

Nanoadsorbents: A green approach for wastewater treatment

Suvankar Nandy,^a Anupam Singha Roy^{b,*}

^aDepartment of Chemistry, Rani Rashmoni Green University, Tarakeswar, Hoogly, West Bengal, 712409.

^bDepartment of Chemistry, School of Allied Sciences, Dev Bhoomi Uttarakhand University, Naugaon, Dehradun, Uttarakhand, 248007.

Abstract: The physical, chemical, and biological properties of water have been changed due to the accumulation of different types of pollutants like organic and inorganic materials, pathogens, heavy metals, and other toxic materials. These unwanted materials make the water unsafe for drinking and for the ecosystem, and we can refer it as wastewater. Industries have taken care of treatment of wastewater before it is released to the nature. Several new technologies are developed over the traditional methods. Nanomaterials, with high degree of functionalization, high reactivity, large specific surface area and because of their size dependent properties, have been used for the wastewater treatment and water purification. In this book chapter, the recent developments and the application of nanoadsorbents in wastewater treatment are briefly discussed. The use of metal and metal oxides nanoparticles, carbon-based nanomaterials, zeolite etc. has been discussed in the purification of wastewater.

Keyword: Wastewater; Pollution; Nano-adsorption; Carbon nanotube; Toxicity.

1. INTRODUCTION

We have unlimited source of water in the world but only 2.5% is useable. Water, as a universal solvent, easily dissolve various substances and origins water pollution. Swage, industrial by-products, and leakage of fertilizer causes water pollution [1, 2]. These types of contamination would spread pathogen microbes and harmful disease. Water has influences on human life through health, food, and energy. 3.6 billion people (~45% of the total world's population) do not have basic sanitation service, clean and safe drinking water is unavailable to 1.2 billion people (~15% of the total world's population). Millions of children have lost their lives due to contaminated water [3, 4]. So, appropriate treatment of wastewater is needed before its release to our ecosystem. Wastewater treatment mainly categorise by three main methods: physical, biological, and chemical. These methods are cost effective, require high energy, large plants infrastructure, significant amount of energy consumed mechanical methods, and engineering expertise. Sometimes chemicals like ammonia, sodium hydroxide, permanganate, chlorine compound, hydrochloric acid, ozone, and ferric salt were used to treat wastewater. But these conventional methods are not effective to remove toxins, phosphorous, nitrogen and heavy metals from wastewater. Therefore, it is very difficult to afford such expensive technologies [5, 6].

Now, it is the challenge for researchers to developed cost-effective alternative wastewater treatment processes with small infrastructure. Nanotechnology has a possible role to purify the wastewater; mainly nanomaterials are contributing more to the development of effective wastewater treatment. Recently, nanostructured materials have been used as adsorbents to remove poisonous and harmful ingredients from wastewater [7]. Higher surface functionalization, large specific surface area, and size dependent reactivity make nanomaterials suitable for wastewater and water purification process [8].

This chapter explores some recent development and application of nanoadsorbents in wastewater treatment. The use of various nanomaterials, e.g. carbon nanotube, metal oxide, metal nanoparticles, and zeolite, as nanoadsorbents has been discussed in detail.

2. WASTEWATER: SOURCES, COMPOSITION AND TREATMENT

2.1. Sources and Composition of Wastewater:

The sources of wastewater can be divided into two classes: residential source and non-residential source. Various sources of wastewater are given in Figure 1. Sewage, known as residential wastewater, is released from public residences. Sewage is mainly composed of water (99.90%) and solid matters (0.10%) which includes suspended solids, decomposable dissolve organic compounds, inorganic compounds, nutrients, metals, and pathogenic microorganisms [9]. The typical composition of the sewage water has been shown in Figure 2.



Figure 1. Various sources of wastewater.

Non-residential wastewater is mainly released from agricultural fields, industries, and commercial sectors (*i.e.*, hospitals, restaurants, and shops). The composition of non-residential wastewater depends on the types of sources. For example, fatty substances and grease were found from

restaurant wastewater, whereas textile industry's wastewater contains organic dyes. Moreover, agriculture fields and industrial wastewater contains biological pollutants, harmful chemicals, and heavy metal ions, and these are toxic to living organisms. Another source of non-residential wastewater rain contains organic and inorganic pollutants from street as well as fertilizer and pesticides from agriculture fields.

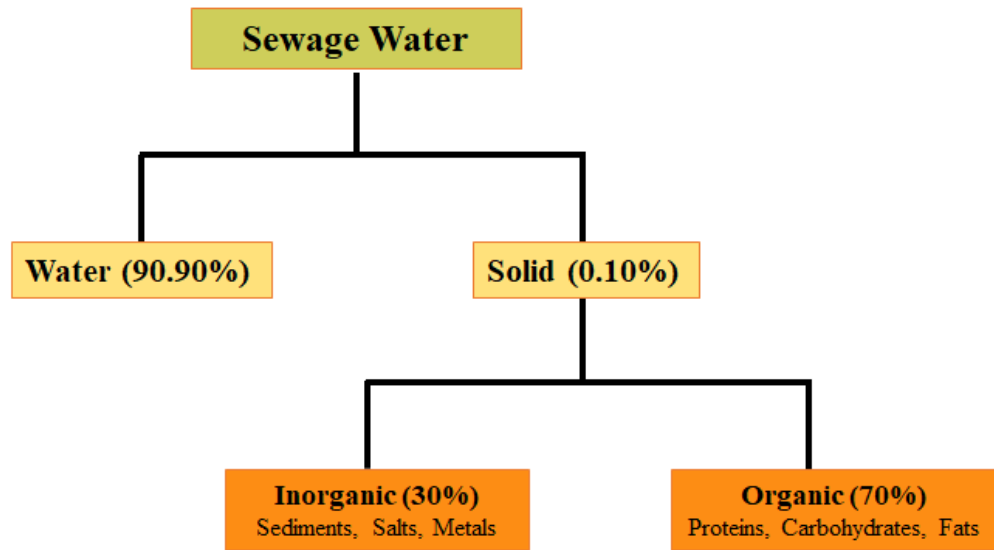


Figure 2. Composition of sewage water

2.2. Wastewater treatment:

Wastewater treatment is a procedure where the pollutants were separated using of physical and chemical methods. Residential and non-residential wastewater can be treated in many ways [10]; at first the wastewater is cleaned in a municipal sewage treatment plant. A large amount of the pollutants can be removed in the treatment plant. The treatment process is composed of three stages: preliminary, primary and secondary stage.

