Chemosphere 280 (2021) 130792

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Review

Detection and remediation of pollutants to maintain ecosustainability employing nanotechnology: A review

Neelam Yadav[a,b,**], Vinod Kumar Garg[c,*], Anil Kumar Chhillar[b], Jogender Singh Rana[a,***]

[a] Department of Biotechnology, Deenbandhu Chhotu Ram University of Science and Technology, Murthal, Sonepat, Haryana, 131039, India
[b] Centre for Biotechnology, Maharshi Dayanand University, Rohtak, Haryana, 124001, India
[c] Department of Environmental Science and Technology, Central University of Punjab, Bathinda, Punjab, 151001, India

ARTICLE INFO

Handling Editor: Y Yeomin Yoon

Keywords:
Nanotechnology
Biosensor
Environment
Sustainability
Pollutant detection methods
Pollution remediation

ABSTRACT

Environmental deterioration due to anthropogenic activities is a threat to sustainable, clean and green environment. Accumulation of hazardous chemicals pollutes soil, water and air and thus significantly affects all the ecosystems. This article highlight the challenges associated with various conventional techniques such as filtration, absorption, flocculation, coagulation, chromatographic and mass spectroscopic techniques. Environmental nanotechnology has provided an innovative frontier to combat the aforesaid issues of sustainable environment by reducing the non-requisite use of raw materials, electricity, excessive use of agrochemicals and release of industrial effluents into water bodies. Various nanotechnology based approaches including surface enhance scattering, surface plasmon resonance; and distinct types of nanoparticles like silver, silicon oxide and zinc oxide have contributed significantly in detection of environmental pollutants. Biosensing technology has also gained significant attention for detection and remediation of pollutants. Furthermore, nanoparticles of gold, ferric oxide and manganese oxide have been used for the on-site remediation of antibiotics, organic dyes, pesticides, and heavy metals. Recently, green nanomaterials have been given more attention to address toxicity issues of chemically synthesized nanomaterials. Hence, nanotechnology has provided a platform with tremendous applications to have sustainable environment for present as well as future generations. This review article will help to understand the fundamentals for achieving the goals of sustainable development, and healthy environment.

1. Introduction

Our surroundings are contaminated with different pollutants that may be organic, inorganic and harmful microorganisms (Guerra et al., 2018a). Various anthropogenic activities by which pollutants are injected in the environment include intensive agriculture, domestic activities and non-sustaining industrial operations. Rapid growth of highly polluting industries such as textile, tannery, food and beverages, cosmetics and pharmaceuticals have contributed to the emission of toxic, bio-recalcitrant and hazardous chemicals in the environment (Pandey, 2018; Razack et al., 2020). Further, extensive consumption of natural resources by the growing population has also challenged the environment sustainability (Pandey, 2018; Mauter et al., 2018; Razack et al., 2020). Therefore, release of contaminants including microbial toxins in the ambient environment causes environmental pollution. In past six decades, excessive utilization of pesticides has not only polluted the groundwater and soil but also caused morbidity and mortality to human and other forms of life. Different sources of environmental pollutants are given in Fig. 1.

Spillage of different types of oils & greases and other toxic non-degradable chemicals is another potential source of environmental pollution (Jadhav et al., 2013). Various developmental projects have also lead to the deforestation, loss of flora and fauna, desertification and ultimately disrupted ecosystem food chains (Brito de Figueiredo et al., 2010). Dumping of diverse range of pollutants into aquatic system has challanged the aquatic organisms. It is well proved that many toxic

* Corresponding author.
** Corresponding author. Department of Biotechnology, Deenbandhu Chhotu Ram University of Science and Technology, Murthal, Sonepat, Haryana, 131039, India.
*** Corresponding author.
E-mail addresses: neelamindia12@gmail.com (N. Yadav), vinodkgarg@yahoo.com (V.K. Garg).

https://doi.org/10.1016/j.chemosphere.2021.130792
Received 28 February 2021; Received in revised form 27 April 2021; Accepted 30 April 2021
Available online 17 May 2021
0045-6535/

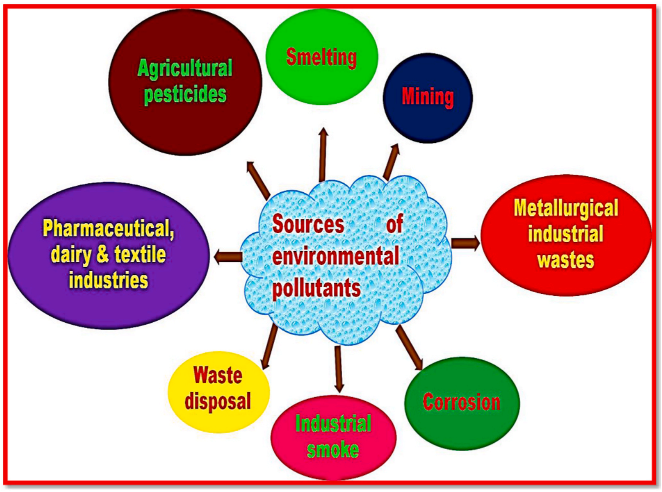

Fig. 1. Different reservoirs of environmental pollutants

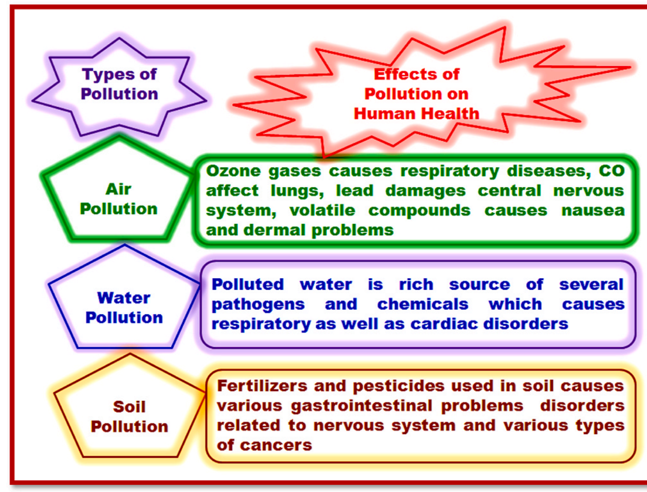

Fig. 2. Illustration of different types of environment pollution and their harmful effects on human health

compounds released into the environment are carcinogenic and mutagenic (Fleeger et al., 2003). Release of several other pollutants in the environment such as gases (CO, CO_2, SOx, NOx etc.), volatile and semi-volatile organic hydrocarbons (aldehydes and ketones), heavy metals including (Hg, Cr, Cd, As, Pb etc.) and persistent organic pollutants like aldrin, dieldrin, endrin, toxaphene, dichlorodiphenyltrichloroethane (DDT), hexachlorobenzene, chlordane, mirex, polychlorinated biphenyls (PCB), dioxins, furans, and several others have interrupted the life cycle of living systems (Zhang and Fang, 2010). Recently, Enfrin et al. (2020) have documented the release of hazardous nanoplastics in the environment as a global challenge. These nanoplastics (size upto 400 nm) may be released into the surroundings due to fragmentation of microplastics by shear force generated by water. Nanoplastics are toxic to all the living organisms as they can easily penetrate the skin. Penetration of nanoplastics via passive diffusion, led to death of >54% zebra fish in the aquatic system (Enfrin et al., 2020). It has been reported that nano- and microplastics are usually more confined near the road areas and from there they are transported to receiving water. These particles come from the roads dust, vehicles, tyre wear, soil erosion, winter road maintenance and sediments. Polukarova et al. (2020) have reported that dispersion of nano/microplastics into the environment can be minimized by treating wash-water with street sweeping machine before their release into water bodies. Introduction of these nano/micro plastics in environment causes toxicity to humans via food chain, ingestion/inhalation, blockage in the blood-brain barriers, lowering in fertility and mental imbalances (Tiwari et al., 2020). This requisites the sensing and prevention of toxic elements present in the environment so that living beings can be protected. Various types of pollutants and their harmful impacts on human health are encapsulated in Fig. 2.

