2016.05.081

Yaseen DA, Scholz M (2019) Textile dye wastewater characteristics and constituents of synthetic effluents: a critical review. Int J Environ Sci Technol 16(2):1193–1226. https://doi.org/10.1007/s13762-018-2130-z