In the preliminary treatment process, large and/or heavy materials were removed. Screening and grit removal processes were usually done during the preliminary treatment. Large floating

fragments including rags (~60%), paper (~25%), and plastic (~5%) were removed during the screening process. After the screening, the grit which includes heavy inorganic particles like sand, was removed by settle down method and used for land filling.

After the preliminary treatment, effluent goes to the primary treatment process where sedimentation process was used to separate the major suspended solid materials from the wastewater. The wastewater is passed through the sedimentation tanks. Most of the solid materials were settle down at the bottom of the tanks, which is known as sludge. These sludges are removed from the bottom of the tank and the effluents moved to the secondary treatment process. Almost 40% of the biological oxygen demand (BOD), 80-90% of suspended solids and up to 55% biological microorganism were removed during the primary treatment process.

In the secondary treatment process organic materials and remaining solid materials were removed. The growth of bacteria and other microorganism were enhanced in this process, and they oxidize the dissolved organic matters to CO_2 and H_2O . In addition, some nutrients such as nitrogen and phosphorus were also removed [9]. A complete process of a wastewater treatment plant is given in Figure 3. After the treatment of sewage, it is very important to make sure that it is safe enough to be released into the environment. Before being released into the environment, the treated sewage is usually disinfected using UV or chlorination method. Anaerobic sludge digestion process is used to treat the sludge, which involves promoting the growth of bacteria inside a digester. The organic particles are reduced by the anaerobic bacteria by degrading them into soluble by-products and gases, mainly CH_4 and CO_2 . The methane gas generated during the process can be used as a fuel for heating the digesters, and for running other power equipment in the plant and the treated sludge is used for land filling or sent to solid waste handling plants.

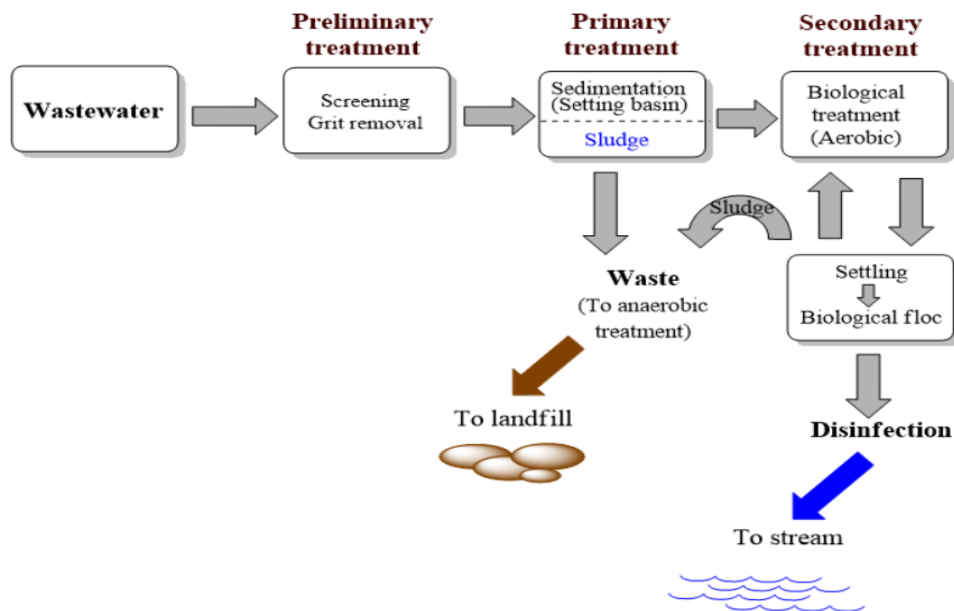


Figure 3. Three stages of the wastewater treatment process in a plant.

Some treatment plants use a tertiary treatment stage along with the above common stages. They use physical and chemical methods to eliminate any remaining organic and inorganic materials as well as microorganisms from the effluent of the secondary stage [11]. The water can satisfy the requirements for drinking water following tertiary treatment.

3. NANOTECHNOLOGY FOR WASTEWATER TREATMENT

Nanotechnology is the synthesis of materials, devices or systems at nanoscale using integration of atoms and molecules. Nanotechnology developed various alternative tools and techniques, especially in the area of treatment of wastewater more efficiently and cost effectively [12]. This is possible because nanomaterials are small in sizes, more accurate, highly reactive, and most importantly they can be synthesized by environment friendly methods that are partially cost effective. Some of the important wastewater treatment techniques or tools introduced by nanotechnology are given below:

- Photocatalysis
- Nanofiltration
- Nanosorbents

3.3. NANOSORBENTS:

In a sorption process, sorbate adsorbs on the surface of sorbent through physical or chemical interactions. Sorbents are commonly used in water purification to remove organic and inorganic pollutants. Generally, there are three processes in sorption through which pollutants were adsorbed on the sorbent surface: (i) the transportation of the pollutants from the water to the sorbent surface, (ii) the adsorption on the surface of sorbent, and (iii) transport within the sorbents. Nanoparticles have higher specific surface area than bulk particles and the addition of different functional groups allows for easy functionalization of the nanomaterials, thereby increasing their affinity towards the target contaminants. Nanosorbents also have pores which help in the sorption process. The reusability of nanosorbents is made possible through the removal of the adsorbed pollutants. For example, it has been shown that the self-assembled 3D flower like iron oxide may successfully filter out heavy metal ions and can adsorb organic dyes from polluted water [13]. Some of the commonly used nanomaterials used as adsorbents are describe bellow:

3.3.1. Carbon nanosorbents:

Carbon nanomaterials have been used for the adsorption of various organic and inorganic contaminants due to their high thermal stability, high adsorption capacity, and low cost. Granular activated carbon (GAC) has been used to remove a wide variety of organic contaminants and odorous pollutants from water [14-16]. The adsorption of benzene and toluene from industrial wastewater on activated carbon was investigated by Asenjo et al [17] and their study reported that benzene exhibited a moderate adsorption capacity of 860 mg/g, whereas toluene showed an even

higher capacity of 1200 mg/g. Activated carbon also active for the elimination of heavy metal ions, like Hg(II), Ni(II), Co(II), Cd(II), Cu(II), Pb(II), Cr(II), and Cr(IV) [18, 19].