Therefore objective of this review article is to awaken the people, environmentalist, governmental and non-governmental policies makers about various harmful effects of environmental pollutants to living systems due to release of pollutants into environment. Release of pollutants into environment may cause respiratory diseases, cancer, reproductive and intestinal ailments to living beings. Fig. 3 shows the mechanism of toxicity caused by pollutants in humans. Therefore, it becomes very pertinent to detect and remediate the environmentally harmful pollutants to prevent the damaging effects on humans, flora and non-human biota.

1.1. Scope of review

In this article different reservoirs of pollutants, challenges of conventional analytical techniques used for the detection of pollutants, and

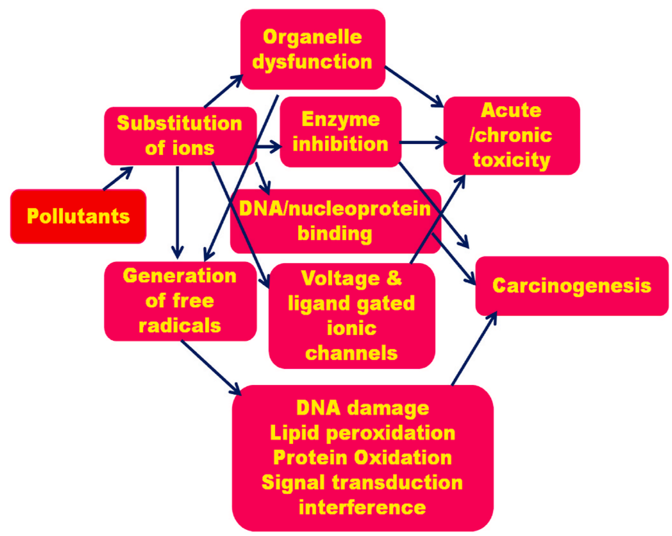

Fig. 3. Diagrammatic representation of mechanism of toxicities caused by environmental pollutants in humans

role of nanotechnology in detection and remediation of certain environmental pollutants has been discussed. The toxicity effects of various pollutants to living systems and their best possible mitigating solutions have also been included in this article. This review article primarily focused on applications of various nanomaterials and biosensing technology that answers the challenges of conventional environmental analytical and remediation techniques. Comparison of distinct analytical parameters of different types of biosensors used for detection of environmental pollutants will provide the fundamental information to the scientific communities for the development of innovative analytical tools and devices for novel environmental based applications. Special emphasis has been given on several nano-based approaches as they are more efficient in terms of specificity, sensitivity, accuracy, simplicity, cost-effectiveness and rapidity. This article deciphers almost all the recent nanomaterials based techniques employed for the detection and degradation of distinct types of pollutants to fill the gaps of previously published review articles.

2. Detection of environmental pollutants

The release of pollutants into the environment has affected all the living systems directly and/or indirectly. So development of some detecting techniques was essential to minimize their effects by treating them before their dispersal into the surroundings. Various pollutant detection techniques are given in the following sections.

2.1. Conventional techniques

Conventionally several chromatographic techniques viz. gas chromatography, high performance liquid chromatography, ion exchange chromatography, size exclusion chromatography and supercritical fluid chromatography have been used for the detection of environmental pollutants (Chaudhery and Rustem, 2020). Several spectroscopic techniques viz. mass spectroscopy, fluorescence spectroscopy, infrared spectroscopy, raman spectroscopy and atomic absorbance spectroscopy have also been recommended and widely used for the detection of pollutants like polycyclic aromatic hydrocarbons, pesticides and heavy metals (Hussain and Kecili, 2020). Moreover, inductively coupled plasma optical emission spectrometry (ICP-OES), ICP-mass spectrometry (ICP-MS), solidified floating organic drop microextraction (SFODME) linked with electrothermal vaporization (ETV)-ICP-MS are used for the detection of traces of heavy metals in waste water samples (Guo et al., 2012; Habte et al., 2015; Sneddon et al., 2008).

2.2. Challenges of conventional techniques

Though, these techniques have extensively been employed owing to their efficiency and sensitivity. However; these techniques have several limitations including higher detection time, tedious methodology, sample pre-treatment, requirement of state-of-the-art laboratories equipped with expensive instruments and skilled manpower (Chaudhery and Rustem, 2020; Zhang and Feng, 2010). These challenges lead the scientific community to develop methods /techniques for sensitive and real time detection of environmental pollutants. The challenges faced while using conventional techniques has been addressed to a large extent by emerging nanotechniques. The potential of nanotechnology in the detection of environmental pollutants is well documented (Zhang and Feng, 2010). Fig. 4 depicts the existing challenges of conventional techniques and their mitigation employing nanotechnology.

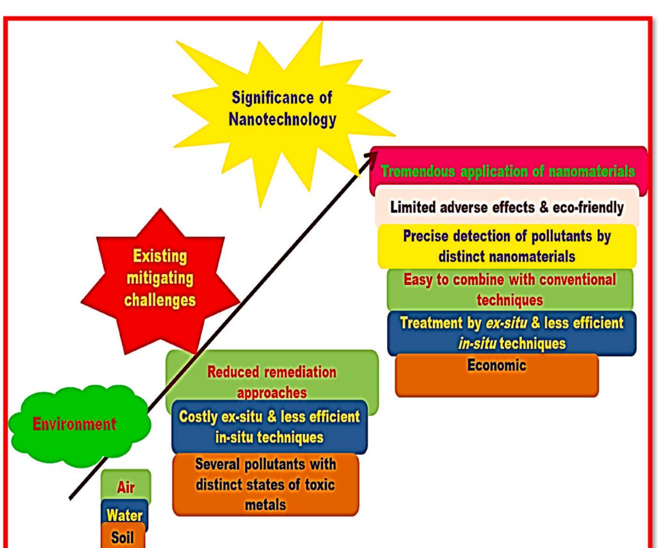

Fig. 4. Significance of nanotechnology for mitigating the challenges faced while using conventional techniques.

3. Rationale of nanotechnology

Nanotechnology has gained attention of scientific community due to its pivotal applications endeavor for detection, prevention and remediation of hazardous chemicals (Besha et al., 2020). The key to success of this emerging technology is the development and fabrication of different kinds of nanomaterials. Nanomaterials can be easily prepared and modified for various applications. Nanotechnology is a multidisciplinary field of sciences that involves the fabrication of materials/particles in the range of nanoscale i.e. 1-100 nm (Mondal, 2020; Khan et al., 2019). Owing of unique properties including high surface to volume ratio, catalytic, electrical, thermal, optical and mechanical properties of nano tools and devices, they have been used in diverse fields including medical, agriculture, food processing industries, and environment (Nile et al., 2020; Jeevanandam et al., 2018). Use of nanomaterials has been suggested in monitoring and remediation of hazardous pollutants (Guerra et al., 2018). Application of nanomaterials for the detection of pollutants in air, water and soil are well documented in literature (Gebre and Sendeku, 2019).