In addition to activated carbon, one dimensional carbon-nanotubes (CNTs) are gaining a lot of attention as an excellent adsorbent because of their high surface area, good thermal stability, and chemical stability, the activity of the CNTs can be tuned by simply functionalizing their surface [20]. Luan et al. investigated the application of CNTs for the adsorption of 1,2-dichlorobenzene, lead and cadmium from water [21]. The morphology of CNTs and their surface have shown a significant impact on the adsorption of these pollutants; the treatment of CNTs with oxidants resulted in an increase in both the CNTs' adsorption capacity and dispersibility. Additionally, it was observed that CNTs have a very high adsorption efficiency against dichlorobenzene [22]. When CNTs were annealed at high temperature ($\sim 2200^{\circ}\text{C}$) in an inert atmosphere, the adsorption capacity was decreased with the formation of defect free smooth surface CNTs. Therefore, the defects and rough surfaces of CNTs are essential for the adsorption process [22].

Kuo et al. investigated the application of CNTs in the adsorption of organic dyes from water via physisorption process [23]. Both CNTs and activated carbon are suitable for water treatment process because of their thermal and chemical stability, and high adsorption capabilities. But, due to their small sizes, it is quite difficult to separate them from the water. Incorporation of magnetic nanoparticles with the CNTs or activated carbon was found to be very effective to resolving the above issue. The separation of these magnetic nanocomposite adsorbents is made very simple with the use of magnetic separation process [24, 25].

3.3.2. Biosorption:

Sometimes, the complete removal of certain organic pollutants from water is difficult due to their low concentration, typically in the range of nanograms per liter [26]. Biosorbents, which are often made from biological and agriculture materials, have been found to be effective for elimination of such contamination. Biosorbents have several benefits over conventional absorbents, such as minimum cost, high efficiency, low agriculture and biological sludge formation, no additional nutrients required, and possible to regenerate. Liu et al. created a DNA matrix using salmon milt DNA hydrogel beads, which was effective in selectively adsorbing dioxin derivative [27]. After the dioxin adsorption, the DNA beads can be regenerated easily by simply rinsing the beads with hexane. In other studies, it has been shown that the use of triolein embedded biosorbents can eliminate organic contaminants from water [28, 29]. Triolein has shown a remarkable ability to accumulate trace amounts of organic contaminants in water [30] and its low membrane solubility and permeability are a result of its large molecular mass of 885.45 Da [31]. The sorption of heavy metal ions from water has been done using biosorbents. A biosorbent derived from black liquor, a waste material from paper industries, was developed by Guo et al. to investigate the sorption capacity of heavy metals [32]. The sorption affinity of this biosorbent against various heavy metal ions were reported in the following order: Pb(II) > Cu(II) > Cd(II) > Zn(II) > Ni(II). Biosorbents prepared from various agriculture and waste materials have been used for the removal of heavy metals from water [33-35].

3.3.3. Metal based nanoadsorbents:

Recently, there has been a growing interest among researchers in the use of metal-based nanomaterials as adsorbents [36]. Metal oxides like Fe₃O₄, TiO₂, MnO₂, MgO, ZnO, and CdO are extensively used for the removal of heavy metals, ions and organic dyes from wastewater [37].

Metal oxide nanomaterials exhibit more effectiveness as an adsorbent for the removal of heavy and radioactive metals when compared to activated carbon. Their small size and large surface area provide a reduce intraparticle diffusion distance which can be compressed without any changes to their surface area. The sorption process is mainly regulated by the complexation between dissolved metals and the oxygen in metal oxides [38, 39].

Various metal ions, like calcium (Ca^{2+}) and copper (Cu^{2+}) are present in the wastewater that comes from oil refineries. He et al. has successfully developed a reusable nano-adsorbents using Fe_3O_4 /carboxylate graphene oxide (GO-COOH). This nanocomposite was synthesized through magnetization and carboxylation of graphene oxide (GO). This nano-adsorbents removed 78.4% of Ca^{2+} and 51% of Cu^{2+} ions after 60 min. Upon completion of five consecutive adsorption-desorption cycles, the nano-adsorbent maintained exceptional high recovery rates (82.1% for Ca^{2+} and 91.8% for Cu^{2+}) and achieved significant removal percentages (72% for Ca^{2+} and 49.33% for Cu^{2+}) [40]. Sadak et al. synthesized magnetic nano-adsorbent by conjugating polyacrylic acid (PAA) with ferric oxide (Fe_3O_4) nanoparticles (MNPs). This magnetic nanocomposite was then further functionalized with an azo dye Congo Red (CR) resulting in (PAA-CR/MNPs). PAA-CR/MNPs system exhibited a strong binding affinity towards various cations like Fe^{2+} , Fe^{3+} , Cd^{2+} , Cu^{2+} , and Pb^{2+} . The heavy metal removal efficiency of PAA-CR/MNPs was studied under different pH, temperatures, reaction conditions, and contact times with a specific emphasis on Pb^{2+} . The maximum removal efficiency and adsorption capacity of PAA-CR/MNPs for Pb^{2+} were observed at a pH 6.5 and reaction time of 45 min [41].

Arshadi et al. developed an adsorbent using sineguelas waste (S-NaOH) derived from agricultural biomass which was further modified with nanoscale zerovalent iron particles (NZVIPs). The above designed system was utilized to study the adsorption and reduction of inorganic pollutants like

Pb²⁺ ions. The NZVIPs have shown proper dispersion throughout the surface of the sineguelas waste [42]. Using lead-doped zinc-aluminium oxide nanoparticles, Jethave et al. developed an effective nano-adsorbent for the adsorption of anionic dyes like methyl orange (MO). After 30 min, the above system has shown an impressive MO removal efficiency of 99.6%, additionally it exhibited a maximum adsorption capacity of 200 mg/g for MO [43].

3.3.4. Polymer based nano-adsorbents:

Over the last few years, a numerous studies have developed on polymer nanocomposites to explore their potential applications in environmental sustainability and wastewater treatment process. Their high surface area for fast decontamination, notable stability, improved processability, cost effectiveness, and selectivity to remove various pollutants from water make them suitable for the treatment of wastewater [44, 45]. Nanocelluloses, derived from cellulose, possess a wide range of advantages and their surface can be effectively modified which make them a suitable candidate for wastewater treatment. In recent years, the development of lignin derived nanomaterials has been studied, and have shown exceptional potential in the field of wastewater treatment. The efficiency of this material has been confirmed in the catalytic decomposition of dyes, nitroarenes, and in the removal of heavy metals [46].

Abdi and Abedini established a metal organic framework adsorbent using zeolitic imidazolate framework (ZIF) within polyether sulfone (PES) nanocomposite beads to remove malachite green (MG) from wastewater [47]. Moharrami and Motamedi developed a biologically derived nanocomposite hydrogel using starch grafted copolymers consisting of 2-acrylamido-2-methyl propene sulfonate and acrylic acid. Its properties can be further enhanced by incorporating cellulose nanocrystals functionalized with magnetic (M-CNCs). This hydrogel demonstrated excellent adsorption capabilities for cationic dyes such as crystal violet (CV) and methylene blue

(MB). For CV, the adsorption capacity of this hydrogel is 2500 mg/g, while for MB it is 1428.6 mg/g [48].