3.1. Pollutants detection methods based on nanomaterials

Nanomaterials have proven a promising tool for the monitoring of hazardous chemicals in various environmental matrices (Baruah and Dutta, 2009). This is possible due to various fascinating chemical and physical properties of nanomaterials including large surface area, composition, electrical properties, magnetic properties, mechanical properties and optical properties (Zhang and Fang, 2008). These nanosensors detect the pollutants by identifying the surface markers of pollutants or enhancing the analytical signal. These unique features of nanosensors are reliable for the sensitive detection of ultra low concentrations of pollutants in comparison to conventional techniques (Zhu et al., 2009). Herein significance of nanoparticles of silver, zinc oxide and silicon oxide is discussed:

3.2. Silver nanoparticles (AgNPs)

Due to unique optical, electrical, and thermal properties AgNPs are used in several pollutant sensing techniques (Daoudi et al., 2021). Moreover, AgNPs based devices have shown enhanced electron kinetics and better consistency (Munonde and Nomngongo, 2021). Eksin et al. (2019) have reported the detection of Hg^{2+} ions in tap water by developing AgNPs and folic acid integrated electrochemical sensor using pencil graphite electrode. This nanosensor had 10–25 μM linear range and 8.43 μM detection limit. Detection of Hg^{2+} ions using aforesaid sensor was sensitive, specific and quick. Sangaonkar et al. (2020) reported colorimetric detection of Hg^{2+} ions in water using AgNPs synthesized from Kokum fruit. Detection of Hg^{2+} ions was revealed from HAADF-STEM images and EDS spectrum showed the amalgam formation through etching and under potential deposition. As a result a visible color was changed from brown to colorless. Consequently, SPR intensity was altered and followed by alteration in memristive switching like property of AgNPs. Detection limits of this colorimetric and memristor-based assay were 6.2 ppb and 8.7 ppb respectively. Hwa et al. (2020) have demonstrated the electrochemical detection of 4-nitrophenol (4-NP) using AgNPs functionalized reduced gaphene oxide. Detection of 4-NP was based on cyclic voltammetry and differential pulse voltammetry. Linear range of this sensor was 0.1–363.9 μM and of 48.6 nM LOD. Moreover sensitivity of this sensor was 35.25 $\mu A/\mu M/cm^2$. Shah et al. (2021) have revealed the application of AgNPs synthesized from *Dodonaea viscosa* for the detection of *Staphylococcus aureus* and *Candida albican* bacteria. They also reported detection of other pollutants such as 2-nitrophenol (2-NP), 4-nitrophenol (4-NP) and azo dyes included Methyl orange (MO), Congo red (CR) and Rhodamine B (RB).

3.3. Zinc oxide nanoparticles (ZnONPs)

ZnONPs exhibit wide band gap, more excitation capacity and thus show unique stability at elevated temperature and electric field (Naveed Ul Haq et al., 2017). Therefore, their applications in designing of solar cells, photo catalysis, and chemical sensors have been preferred. Nanocrystals of ZnO have shown potent piezoelectricity and thus they are used as acoustic wave resonators and acoustic-optic modulators. Balram et al. (2020) have demonstrated the detection of 4-NP by constructing electrochemical biosensor based on ZnONPs decorated functionalized multi-walled carbon nanotubes (fMWCNTs). Aforesaid biosesnor exhibited high sensitivity i.e. 11.44 μA/μM/cm^2 and 0.013 μM LOD. Linear range of this sensor was 0.06–100 μM. Moreover, this biosensor showed improved stability, reproducibility, repeatability and no-interference.

Moreover, Carbon nanotubes (CNTs) conjugated with enzymes enhances the electron transfer kinetics from the enzyme active site; consequently, accelerate the electrochemical reactions of the biomolecules (Valcarcel et al., 2008). Further, the sensing features of CNTs have been improved by surface functionalization and their deposition on the matrix materials. Sensors integrated with CNTs have been employed for the targeted analysis of glucose, ethanol, sulfide and sequence-specific DNA segment (Valcarcel et al., 2008). Due to high sensitivity of CNTs, they can also be used for the detection of drugs in traces amount (Shufang et al., 2021). Beside these, combination of magnetic nanoparticles with antibodies renders the specific and fast detection of target bacterium from matrices (Chang and Adriaens, 2007). Single walled carbon nanotubes (SWCNTs) have been used for the detection of polychlorinated biphenyls (Mahdavian and Mousavi, 2019). Fig. 5 shows the uses and advantages of nanoparticles for the control of environmental pollutants.

3.3.1. Functionalization of CNTs

Application of carbon nanotubes (CNTs) has been established in detection of environmental pollutants by several researchers. CNTs have high surface to volume ratio, characteristic optical, electrical, mechanical and chemical properties (Schroeder et al., 2018). However, devices with non-functionalized CNTs are less sensitive and specific. Therefore functionalization of CNTs enhances sensitivity and specificity of detecting devices. Because functionalization of CNTs augments chemical and electrical properties of CNTs by exposing several active sites to capture target pollutant. CNTs can be functionalized covalently and non-covalently.

(i) Covalent functionalization of CNTs

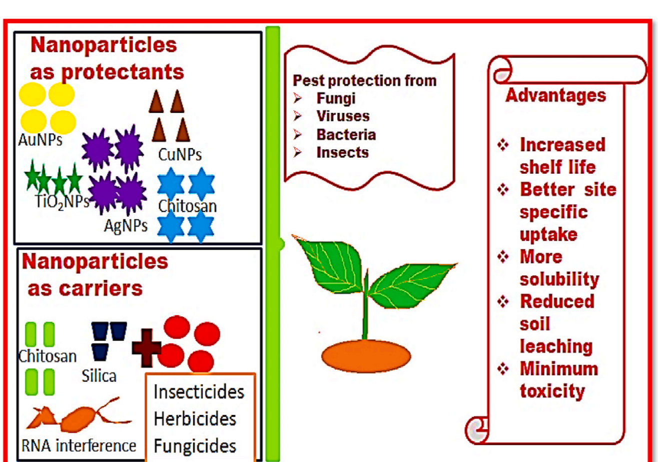

Fig. 5. Diagrammatic illustration of applications and advantages of nanoparticles.

Covalent functionalization of CNTs provide sites for attaching functional groups and also provide robust stability in *in vivo* as well as extreme environmental conditions (Schroeder et al., 2018). This is so because covalent immobilization offers unique stability, reproducibility and defined composition due to precise attachment of functional groups with CNTs. For instance, functionalization of SWCNTs with pendant hexafluoroisopropanol (HFIP) was used for the detection of DMPP. Covalent modifications of CNTs facilitates the efficient chemical reactions (Karousis et al., 2010). For example surface of CNTs was modified using 4-dimethylaminopyridine (DMAP) and disubstituted acetylene dicarboxylates causes *in-situ* formation of zwitterionic intermediates (Zhang et al., 2009). Moreover, CNTs can be functionalized by the addition of chemically active groups such as alkynes and allyl groups. These groups facilitates the post-functionalization processes of CNTs by adding 1, 3-dipolar cyclo, thiol-ene, and olefin cross-metathesis reactions for further variation. Chemically modified MWCNTs with allyl, propargyl, alkyl triazole, thioalkyl chain, carboxylic, HFIP, calix[4]arene, and crown ether groups has been used for the fabrication of sensors for the precise detection of diverse range of volatile organic compounds.

Covalent functionalization of CNTs has also been performed by adding organic azides by thermal aziridination that causes minimum fluctuation in the transport characteristics (Schroeder et al., 2018). Schnorr et al. (2013) have reported advantages of functionalized SWCNTs in early detection of target anayte. These SWCNTs were covalently modified by diverse functional groups of thiourea, urea, and squaramide by thermal aziridination to form H-bonds. Application of such functionalized SWCNTs was revealed in development of chemiresistive sensor for the detection of cyclohexanone and nitromethane, explosives vapors in very minute concentrations (ppm). In addition to these, these chemiresistive sensors have shown unique reproducibility and consistency (Schroeder et al., 2019). Covalent functionalization of SWCNTs by thermal aziridination based on tetraphosphonate cavit was used to detect N-methylammonium in humid. SWCNTs modified covalently with methyl pentafluorobenzoate and pentafluorobenzoic acid was used in sensitive detection of ammonia and trimethylamines. Sensors based on SWCNTs do not cause any intervention from volatile organic compounds and work efficiently in air and aqueous conditions.