The preparation of nano-adsorbents for arsenic (As) removal was reported by Priya et al. These nano-adsorbents were based on iron-aluminium (Fe-Al) layered dual hydroxide/reduced GO (rGO) coated with sodium alginate (SA). The resulting nano-adsorbents were denoted as FAH-rGO/SA. It was determined that the FAH-rGO/SA-4, FAH-rGO/SA-1, and FAH-rGO samples exhibited maximum adsorption capacities of 190.84 mg/g, 151.29 mg/g, and 115.39 mg/g, respectively. The result showed that a high weight percentage of SA was responsible for the excellent removal efficiency (> 98%) of FAH-rGO for As(V) [49]. Oilfield produced water is highly salinized because it contains metal like Ca^{2+} and Mg^{2+} . He et al. created nano-adsorbents composed of polyethylene glycol (PEG), aminated GO (NH_2 -GO), and magnetic Fe_3O_4 nanoparticles. This prepared system showed removal rates 69.8% for Ca^{2+} and 61.1% for Mg^{2+} at 10 min. Overall results indicated that it was stable and reusable for treating oilfield wastewater [50].

3.3.5. Zeolites:

Zeolites are crystalline microporous materials with a three-dimensional structure. They possess well defined voids and channels of distinct sizes. These can be easily accessed through pores with well-defined molecular dimensions. These pores can retain aluminium, silicon and oxygen within their normal framework [51, 52]. With its high specific surface area and high ion exchange capacity, zeolites prove to be highly attractive adsorbent for wastewater treatment. Dong et al. developed a modified zeolite known as hexadecyltrimethylammonium (HDTMA) [53], which was utilized in the removal of phenol derivatives from water. The bilayer micelle formed by the HDTMA on the zeolite surface enhances the adsorption capacity of the nano-adsorbents. Bai et al. studied the degradation of pyridine and quinoline in wastewater utilizing zeolite [54]. The

researchers created a biological modified zeolite containing a combination of bacteria for the decomposition of pyridine and quinoline. The biodegradation of pyridine and quinoline in water generate ammonium ions which are adsorbed by the zeolites.

Zeolites have also been used for adsorption of heavy metal ions. The investigation on the adsorption of lead and cadmium was carried out by Perry et al. using two natural zeolites, chabazite and clinoptilolite [55]. The author showed an exceptional adsorption capacity for lead (Pb) and cadmium (Cd) by utilizing two naturally occurring zeolites that were treated with NaOH, achieving a metal removal efficiency exceeding 99%. Zeolite has higher adsorption capacity due to its high porosity. Additionally, zeolite's photocatalytic reduction property facilitates the conversion of high valence metal ions to lower valence metal ions and effectively reducing their toxicity.

4. LIMITATIONS AND RISKS ASSOCIATED WITH NANOTECHNOLOGY

Nanotechnology has demonstrated encouraging results in the treatment of wastewater; however, there are considerable limitations in the way of these successful outcomes. The primary limitations involve nanomaterial toxicity, cost effectiveness, and social acceptability. Risks may arise from nanomaterials transformation, ecotoxicity linked to engineered nanomaterials, and water pollutions.

4.1. Nanomaterial toxicity:

Several past wastewater treatment methods have produced adverse effects. Chlorination, a traditional method of wastewater treatment, was initially believed to have a positive impact on global life. However, further research found that it actually generates harmful by-products, such as N-nitrosodimethylamine and trihalomethanes. The characteristics properties that contribute to the effectiveness of nanomaterials are also the ones that make them prone to toxicity. Toxicity

level is determined by the molecular structure of the components, which in turn influences the toxicity endpoint, while the size of the nanomaterials regulates their uptake by cells. Due to their small size, nanoparticles can penetrate epithelial and endothelial barriers, enable to enter the lymph and blood. They can distribute to various organs and tissues, such as the brain, heart, kidneys, liver, spleen, bone marrow and nervous system [56]. It has been observed that the toxicity of Ag nanoparticles, carbon nanotubes, and various metal nanoparticles is dependent on their size and shape. Nanoparticles, ranging from 1 to 100 nm in size, share similarities in dimensions with protein globules (2-10 nm), DNA helix (2 nm) and cell membranes thicknesses (10 nm), allowing them to easy penetrate into cells and cell organs [57]. According to Huo et al. gold nanoparticles size smaller than 6 nm can efficiently enter the nucleus, whereas larger nanoparticles, ranging in size from 10 to 16 nm, are capable of penetrating the cell membrane and are located in the cytoplasm [58]. According to the reports, TiO₂ nanoparticles induce a conformational change in tubulin, leading to the inhibition of its polymerization. Consequently, this has a significant impact on intracellular transport, cell migration and cell division. Spherical nanoparticles exhibit a higher susceptibility to endocytosis compared to nanotubes and nanofibers. Studies have indicated that single-walled CNTs have proven to be more efficient in blocking calcium channels than spherical nanoparticles. Plate, rod, needle, and spherical hydroxyapatite nanoparticles were used for toxicity testing, also their impact on nontumorigenic lung epithelial cells was evaluated. The results showed that plate and needle-like nanoparticles killed a higher percentage of nontumorigenic lung epithelial cells than spherical or rod like nanoparticles.

4.2. Cost effectiveness:

The acceptability of nanotechnology is directly depending on its effectiveness and affordability in wastewater treatment. In developing countries, advanced technologies are employed to remove a

wide range of pollutants in wastewater treatment, whereas in developing countries, the primary focus is on fulfilling basic requirements such as disinfectant. The treatment of increasingly complex pollutant mixtures is utilized in both cases to attain a superior water quality at a reduced cost. This approach pushes the limits of recent wastewater treatment models. The production cost of nanomaterials is directly linked to the methods of separation and purification. Lowering the purity levels of nanomaterials can enhance their applicability for wastewater treatment purposes. A significant cost reduction of approximately 90% can be achieved by substituting ultrapure C60 with fullerene soot in the production of amino-fullerene [59]. However, this replacement leads to a decrease in its effectiveness. The long-term responsibility of nanomaterials can also improve their cost effectiveness. The given example showed that the application of photocatalysis retains its functionality by regenerating nano-adsorbents. Additionally, it involves magnetically separable multifunctional nanomaterials that allow for multiple reuse cycles [60].