Sol-gel mechanism is used in covalent modification by adding diverse metal oxides that involve the oxidation of CNTs to expose carboxyl and hydroxyl groups to react with metal alkoxide or metal halide precursors found in colloidal solution (Cargnello et al., 2012). This is followed by hydrolysis and condensation to produce gel of metal oxide on CNTs surface. Functionalization of MWCNTs by coating tin oxide nanocrystal was obtained from sol-gel method based on tin(II) chloride. These modified MWCNTs were used in detection of NO, NO_2, ethanol, and acetylene gas in trace amount at 300 °C. Schroeder et al. (2019) reported the detection of dopamine and ascorbic acid by covalent functionalization of MWCNTs using silica network and gold nanoparticle.

(ii) Non-covalent functionalization of CNTs

Non-covalent functionalization of CNTs is used for the physiosorption of simple aromatic compounds and surfactants via π-π and hydrophobic interactions (Schroeder et al., 2019). CNTs attached with pyrene units including amino-groups, cyclodextrin, and boronic acid were used to detect trinitrotoluene (TNT), organic intermediates and glucose respectively (Wei et al., 2014). Two main non-covalent approaches for the functionalization of CNTs include coating or wrapping of CNTs with polymers and immobilization of metal nanoparticles on the CNTs for the detection of environmental pollutants. CNTs modification by conjugating polymers helps in selective detection of analyte. Moreover, CNTs are also non-covalently functionalized by polymeric surfactants consisting lengthy alkyl chains for the hydrophobic interactions (So et al., 2005). Non-covalent functionalized CNTs are also used for the adsorption of Tween 20 conjugates comprised of biotin, staphylococcal protein A (SpA), or human autoantigen. Immobilization of metallic nanoparticles on CNTs surface has increased the sensitivity and stability of sensing device (Schroeder et al., 2019). MWCNTs functionalized with SnO_2 nanocrystals were used in sensitive detection of H_2, CO and NO_2 gases in traces amount (K. Chen et al., 2012).

3.3.2. Functionalization of graphene oxide

Graphene oxide (GO) has shown several unique features of electrical, optical, mechanical and catalytical nature (Yu et al., 2020). These features can further be improved by the functionalization for the interactions. Functionalization of GO prevents their aggregation during reduction process. GO can be functionalized by covalently, non-covalently and doping elements. Covalent functionalization of GO introduces new functional groups to form covalent bond with GO and exposed functional groups. Surface of GO consists of several hydroxyl groups, carboxyl groups, and epoxy groups which make functionalization process easy and form covalent bond during chemical reactions including isocyanation, carboxylic acylation, epoxy ring opening, diazotization, and addition (Chu and Pumera, 2013). Non-covalent functionalization of GO forms composite material due to interaction between H-bond and electrostatic bonds between graphene and functional molecules. Non-covalent functionalization improves dispersibility and stability of GO. Approaches used for non-functionalization GO include p–p bond interaction, hydrogen bonding, ionic bonding, and electrostatic interaction modification. This approach of functionalization is simple in mild conditions however addition of auxiliary components like surfactants is the main limitation of this approach. Element doping is another approach for the functionalization of GO. Functionalization by this approach is based on annealing heat treatment, ion bombardment, arc discharge to introduce different elements into graphene. This causes substitution of defects and vacancy defects in graphene and retain intrinsic two-dimensional structure of graphene.

Functionalized GO nanomaterials have been used for the detection of distinct types of pollutants. K.J. Chen et al. (2012) have reported the quick detection of Hg^{2+} using field –effect transistor (FET) sensors based on reduced GO functionalized with AuNPs in 10 s. Electrochemical sensor fabricated by using glassy carbon electrode modified with GO, functionalized with L-cystein graphene was used for the detection of hydroquinone (Xia et al., 2021). Linearity and detection limit of this sensor was 2–160 μM and 1.5 μM respectively. Sablock et al. (2013) have demonstrated the detection of trinitrotoluene by developing electrochemical sensor integrated with amine functionalized GO/CNT nanocomposite immobilized onto screen printed electrode. This sensor showed ultra high sensitivity by exhibiting very low limit of detection *i.e.*10 ppb. Hanif et al. (2019) have demonstrated the detection of $Cd^{2+}$and Pb^{2+} ions in tap water using electrochemical sensor fabricated with glycine functionalized reduced graphene oxide/polyaniline nanocomposite. They revealed high sensitivity, selectivity, and quick detection of heavy metallic ions. This sensor exhibited very low limit of detection i.e. 0.07 nM and 0.72 nM for $Cd^{2+}$and Pb^{2+} ions respectively. Sakthinathan et al. (2017) have reported the application of amperometric biosensor based on reduced graphene oxide/platinum(II) tetraphenylporphyrin nanocomposite immobilized onto glassy carbon electrode for the detection of hydrazine. Detection of hydrazine using this sensor was based on cyclic voltammetry. Moreover, this sensor showed high sensitivity, consistency, reproducibility, wide linearity range (13–232 μM) and 5 nM LOD.

Recently, Jiang et al. (2020) have documented the significance of whole cell bioreporters (WCBs) in sensing the petroleum hydrocarbons including n-alkanes, aromatic hydrocarbons and their toxicities. These WCBs analytical tools and devices are composed of modified genome of microbes for the investigation of toxic chemicals by generating measurable signals. Detection of chemical pollutants by using these WCBs has exhibited several advantages such as quick, simple, reproducible, efficient, stable and cost-effective.

3.4. Synthesis of nanomaterials

Synthesis of nanomaterials involves mainly two methods, i.e., top-down and bottom-up approach (Dhand et al., 2015). In top-down approach initiation step involves the systematic percolating of bulk material which leads to synthesis of nanoparticles. Various approaches of top-down method include photolithography, electron beam lithography, milling techniques, anodization, ion and plasma etching for bulk suynthesis of NPs. Bottom-up approach involves the assembling of atoms and molecules to produce varying size of NPs. Nanoparticles synthesis using bottom-up approach is based on self-assembly of monomer/-polymer molecules, chemical or electrochemical nanostructural precipitation, sol–gel processing, laser pyrolysis, chemical vapour deposition (CVD), plasma or fame spraying synthesis and bio-assisted synthesis. Generally, methods for synthesis of NP synthesis are divided in three groups viz. physical methods, chemical methods and bio-assisted methods. Fig. 6 shows the various methods of synthesis of nanomterials.

3.5. Characterization of nanomaterials

Characterization techniques help to decode the shape, size, distribution, degree of aggregation, surface charge, surface area of nanoparticles to understand surface chemistry of nanoparticles (Mourdikoudis et al., 2018). Various techniques used for characterization of nanoparticles has been depicted in Fig. 7.

3.6. Nanomaterials used for the detection of water pollutants

Limited availability of potable water has necessitated the treatment of contaminated water to make it useable. Generally wastewater released from pharmaceutical industries contains endocrine disrupting compounds, radionuclides, flame retardants, surfactants and toxins from microbial sources. These pollutants cannot be detected by conventional methods. Conventional methods used for detection of pollutants in wastewater are inductively coupled plasma-optical emission spectrometry (ICP-OES), inductively coupled plasma-mass spectrometry (ICP-MS), flame atomic absorption spectroscopy (FAAS), graphite furnace atomic absorption spectroscopy (GFAAS) and x-ray fluorescence (XRF) (Munonde and Nomngongo, 2021). However, these methods have several limitations such as need of sample collection, sample pre-treatment, skilled personnel, expensive instruments and more power consumption. Nanomaterials based sensing devices have overcome these limitations as they are economic, efficient, selective, sensitive, and flexible. Scientific communities have developed different types of sensing devices based on nanomaterials for the detection of pollutants in

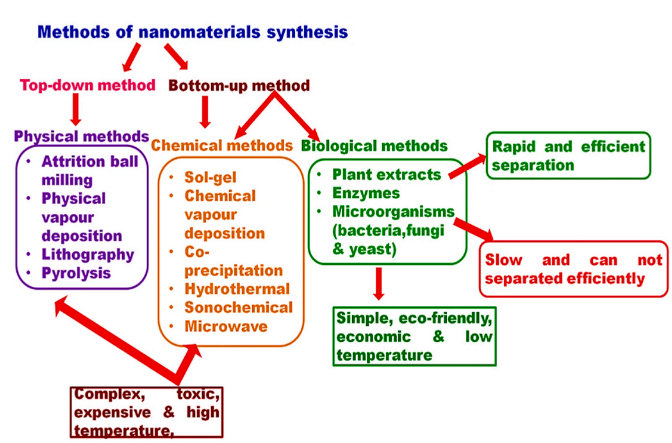

Fig. 6. Diagrammatic representation of various methods used for the synthesis of nanomaterials.