4.3. Transformation of nanomaterials risk in water:

Compared to larger particles, nanoparticles have a slower settling rate. However, owing to their significant surface area, they have the ability to adsorb a great number of sediment particles and soil. Their insolubility in water, mainly carbon nanotubes and fullerenes, makes them easily removable through water columns. Engineered nanomaterials are occasionally utilized for specific purposes, pristine-engineered nanomaterials that have the potential to transform into different forms such as product-modified, product-weathered, and environmentally transferred engineered nanomaterials. Light can sometimes enhance the oxidation-reduction process, leading to photochemical transformations. The interactions between nanoparticles and the environment led to subsequent transformations, ultimately governing the adsorption and desorption of pollutants in water [61].

4.4. Ecotoxicity associated with nanomaterials:

Ecotoxicity is the likelihood of chemical, physical or biological stressors causing disturbance to the ecosystem. Nanomaterials carry a risk of leaching into the treated water during the production, usage, and disposal of products containing nanoparticle. Emerging metal nanoparticles such as Ag and TiO₂ have a higher production rate per year [62]. These rising nanomaterials are raising serious concern for the aquatic environment, as shown in a study that investigated the inhibitory effects of Ag nanoparticles and TiO₂ nanoparticles on the growth of duckweed, an aquatic plant [63].

Nanoparticle concentrations in some natural surface waters are estimated to be in the nano or micro g/L range. These concentrations are expected to increase with the growing productions of nanoparticles. Most developing countries use silver, titanium, and zinc oxide nanoparticles to disinfect water and replace chemical disinfectants due to their antibacterial properties [64]. Ceramic filters containing Ag nanoparticles impregnated are utilized for water filtration. Following filtration through nano-Ag-coated filter papers, detectable amounts of Ag nanoparticles were identified in the filtered water, significantly lower than the WHO's established threshold [65]. Some studies have reported significant organ damage in rats that consumed TiO₂ nanoparticles in contaminated water. Similarly, engineered nanoparticles have been linked to various health issues such as pulmonary inflammation, genotoxicity, carcinogenicity, and circulatory effects [66].

4.5. Water pollutions:

Several research works have been conducted to test the toxic effects of nanomaterials contaminated water. The toxic effect of MWCNTs on *Astyanax altiparanae* and *Danio rerio* fish species were investigated by Cimbaluk et al. They identified the potential for CNTs-DNA crosslinking, the development of oxidative stress, as well as acute and subchronic nanotoxicity in these species [67].

The effects of Ag nanoparticle treated water on freshwater fish were examined by Khan et al., they observed a rise in oxidative stress and genotoxicity [68]. Due to the limited solubility of nanomaterials in water, it has been suggested that their toxicity is attributed to the dispersant employed to disperse them. For example, tetrahydrofuran is an excellent dispersant used for CNTs and C60 fullerenes, which gives rise to concerns regarding its potential toxicity [69]. The possible biological and ecological toxicity of using nanotechnology in wastewater treatment is systematically investigated. One such possibility has been ruled out, the applications of nanotechnology could yield favorable results in this field, depending on the approaches being explored by scientists to decrease the cost associated with nanomaterials. But, the preliminary findings shows that nanotechnology can effectively clean wastewater and the development is expected to enhance their safety threshold.

Conclusion

The inorganic and organic waste from water can be controlled by current wastewater treatment process. However, these techniques require a significant amount of energy and are not cost-effective due to the challenges to fully purifying water and reusing the remaining substances. In future, nanotechnology will have a significant impact on the wastewater treatment. Due to their exceptional qualities, nanomaterials are highly suitable for use in water treatment. Their high surface to volume ratio, reactivity, sensitivity, and adsorption capabilities allow for efficient removal of diverse organic and inorganic pollutants, heavy metal and harmful microbes that contaminate water sources. The design of nanomaterials allows for the efficient utilization of solar energy, a readily available resource. These nanomaterials can serve as visible light photocatalysts, offering a cost-effective solution for treating contaminated water. The future of wastewater treatment will see nanomaterials taking on a vital role, thanks to ongoing developments in

economically efficient and eco-friendly technology. Nanoengineered materials hold immense promise for water treatment in the forthcoming decades, particularly in the realm of decentralized treatment system, point-of-use devices, and highly degradable pollutants.

Acknowledgement

Suvankar Nandy thankful to all the faculty members of Department of Chemistry, Rani Rashmoni Green University for their guidance and advice. Anupam Singha Roy acknowledges Dev Bhoomi Uttarakhand University.

References:

1. R. C. Olvera, S. L. Silva, E. Robles-Belmont, E. Z. Lau, Review of nanotechnology value chain for water treatment applications in Mexico, *Resour. Technol.* 3 (2017) 1-11. <https://doi.org/10.1016/j.reffit.2017.01.008>
2. I. Singh, P. K. Mishra, Nano-membrane Filtration a Novel Application of Nanotechnology for waste Water Treatment, *Mater. Today Proc.* 29 (2020) 327-332. <https://doi.org/10.1016/j.matpr.2020.07.284>
3. S. Kumar, W. Ahlawat, G. Bhanjana, S. Heydarifard, M. M. Nazhad, N. Dilbaghi, Nanotechnology-Based Water Treatment Strategies, *J. Nanosci. Nanotechnol.* 14 (2014) 1838-58. <https://doi.org/10.1166/jnn.2014.9050>
4. H. Yamamura, M. Hashino, N. Kubota, Membrane Filtration: Principle and Applications in Water Treatment, SEN-I GAKKAISHI 2011.
5. X. Qu, J. Brame, Q. Li, P. J. J. Alvarez, Nanotechnology for a Safe and Sustainable Water Supply: Enabling Integrated Water Treatment and Reuse, *Acc. Chem. Res.* 46 (2013) 834-843. <https://doi.org/10.1021/ar300029v>
6. P. Rajasulochana, V. Preethy, Comparison on efficiency of various techniques in treatment of waste and sewage water – A comprehensive review, *Resour. Technol.* 2 (2016) 175-184. <https://doi.org/10.1016/j.reffit.2016.09.004>
7. N. H. H. Hairom, C. F. Soon, R. M. S. R. Mohamed, M. Morsin, N. Zainal, N. Nayan, C. Z. Zulkifli, N. H. Harun, A review of nanotechnological applications to detect and control