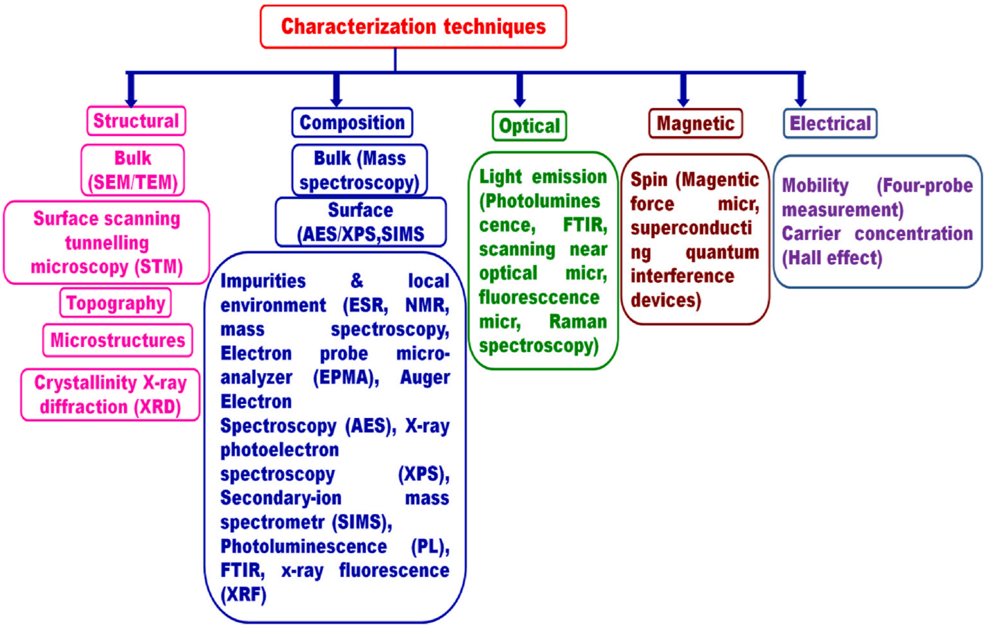

Fig. 7. Various techniques used for the characterization of nanomaterials.

wastewater. Table 1 encapsulates various nanomaterials based sensors used for the detection of pollutants in water in yesteryears.

4. Biosensors applications for the detection of environmental pollutants

Biosensors are quantitative analytical devices which have three main components, viz; biological/recognition element, transducer and signal amplifying detector. Recognition elements used in biosensors are generally enzymes, antibodies, phages, aptamers or single stranded DNA (Neelam et al., 2019; Yadav et al., 2018, 2019; Pundir et al., 2019). Transducer transmits the signal in the form of current, voltage, heat or light depending on the type of transducer used in the biosensor. Finally, detector senses the signal that is directly proportional to the interaction between bound analytes to their specific receptors. Biosensors are largely used in medical sector, agriculture, environment monitoring, food and pharmaceutical industries (Yadav et al., 2019; Amine et al., 2006). Biosensors have also been used to detect soil pathogens by estimating their constructive comparative activity and varying oxygen requirement during respiration process (Raul et al., 2016; Bontidean et al., 2004; Vidic et al., 2017). Hence, biosensors have provided a pioneer practice for assessing the soil condition.

There are several types of biosensors such as electrochemical, optical, piezoelectric and thermometric biosensors.

Electrochemical biosensors involve the redox reactions for the measurement of analyte concentration. The response measured by such biosensors either in the form of current peaks or difference in potential between the working and reference electrode due to oxidation reaction in the reaction system (Yadav et al., 2018; Neelam et al., 2019; Pundir et al., 2019). Piezoelectric or acoustic biosensors are mass sensitive sensors where analyte concentration can be quantified by measuring the electrical signals produced due to mechanical force (Damiati et al., 2017). On the other hand optical biosensors measure the signal in the form of heat generated by the enzymatic reactions (Kaur and Singh, 2020). Fig. 8 presents the working and principle of a biosensor.

Scientists have developed various electrochemical, optical and piezoelectric biosensors for the detection of environmental pollutants (Virkutyte and Varma, 2010). Biosensing technology has several advantages over other techniques in environmental monitoring viz. rapid, simple, economically cheaper, specific, reliable, ease of portability, work on affected area, detect complex pollutants even in traces amounts (Nigam and Shukla, 2015a,b; W. Zhang et al., 2014). Therefore, a number of biosensors have been developed for the detection of pollutants from various sources such as hospitals, kitchen, agriculture, sewage

Table 1
Various nanomaterials used for the detection of pollutants in water.

Name of nanomaterials	Name of matrix	Target pollutant	Detection technique	Reference
Carboxylated multi-walled carbon nanotubes (MWCNTs−COOH) and Zr-metal-organic frameworks (UiO-66-NH_2)	Glassy carbon electrode	Cd^{2+} and Pb^{2+} ions	Electrochemical sensor	Lu et al. (2021)
Nanocomposite of magnetite nanoparticles and AuNPs	Glassy carbon electrode	As(III)	Electrochemical biosensor	Sedki et al. (2021)
double-shelled carbon nanocages material derived from zeolitic imidazolate frameworks	–	Pb^{2+} ions	Aptasensor	Ding et al. (2021)
Cu–Ag core shell NPs	SiO_2–TiO_2–ZrO_2 ternary grid	Hg^{2+} ions	Optical sensor	Prakashan et al. (2020)
Au-film	–	R6G and p-nitrophenol	SERS	Wang et al. (2020)
Xylenol orange functionalized AuNPs	–	Al^{3+} ions	SPR	Garg et al. (2020)
Nitrogen and sulfur co-doped molybdenum selenide nanosheets	–	Hg^{2+} ions	Fluorescence	Long et al. (2021)
Bismuth nanoparticle-and cobalt ferrite	Glassy carbon electrode	Pb^{2+} and Cd^{2+} ions	Electrochemical	He et al. (2020)
Co_3O_4 nanosheets	indium tin oxide	Pb^{2+} ions	Electrochemical	Yu et al. (2017)
Cu based MOFs	Glassy carbon electrode	Pb^{2+} ions	Electrochemical	Hu et al. (2020)

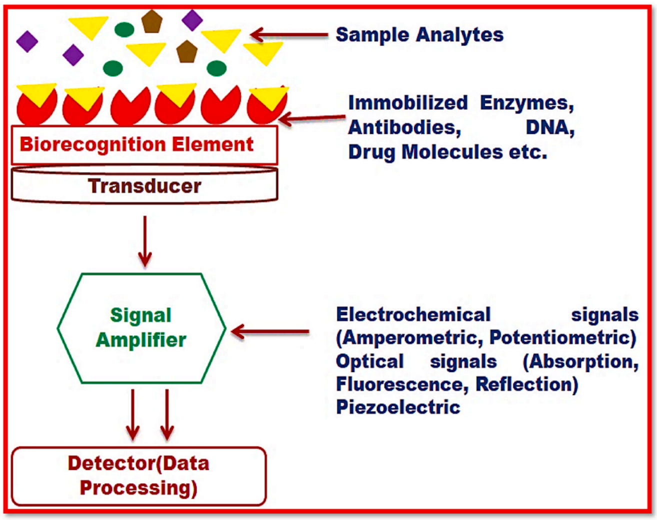

Fig. 8. Working and principle of a biosensor.

water, textiles etc. These nano devices detect the specific analyte by sensing the biological reactions associated with the target analyte. Thus, biosensing methods help in protection of humans from diseases causing pathogens (Srinivasan and Tang, 2015; Syam et al., 2012).

Presently, DNA microarrays based techniques have also been used for the monitoring of environmental pollutants. However, these microarray approaches are costly and also have complicated operation system. Marker free hybridized pathogenic DNA can also be sensed by low-temperature polycrystalline silicon thin-film transistors (LTPS-TFT) (Estrela et al., 2005).

4.1. Nanomaterials based biosensors

Scientists have shown their interest in fabrication of nanomaterials based biosensors for the detection of environmental pollutants including heavy metals, pesticides and pathogens (Lukyanenko et al., 2019). Nanomaterials increase the surface area to volume ratio, enhance catalytic, mechanical and thermal properties. Therefore, they are used as recognition element for the fabrication of biosensors. Biosensors fabricated with nanomaterials have shown promising applications for the detection of environmental hazardous compounds. These biosensors have offered many advantages such as high sensitivity, selectivity, efficiency, stability and rapidity. Furthermore, nanosensors used for the detection of pollutants have very low limit of detection. Different types of nanomaterials including quantum dots, metallic and carbonaceous nanoparticles have been used for the construction of biosensors for sensing the environmental pollutants. Zhou et al. (2019) reported that the nanoporous materials such as metal/metal oxide are the promising platform for the fabrication of sensors which can detect pollutants in the contaminated samples very quickly and efficiently. Nanoporous metal oxide based gas sensors have been developed for the investigation of environmental pollutants coming from agriculture and medical sectors (Zhou et al., 2019). Pollutants residing in water, food products and agriculture land have been detected by developing nano-based devices such as biosensors. Researchers have developed several nanomaterials integrated sensing devices for the investigation of various organic pollutants ((Su et al., 2018). Taurozzi and Tarabara (2007) reported that the quality of water can be assessed by the sensor integrated with silver nanoparticles (Taurozzi and Tarabara, 2007).

Electrochemical sensors fabricated with carbon nanotubes (CNTs) have shown exceptional characteristics like large surface area, sensitive, specific, stable and better analytical performance (Wang, 2005; Trojanowicz, 2006; Merkoci, 2006). Thus, these CNTs are the chief components of biosensor fabrication. Biosensors integrated with CNTs have been employed for the investigation of harmful gases including NO_2, NH_3, or O_3. Detection of harmful gases by biosensing devices integrated with CNTs involves the significant alteration in the electrical resistance of CNTs that was because of charge transfer by the gas molecules or physical adsorption (Dai et al. (2012) and Sano and Ohtsuki, 2007). Cesewski and Johnson (2020) have reported that biosensing devices also can detect environmental pathogens. Researchers have reported that toxin producing algae and sulfur reducing bacteria can be detected successfully using electrochemical biosensors (Cesewski and Johnson, 2020) .

Jia et al. (2016) have fabricated a highly advanced biosensor by immobilizing the MNPs functionalized with whole-cell-bioreporters. This functionalized MNPs device was employed to evaluate soil toxicity. This biosensing device was sensitive and give reproducible results in varying parameters of soil including temperature, pH, and salinity. They also performed a case study by using MNPs integrated bioreporter system for accessing the ecological toxicity caused by heavy metal contamination at the coal cinder site. From this study they concluded that there was inverse relationship between toxicity and distance from the coal cinder site that was the chief reservoir of heavy metal accretion.

4.2. Classification of biosensors

Depending upon type of analytical signals generated by transducing elements, biosesnors having been classified into various types:

4.2.1. Electrochemical biosensors for pollutants detection

Electrochemical biosensors measure the analytical signals in the form of current, voltage, conductance or impedance (Pundir et al., 2019; Neelam et al., 2019). Intensity of generated signal is directly proportional to binding of analytes to their specific bioreceptor. Significance of electrochemical biosensors for the monitoring of diverse range of pollutants is well documented (Kumar et al., 2020). Khanmohammadi et al. (2020) have documented the importance of electrochemical biosensors in detection of various heavy metals like Pb^{2+}, Cd^{2+}, Cu^{2+}, Hg^{2+}, Zn^{2+}, As^{3+} etc. For example, Lu et al. (2021) have demonstrated the detection of Cd^{2+} and Pb^{2+} in water by fabricating electrochemical biosensors using glassy carbon electrode modified with carboxylated multi-walled carbon nanotubes (MWCNTs−COOH) and Zr-metal-organic frameworks (UiO-66-NH_2). They added huge adsorption sites of UiO-66-NH_2 for enhancing the redox reactions. This biosensor showed high sensitivity for 0.2528 μA/ppb for Cd^{2+} and 0.3012 μA/ppb for Pb^{2+}. Detection of As(III) in polluted water was reported by fabricating marker free electrochemical biosensor based on glassy carbon electrode integrated with nanocomposite of magnetite nanoparticles and AuNPs (Sedki et al., 2021). Detection limit of this biosensor was 0.22 μg/L and linearity ranges between 1 and 100 μg/L. Moreover, this biosensor showed better analytical recovery i.e. 95-101%. Ding et al. (2021) have reported the detection of Pb^{2+} ions in the real water sample and polluted soil digestion solution. They developed an aptasensor by using double-shelled carbon nanocages material derived from zeolitic imidazolate frameworks. Aptamer was converted into G-quadruplex structure in the presence of Pb^{2+}. Detection and wide working range of this aforesaid aptasensor was 0.096 μg/L and 0.1–10 μg/L.

Khanmohammadi et al. (2020) have also reported the investigation of various organic compounds including parathion, diazinon, chlorpyrifos, bisphenol A, fenthion, 3-methoxy phenol, p-nitrophenol, hydroquinone, paracetamol and many more. Uniyal and Sharma (2018) have reported the detection of chlorpyrifos using electrochemical biosensors. Detection of glyphosate by AuNPs based potentiometric biosensor has also been investigated (Kucherenko et al., 2019). Detection limit and linear range of this biosensor were 0.5 ppm and 0.5–50 ppm respectively. Zhao et al. (2021) have reported the detection of methyl parathion in real sample by developing an electrochemical biosensor integrated with nanocomposite of halloysite (Hal) nanotubes and

MWCNTs. This Hal-MWCNTs nanocomposite was immobilized on glassy carbon electrode. This biosensor exhibited 0.034 μM detection limit and 0.5–11 μM linear range. Furthermore, aforesaid biosensor showed better analyticl recoveries i.e. 98.8 of 101.8%.

Electrochemical biosensor integrated with Pt–Au nanowire/nanoparticle hybrid array with several bioreceptors was used for the detection of penicillin and tetracycline antibiotics in real samples (Li et al., 2019). The detection limits of this biosensor was 41.2 μAμM $^{-1}$ cm $^{-2}$ and 26.4 μA μM $^{-1}$ cm $^{-2}$ for penicillin and tetracycline respectively. This biosensor showed better recovery and efficiency in the investigating samples. Ramnani et al. (2016) have also reported the sensitive and quick investigation of TNT using an immunosensor integrated with single walled carbon nanotubes. This immunosensor was analysed with a concentration ranges from 0.5 to 5000 ppb in spiked samples. Furthermore, due to their fascinating advantages as discussed above researcher can develop the miniaturized sensing devices for the detection of array of environmental pollutants. In Table 1 various analytical parameters of different types of biosensors are given.