- surface water pollution, *Environ. Technol. Innov.* 24 (2021) 102032.
<https://doi.org/10.1016/j.eti.2021.102032>
- 8 E. T. Cloete, M. de Kwaadsteniet, M. Botes, J. M. Lopez-Romero, *Nanotechnology in Water Treatment Applications*, Caister Academic Press, Poole, UK (2010). <https://doi.org/10.21775/9781910190098>
 - 9 M. R. Templeton, P. D. Butler, *Introduction to Wastewater Treatment*, Bookboon, London (2011)
 - 10 F. S. G. Einschlag, *Waste Water—Evaluation and Management*, InTech, Rijeka, Croatia (2011)
 - 11 G. Tchobanoglous, F. L. Burton, H. D. Stensel, *Wastewater Engineering: Treatment and Reuse*, McGraw-Hill Education, Whitby, Canada (2003).
 - 12 S. Baruah, S. K. Pal, J. Dutta, *Nanostructured Zinc Oxide for Water Treatment*, *Nanosci. Nanotechnol. Asia* 2 (2012) 90-102.
<https://doi.org/10.2174/2210681211202020090>
 - 13 L. S. Zhong, J. S. Hu, H. P. Liang, A. M. Cao, W. G. Song, L. J. Wan, *Self-Assembled 3D Flowerlike Iron Oxide Nanostructures and Their Application in Water Treatment*, *Adv. Mater.* 18 (2006) 2426- 2431. <https://doi.org/10.1002/adma.200600504>
 - 14 A. Dabrowski, *Adsorption—From Theory to Practice*, *Adv. Colloid Interface Sci.* 93 (2001) 135-224. [http://dx.doi.org/10.1016/S0001-8686\(00\)00082-8](http://dx.doi.org/10.1016/S0001-8686(00)00082-8)
 - 15 D. S. Chaudhary, S. Vigneswaran, V. Jegatheesan, H. H. Ngo, H. Moon, W. G. Shim, S. H. Kim, *Granular activated carbon (GAC) adsorption in tertiary wastewater treatment: experiments and models*, *Water Sci. Technol.* 47 (2003) 113-120.
<https://doi.org/10.2166/wst.2003.0030>
 - 16 F. Cecen, O. Aktas, *Activated Carbon for Water and Wastewater Treatment: Integration of Adsorption and Biological Treatment*, Wiley-VCH, Weinheim, Germany (2011)
 - 17 N. G. Asenjo, P. Alvarez, M. Granda, C. Blanco, R. Santamaria, R. Menendez, *High performance activated carbon for benzene/toluene adsorption from industrial wastewater*, *J. Hazard Mater.* 192 (2011) 1525-1535.
<https://doi.org/10.1016/j.jhazmat.2011.06.072>

- 18 M. Kobyas, E. Demirbas, E. Senturk, M. Ince, Adsorption of heavy metal ions from aqueous solutions by activated carbon prepared from apricot stone, *Bioresource Technol.* 96 (2005) 1518-1521. <https://doi.org/10.1016/j.biortech.2004.12.005>
- 19 M. A. Al-Omair, E. A. El-Sharkawy, Removal of Heavy Metals Via Adsorption on Activated Carbon Synthesized from Solid Wastes, *Environ. Technol.* 28 (2007) 443-451. <https://doi.org/10.1080/09593332808618808>
- 20 E. Tamburri, S. Orlanducci, M. L. Terranova, F. Valentini, G. Palleschi, A. Curulli, F. Brunetti, D. Passeri, A. Alippi, M. Rossi, Modulation of electrical properties in single-walled carbon nanotube/conducting polymer composites, *Carbon* 43 (2005) 1213-1221. <https://doi.org/10.1016/j.carbon.2004.12.014>
- 21 Y. H. Li, Y. M. Zhao, W. B. Hu, I. Ahmad, Y. Q. Zhu, X. J. Peng, Z. K. Luan, Carbon nanotubes-the promising adsorbent in wastewater treatment, *J. Phys.: Conf. Ser.* 61 (2007) 698. [10.1088/1742-6596/61/1/140](https://doi.org/10.1088/1742-6596/61/1/140)
- 22 X. Peng, Y. Li, Z. Luan, Z. Di, H. Wang, B. Tian, Z. Jia, Adsorption of 1,2-dichlorobenzene from water to carbon nanotubes, *Chem. Phys. Lett.* 376 (2003) 154-158. [https://doi.org/10.1016/S0009-2614\(03\)00960-6](https://doi.org/10.1016/S0009-2614(03)00960-6)
- 23 C.-Y. Kuo, C.-H. Wu, J.-Y. Wu, Adsorption of direct dyes from aqueous solutions by carbon nanotubes: Determination of equilibrium, kinetics and thermodynamics parameters, *J. Colloid Interface Sci.* 327 (2008) 308-315. <https://doi.org/10.1016/j.jcis.2008.08.038>
- 24 L. C. V. de Oliveira, R. V. R. A. Rios, J. D. Fabris, V. K. Garg, K. Sapag, R. M. Lago, Activated Carbon/Iron Oxide Magnetic Composites for the Adsorption of Contaminants in Water, *Carbon* 40 (2002) 2177-2183. [10.1016/S0008-6223\(02\)00076-3](https://doi.org/10.1016/S0008-6223(02)00076-3)
- 25 P. Gorria, M. Sevilla, J. A. Blanco, A. B. Fuertes, Synthesis of magnetically separable adsorbents through the incorporation of protected nickel nanoparticles in an activated carbon, *Carbon* 44 (2006) 1954-1957. <https://doi.org/10.1016/j.carbon.2006.02.013>
- 26 Z. L. Zhang, H. S. Hong, J. L. Zhou, J. Huang, G. Yu, Fate and assessment of persistent organic pollutants in water and sediment from Minjiang River Estuary, Southeast China, *Chemosphere* 52 (2003) 1423-1430. [https://doi.org/10.1016/S0045-6535\(03\)00478-8](https://doi.org/10.1016/S0045-6535(03)00478-8)