Merits: These biosensors have high sensitivity, selectivity and can be easily miniaturized for the fast and on-site monitoring of environmental hazardous components (Hernandez-Vargas et al., 2018).

Demerits: These electrochemical biosensors have poor stability.

4.2.2. *Electromechanical biosensors for pollutants detection*

Moisture and temperature of soil are the major parameters for the regulation of energy transfer in the form of heat on land surface and atmosphere occur through evaporation and plant water transportation system (Jackson et al., 2007). The conventional techniques used to monitor moisture and temperature of soil have several limitations like they are massive, less efficient, non-reliable and costly. The aforementioned problems have been resolved by fabricating economic wireless sensors using nanotechnology. These biosensors have micro machined micro electromechanical system (MEMS) with cantilever beams that are coated with a nanopolymer which is sensitive to water and thus have been used for monitoring humidity content. The chip based piezo-resistive temperature sensors have also been designed which monitor the slight variation of temperature. These nano integrated MEMS sensors, having microelectronic circuits, are beneficial for efficient sensing as well as capable of reacting with changed environmental components (Madou, 1997). Bao et al. (2019) developed 3DG-CuONFs nanocomposites integrated acetylcholinesterase electrochemical biosensor for the detection of melathion an organic pesticide in the water samples.

Nanomaterials integrated biosensors have shown profound impact on detection of various heavy metallic pollutants (Willner and Vikesland, 2018). For instance heavy metallic ions like Pb^{2+}, Ni^{2+}, Co^{2+}, Cu^{2+}, Cd^{2+}, Mn^{2+}, Hg^{2+} etc. have been detected by using biosensing technology (Balasurya et al., 2020). A biosensing chip was designed for the detection of diverse range of pollutants including Zn ions, pesticides like DDVP and petrochemicals such as pentane in water samples. This bio-chip confined with three bacteria namely *Escherichia coli*, *Shewanella oneidensis* and *Methylosinus trichosporium* was immobilized on screen printed gold electrode and used for the detection of pollutants (Abu-Ali et al., 2019). Peng et al. (2019) have fabricated an amperometric biosensor by immobilizing poly (diallyldimethylammonium chloride) conjugated with nanoparticles of graphene and platinum on glassy carbon electrode. This biosensor can be used for the detection of N-nitrosodiphenylamine, a cancer causing agent, found in food and other consumer products.

Merits: These biosensors are economic, rapid, highly sensitive, easy to miniaturize, user friendly and require minimum quantity of reagents (Menon et al., 2020).

Demerits: These sensing devices have susceptibility to react with matrices, varying temperatures and poor in consisancy (Menon et al., 2020).

4.2.3. *Optical biosensors for pollutants detection*

An optical biosensor is an analytical device composed of a recognition element and transducing element (Chen and Wang, 2020). Recognition elements such as enzymes, nucleic acid, hormones, antigens, antibodies and whole cells have been used for the fabrication of optical biosensors. SPR, optical resonator, optical waveguide, optical fibre and photonic crystal are some of chief transducing elements. When specific analyte interacts with its corresponding receptor results in generation of analytical signals in the form of fluorescence, change in color, absorbance, reflectance, Raman scattering, refractive index of investigating sample (Malhotra and Ali, 2018). Detection of analyte by such biosensors is based on bio-affinity or biocatalysis (Su et al., 2017). These optical biosensors have shown many advantages such as high sensitivity, specificity, on-site detection of pollutants, unaffected from external disturbances, minimum noise and better consistency (Chen and Wang, 2020). Researchers have reported the significance of optical biosensors in detection of environmental pollutants (Willner and Vikesland, 2018; Nigam and Shukla, 2015a,b). De Stefano et al. (2005) have developed a facile, cost-effective optical biosensor for pesticides determination in water and humic acid. Water with heavy metals like Zn^{2+} and Cu^{2+} can be detected by gold nanoparticles coated with biopolymer and chitosan (chelating agent). Chitosan after chelation agglomerate the heavy metals, gold nanoparticles and produce an altered signal which was measured by optical biosensors (Sugunan et al., 2005). An optical biosensor has been developed for the assessment of NH_4^+. This optical biosensor was fabricated by immobilization of green AgNPs prepared from aqueous solution of polysaccharide *Cyamopsis tetragonaloba*. The response time of this biosensor was 2–3 s and 1.0 ppm detection limit (Pandey et al, 2012). Thus the biosensor was very quick response generating and also exhibited high sensitivity. This demonstration have provided the idea to researchers for the future research for the investigation of NH_4^+ level in body fluids such as in plasma, sweat, saliva and cerebrospinal fluids.

Li et al. (2020) have fabricated photo-electrochemical (PEC) biosensor integrated with Bi SPR enhanced $BiPO_4$/BiOI composites synthesized by hydrothermal approach. This PEC sensor was used for the detection of Cr(VI). This biosensor has shown good linearity between 0.5 and 180 μM. Prakashan et al. (2020) have detected the mercury in the water samples by designing optical sensor integrated with Cu–Ag core shell NPs. These NPs were drizzled in SiO_2–TiO_2–ZrO_2 ternary grid. This aforesaid analytical nano device has exhibited 0.01 μM detection limit and wide linear range i.e. 0.01–1000 μM. Balasurya et al. (2020) have documented the colorimetric investigation of mercury in water samples using AgNPs statbilized with polyvinylpyrrolidone. Detection of mercury was based on the formation of AgNPs-methionine complex that change colour of sample from brown yellow to colourless. Linearity of this biosensor ranges between 0 and 20 nM. Optimum temperature and pH of this biosensor was 35 °C and 8.0, respectively. This biosensor during mercury investigation has shown high sensitivity and selectivity.

4.2.3.1. Surface enhanced Raman scattering (SERS). Surface-enhanced Raman scattering (SERS) is a sensing technique that involves enhancing the inelastic light scattering of molecules up to $>10^8$ due to adsorption of molecules onto corrugated metal surfaces. These metallic surfaces include nanoparticles of silver or gold. This technique has lead to the development of several other spectroscopic techniques by taking advantage of enhanced local fields that arise from plasmon excitation of nanoparticles for producing optical processes like fluorescence or nonlinear optics (Langer et al., 2019). It is a molecular analytical approach used for the detection of structurally similar analytes (pollutants) with minimum interference of scattering from water (Ong et al., 2020). This technique can be used for *in vivo* detection of the pollutants. Zhang and Fang (2008) have reported the detection of traces amount of polycyclic aromatic hydrocarbons (PAHs) and PCB using SERS. Detection of these pollutants using SERS was based on the designing of partition layer-functionalized nanostructured substrates. This partition layer facilitated the accumulation of pollutants within the augmented electromagnetic field as a result the targeted pollutant settled near rough surface of the substrate. Zhang and Fang (2008) have reported the investigation of rhodamine (R6G) dye using Ag nanowire independent of partition layer. They also reported that detection of R6G using SERS has shown unique sensitivity and measurable molecular signal. The detection limit for R6G was 10^{-13} M. Xu et al. (2009) have demonstrated the simultaneous detection of several pollutants at a contaminated site. This was achieved by Ag nanostructures used in SERS that generated very strong molecular signal after capturing the pollutants. SERS is also helpful in fingerprint detection of PCB by producing SERS spectra. Yajun and Meng (2010) reported the detection of different PCB by producing SERS spectra. Recently, Wang et al. (2020a,b) have demonstrated the quantitative detection of organic pollutants like R6G and p-nitrophenol (PNP) in polluted water using SERS. This SERS analytical technique was integrated with pulse field technology to create roughness on the surface of Au film. This enhanced the Raman signal leading to better performance of SERS technology. The signal intensity was greatly affected with alteration in electrochemical parameters and diameter of Au films. They reported wide linear range i.e. 10^{-9} to 10^{-5} M for R6G and for PNP 10^{-9} to 10^{-3} M while detection limit of R6G was 10^{-11} M. This studies prove that this technique is sensitive, stable and has very high reproducibility.