- 27 X. D. Liu, Y. Murayama, M. Matsunaga, M. Nomizu, N. Nishi, Preparation and characterization of DNA hydrogel bead as selective adsorbent of dioxins, *Int. J. Biol. Macromol.* 35 (2005) 193-199. <https://doi.org/10.1016/j.ijbiomac.2005.01.008>
- 28 J. Huo, H. Liu, J. Qu, Z. Wang, J. Ge, H. Liu, Preparation and characteristic of triolein-embedded composite sorbents for water purification, *Sep. Purif. Technol.* 44 (2005) 37-43. <https://doi.org/10.1016/j.seppur.2004.12.001>
- 29 H. Liu, J. Qu, R. Dai, J. Ru, Z. Wang, A biomimetic absorbent for removal of trace level persistent organic pollutants from water, *Environ. Pollut.* 147 (2007) 337-342. <https://doi.org/10.1016/j.envpol.2006.06.031>
- 30 C. T. Chiou, Partition coefficients of organic compounds in lipid-water systems and correlations with fish bioconcentration factors, *Environ. Sci. Technol.* 19 (1985) 57-62. <https://doi.org/10.1021/es00131a005>
- 31 J. N. Huckins, M. W. Tubergen, G. K. Manuweera, Semipermeable membrane devices containing model lipid: A new approach to monitoring the bioavailability of lipophilic contaminants and estimating their bioconcentration potential, *Chemosphere* 20 (1990) 533-552. [https://doi.org/10.1016/0045-6535\(90\)90110-F](https://doi.org/10.1016/0045-6535(90)90110-F)
- 32 X. Guo, S. Zhang, X.-q. Shan, Adsorption of metal ions on lignin, *J. Hazard Mater.* 151 (2008) 134-142. <https://doi.org/10.1016/j.jhazmat.2007.05.065>
- 33 H. Aydın, Y. Bulut, Ç. Yerlikaya, Removal of copper (II) from aqueous solution by adsorption onto low-cost adsorbents, *J. Environ. Manage.* 87 (2008) 37-45. <https://doi.org/10.1016/j.jenvman.2007.01.005>
- 34 U. Kumar, M. Bandyopadhyay, Sorption of cadmium from aqueous solution using pretreated rice husk, *Bioresour. Technol.* 97 (2006) 104-109. <https://doi.org/10.1016/j.biortech.2005.02.027>
- 35 K. Conrad, H. C. B. Hansen, Sorption of zinc and lead on coir, *Bioresour. Technol.* 98 (2007) 89-97. <https://doi.org/10.1016/j.biortech.2005.11.018>
- 36 H. Lu, J. Wang, M. Stoller, T. Wang, Y. Bao, H. Hao, An Overview of Nanomaterials for Water and Wastewater Treatment, *Adv. Mater. Sci. Eng.* 2016 (2016) 1–10. <https://doi.org/10.1155/2016/4964828>
- 37 H. Sadegh, G. A. M. Ali, V. K. Gupta, A. S. H. Makhlof, R. Shahryari-ghoshekandi, M. N. Nadagouda, M. Sillanpää, E. Megiel, The role of nanomaterials as effective adsorbents

- and their applications in wastewater treatment, *J. Nanostruct. Chem.* 7 (2017) 1–14. DOI 10.1007/s40097-017-0219-4
- 38 M. E. A. El-Sayed, Nanoadsorbents for water and wastewater remediation, *Sci. Total Environ.* 739 (2020) 139903. <https://doi.org/10.1016/j.scitotenv.2020.139903>
- 39 X. Qu, P. J. J. Alvarez, Q. Li, Applications of nanotechnology in water and wastewater treatment, *Water Res.* 47 (2013) 3931–3946. <https://doi.org/10.1016/j.watres.2012.09.058>
- 40 L. He, L. Wang, H. Zhu, Z. Wang, L. Zhang, L. Yang, Y. Dai, H. Mo, J. Zhang, J. Shen, A reusable Fe₃O₄/GO-COOH nanoadsorbent for Ca²⁺ and Cu²⁺ removal from oilfield wastewater, *Chem. Eng. Res. Des.* 166 (2021) 248–258. <https://doi.org/10.1016/j.cherd.2020.12.019>
- 41 O. Sadak, R. Hackney, A. K. Sundramoorthy, G. Yilmaz, S. Gunasekaran, Azo dye-functionalized magnetic Fe₃O₄/polyacrylic acid nanoadsorbent for removal of lead (II) ions, *Environ. Nanotechnol. Monit. Manag.* 14 (2020) 100380. <https://doi.org/10.1016/j.enmm.2020.100380>
- 42 M. Arshadi, M. Soleymanzadeh, J. W. L. Salvacion, F. SalimiVahid, Nanoscale Zero-Valent Iron (NZVI) supported on *sineguas* waste for Pb(II) removal from aqueous solution: Kinetics, thermodynamic and mechanism, *J. Colloid Interface Sci.* 426 (2014) 241–251. <https://doi.org/10.1016/j.jcis.2014.04.014>
- 43 G. Jethave, U. Fegade, S. Attarde, S. Ingle, Facile synthesis of Lead Doped Zinc-Aluminum Oxide Nanoparticles (LD-ZAO-NPs) for efficient adsorption of anionic dye: Kinetic, isotherm and thermodynamic behaviors, *J. Ind. Eng. Chem.* 53 (2017) 294–306. <https://doi.org/10.1016/j.jiec.2017.04.038>
- 44 N. Pandey, S. K. Shukla, N. B. Singh, Water purification by polymer nanocomposites: an overview, *Nanocomposites.* 3 (2017) 47–66. <https://doi.org/10.1080/20550324.2017.1329983>
- 45 M. R. Berber, Current Advances of Polymer Composites for Water Treatment and Desalination, *J. Chem.* 2020 (2020) 1–19. <https://doi.org/10.1155/2020/7608423>
- 46 D. H. K. Reddy, S.-M. Lee, Application of magnetic chitosan composites for the removal of toxic metal and dyes from aqueous solutions, *Adv. Colloid Interface Sci.* 201 (2013) 68–93. <https://doi.org/10.1016/j.cis.2013.10.002>

- 47 J. Abdi, H. Abedini, MOF-based polymeric nanocomposite beads as an efficient adsorbent for wastewater treatment in batch and continuous systems: Modelling and experiment, *Chem. Eng. J.* 400 (2020) 125862.
<https://doi.org/10.1016/j.cej.2020.125862>
- 48 P. Moharrami, E. Motamedi, Application of cellulose nanocrystals prepared from agricultural wastes for synthesis of starch-based hydrogel nanocomposites: Efficient and selective nanoadsorbent for removal of cationic dyes from water, *Bioresour. Technol.* 313 (2020) 123661. DOI: 10.1016/j.biortech.2020.123661
- 49 V. Nithya Priya, M. Rajkumar, J. Mobika, S. P. Linto Sibi, Alginate coated layered double hydroxide/reduced graphene oxide nanocomposites for removal of toxic As (V) from wastewater, *Phys. E: Low-Dimens. Syst. Nanostructures* 127 (2021) 114527.
<https://doi.org/10.1016/j.physe.2020.114527>
- 50 L. He, L. Yang, L. Zhang, Z. Wang, H. Cheng, X. Wang, J. Lv; J. Zhang, H. Mo, J. Shen, Removal of Ca^{2+} and Mg^{2+} from oilfield wastewater using reusable PEG/ Fe_3O_4 /GO- NH_2 nanoadsorbents and its efficiency for oil recovery, *J. Environ. Chem. Eng.* 9 (2020) 104653. <https://doi.org/10.1016/j.jece.2020.104653>
- 51 A. Esmaili, B. Saremnia, Synthesis and characterization of NaA zeolite nanoparticles from *Hordeum vulgare* L. husk for the separation of total petroleum hydrocarbon by an adsorption process, *J. Taiwan Inst. Chem. Eng.* 61 (2016) 276–286.
<https://doi.org/10.1016/j.jtice.2015.12.031>
- 52 M. E. Ali, M. E. Hoque, S. K. S. Hossain, M. C. Biswas, Nanoadsorbents for wastewater treatment: Next generation biotechnological solution, *Int. J. Environ. Sci. Technol.* 17 (2020) 4095–4132. <https://doi.org/10.1007/s13762-020-02755-4>
- 53 Y. Dong, D. Wu, X. Chen, Y. Lin, Adsorption of bisphenol A from water by surfactant-modified zeolite, *J. Colloid Interface Sci.* 348 (2010) 585-590.
<https://doi.org/10.1016/j.jcis.2010.04.074>
- 54 Y. Bai, Q. Sun, R. Xing, D. Wen, X. Tang, Removal of pyridine and quinoline by bio-zeolite composed of mixed degrading bacteria and modified zeolite, *J. Hazard Mater.* 181 (2010) 916-922. <https://doi.org/10.1016/j.jhazmat.2010.05.099>

- 55 S. Kesraoui-Ouki, C. Cheeseman, R. Perry, Effects of conditioning and treatment of chabazite and clinoptilolite prior to lead and cadmium removal, *Environ. Sci. Technol.* 27 (1993) 1108-1116. <https://doi.org/10.1021/es00043a009>
- 56 A. Sukhanova, S. Bozrova, P. Sokolov, M. Berestovoy, A. Karaulov, I. Nabiev, Dependence of Nanoparticle Toxicity on Their Physical and Chemical Properties, *Nanoscale Res. Lett.* 13 (2018) 1–21. <https://doi.org/10.1186/s11671-018-2457-x>
- 57 A. Anand, U. Rajchakit, V. Sarojini, Detection and removal of biological contaminants in water. In *Nanomaterials for the Detection and Removal of Wastewater Pollutants*, Elsevier: Amsterdam, Netherlands (2020) pp. 69–110. DOI:10.1016/B978-0-12-818489-9.00004-9
- 58 S. Huo, S. Jin, X. Ma, X. Xue, K. Yang, A. Kumar, P. C. Wang, J. Zhang, Z. Hu, X. J. Liang, Ultrasmall Gold Nanoparticles as Carriers for Nucleus-Based Gene Therapy Due to Size-Dependent Nuclear Entry, *ACS Nano* 8 (2014) 5852-5862. <https://doi.org/10.1021/nn5008572>
- 59 Y. Pan, X. Liu, W. Zhang, Z. Liu, G. Zeng, B. Shao, Q. Liang, Q. He, X. Yuan, D. Huang, M. Chen, Advances in photocatalysis based on fullerene C₆₀ and its derivatives: Properties, mechanism, synthesis, and applications, *Appl. Catal. B: Environ.* 265 (2020) 118579. <https://doi.org/10.1016/j.apcatb.2019.118579>
- 60 P. Kokkinos, D. Mantzavinos, D. Venieri, Current Trends in the Application of Nanomaterials for the Removal of Emerging Micropollutants and Pathogens from Water, *Molecules* 25 (2020) 2016. <https://doi.org/10.3390/molecules25092016>
- 61 P. K. Westerhoff, M. A. Kiser, K. Hristovski, Nanomaterial Removal and Transformation During Biological Wastewater Treatment, *Environ. Eng. Sci.* 30 (2013) 109–117. DOI:10.1089/ees.2012.0340
- 62 C. O. Robichaud, A. E. Uyar, M. R. Darby, L. G. Zucker, M. R. Wiesner, Estimates of Upper Bounds and Trends in Nano-TiO₂ Production As a Basis for Exposure Assessment, *Environ. Sci. Technol.* 43 (2009) 4227–4233. <https://doi.org/10.1021/es8032549>
- 63 E. Kim, S.-H. Kim, H.-C. Kim, S. G. Lee, S. J. Lee, S. W. Jeong, Growth inhibition of aquatic plant caused by silver and titanium oxide nanoparticles, *Toxicol. Environ. Health Sci.* 3 (2011) 1–6. <https://doi.org/10.1007/s13530-011-0071-8>

- 64 N. B. Abramenko, T. B. Demidova, E. V. Abkhalimov, B. G. Ershov, E. Y. Krysanov, L. M. Kustov, Ecotoxicity of different-shaped silver nanoparticles: Case of zebrafish embryos, *J. Hazard. Mater.* 347 (2018) 89–94.
<https://doi.org/10.1016/j.jhazmat.2017.12.060>
- 65 S. M. Albukhari, M. Ismail, K. Akhtar, E. Y. Danish, Catalytic reduction of nitrophenols and dyes using silver nanoparticles @ cellulose polymer paper for the resolution of waste water treatment challenges, *Colloids Surf. A Physicochem. Eng. Asp.* 577 (2019) 548–561. <https://doi.org/10.1016/j.colsurfa.2019.05.058>
- 66 V. De Matteis, R. Rinaldi, Toxicity Assessment in the Nanoparticle Era. In *Cellular and Molecular Toxicology of Nanoparticles*; Springer: Cham, Switzerland (2018) pp. 1–19. DOI:10.1007/978-3-319-72041-8_1
- 67 G. V. Cimbaluk, W. A. Ramsdorf, M. C. Perussolo, H. K. F. Santos, H. C. Da Silva De Assis, M. C. Schnitzler, D. C. Schnitzler, P. G. Carneiro, M. M. Cestari, Evaluation of multiwalled carbon nanotubes toxicity in two fish species, *Ecotoxicol. Environ. Saf.* 150 (2018) 215–223. <https://doi.org/10.1016/j.ecoenv.2017.12.034>
- 68 M. S. Khan, N. A. Qureshi, F. Jabeen, Assessment of toxicity in fresh water fish *Labeo rohita* treated with silver nanoparticles, *Appl. Nanosci.* 7 (2017) 167–179. <https://doi.org/10.1007/s13204-017-0559-x>
- 69 R. Das, B. F. Leo, F. Murphy, The Toxic Truth About Carbon Nanotubes in Water Purification: a Perspective View, *Nanoscale Res. Lett.* 13 (2018) 1–10. <https://doi.org/10.1186/s11671-018-2589-z>