4.2.3.2. Surface plasmon resonance (SPR) technique. SPR technique uses novel metals for sensing traces of persistent organic particles (POPs) including heavy metals (Mahmoudpour et al., 2019). In SPR approach, intensity of signal can be regulated by controlling the configuration of a metallic surface, dimension of nanoparticles, dielectric environment, structural alignment, distance between particles and interior shell structure [Chen et al. (2009); Moskovits et al. (2002)]. Biosensors integrated with surface plasmon resonance (SPR) using metalic nanoparticles produce characteristic SPR spectra by dispersing light of varying wavelength (Taton et al., 2001; Haes and Van Duyne, 2002). The surface features of nanoparticles can be modified by conjugating peptides and carbohydrates which improves the biorecognition properties of biosensing devices (Cao et al., 2001). Furthermore, a small segment of deoxyribonucleic acid (DNA) can be conjugated with gold nanoparticles to form complex. This complex formation changes the colour from red to blue. This change in colour was because of the inter-particle electromagnetic coupling.

Detection of environmental pollutants like 2,3,7,8-TCDD (tetrachlorodibenzo-*p*-dioxin), PCB, and atrazine have been carried out using SPR technique involving gold thin layer (Zhang and Fang, 2010). Mohmoudpour et al. (2019) detected pesticides, polycyclic aromatic hydrocarbons (PAHs), heavy metals and polychlorinated biphenyls (PCBs) by SPR technique in environmental samples. Hashim et al. (2020) used SPR technique based on Au modified-tyrosinase (Tyr) enzyme integrated graphene oxide (GO) thin film for the detection of phenol. Kołątaj et al. (2019) have reported the plasmonic properties of AuNPs and AgNPs based biosensors for the detection of environmental pollutants. An optical sensor based on Au nanostructures for the detection of environmental pollutants with main emphasis on fugal toxin i.e. mycotoxins has also been designed (Al-Rubaye, 2019).

Recently, Garg et al. (2020) have reported the application of optical biosensor combined with SPR technique for the detection of Al^{3+} ions in the water samples. They used xylenol orange functionalized AuNPs for the fabrication of above this biosensor. The biosensor was found to be very sensitive by exhibiting 12 ppb limit of detection in potable water and linearity range s 50–300 ppb. This sensor was selective and specific. Fallah et al. (2020) have developed optical biosensor coupled with SPR technique. This biosensor sensed the CO gas by shifting of plasmon resonance peak in AuNPs confined on ZnO nanorods layered on SiO_2 surface. Detection limit of this device was 15 ppm with 10 s response time for sensing of CO gaseous pollutant. Singh et al. (2020) have reported the ultrasensitive detection of heavy metallic pollutants like lead and methylmercury in drinking and agriculture water using SPR integrated optical biosensor. Hyeon et al. (2020) have developed optical biosensor linked with SPR technique for the investigation of *S. typhimurium* found in different sources of environment. The selective investigation of this bacterium by above said biosensor was based on the use of entire Det7 phage tail protein. The working range of this biosensor was 0.8–24.6 μg/mL and 20 min response time.

4.2.3.3. Fluorescence biosensors in detection of pollutants. Fluorescence detection approach has been widely employed in biosensors. The fluorescence detection signal is assessed by spectrofluorimeter. Very low concentration of various pollutants in environmental samples can be detected by this technique (Gaviria-Arroyave et al., 2020). This approach has offered several advantages such as facile, fast, sensitive and reproducible. The intensity of generated fluorescence is correlated with the concentration of the pollutants. For the detection of ultra low concentration of pollutants semiconductor crystals have been found suitable, as they are photochemically stable components.

Qi et al. (2018) have demonstrated the fluorescent detection of phenolic pollutants like 4-nitrophenol (4-NP) and 2,4,6-trinitrophenol (TNP) by designing rotational paper based microfluidic chip device based on molecular imprinting polymer. Linearity range of this microfluidic system ranges between 0.5 and 20.0 mg/L and detection limit of 4-NP and TNP was 0.097 mg/L 0.071 mg/L respectively. This microfluidic system was found cost-effective, user-friendly and flexible. Lefever et al. (2012) have reported the detection of diuron pesticides in water by using fluorescent microfluidic device based on *Chlamydomonas reinhardtii* green algae, organic light emitting dioide and organic photodetector. Limit of detection this device was 11 nM. Ayodhya and Veerabhadram (2018) have demonstrated detection of Hg^{2+} ions in the pollutant water by fabricating optical sensor based on multifunctional graphite oxide (GO)-Bismuth sulphite (Bi_2S_3) nanostructures (NS) synthesized by sonochemical process. They used Bi_2S_3NS and GO as a photocatalyst and capping agent respectively. Developed sensor showed improved photo stability and sensitive detection of Hg^{2+} ions in the contaminated samples. Various pesticides *viz.* paraquat, parathion, pentachlorophenol, carbaryl, glyphosate, chlorpyrifos, pentachlorophenol etc. have been detected in water using quantum dots (Nsibande and Forbes, 2016). Moreover, owing of various advantages of using quantum dots including wide absorption spectra, augmented quantum yield and prolong fluorescence emitting capability, they emphasized the development of quantum dots based sensors for the detection of pesticides. However, they also revealed synthesis of quantum dots using heavy metals like cadmium has showed toxicity to living beings consequently detection of quantum dots from living source can resolve the toxicity issues. They reported fluorescent sensors are sensitive, selective and cost-effective. They also reported the significance of diverse range of recognition elements such as MIP, enzymes and supra molecules can enhance the analytical performance of sensing fluorescent devices. Mitra and Saha (2017) have demonstrated the detection of organic pollutants such as bisphenol-A, 1-napthol, phenol and picric acid in real water samples by fabricating fluorescence sensor. They used a dextran-fluorescein functionalized graphene composite.

Zheng et al. (2019) have reported fluorescently detection of perflurinated pollutants such as perflurooctane sulfonate (PFOS) and perflurooctanoicacid (PFOA) in contaminated water. Detection of perflurinated pollutants was based on guanidinocalix[5]arenes such as 5,11,17,23,29-Pentaguanidinium-31,32,33,34,35-penta(4-methylpentloxy)calix[5]arene (GC5A-6C), 5,11,17,23,29-pentaguanidinium-31, 32,33,34,35-penta dodecyloxy-calix[5]arene (GC5A-12C) for the precise and efficient capturing of pollutants. Moreover, guanidinocalix[5] arenes were co-assembled with iron oxide nanoparticles were used to absorb and filter the PFOS and PFOA from polluted water. Detection limits of this approach were 21.4 ± 0.4 nM and 26.4 ± 0.2 nM for PFOS and PFOA respectively. Sensitivity of this assay was better as compared to chromatographic techniques. Rasheed et al. (2018a,b) have also reported the application of fluorescence biosensors in detection of heavy metallic pollutants such as chromium, manganese, cobalt, nickel, copper, and zinc in real samples.

Merits: These biosensors are simple, fast, reproducible and can detect multiple pollutants simultanelously (Mehrvar and Abdi, 2004).

Demerits: These devcies are poor in sensitivity, stability and furthermore, they are difficult to miniaturize (Mehrvar and Abdi, 2004).

Comparison of different biosensors developed for the detection of hazardous components found in the environment has been illustrated in Table 2.

5. Remediation of environmental pollutants

Industrialization and various other anthropogenic activities release different types of hazardous components (i.e. physical, chemical and biological) into the environment (Manisalidis et al., 2020). Due to which climate of surroundings may get changed. As a result several harmful impacts may appear on living beings. Therefore, efficient, cost-effective, fast, on-site and eco-friendly remediation of such environmental pollutants is utmost important for environmentalists, governmental and non-governmental policies makers.

Conventional approaches for the remediation of environmental pollutants.

Conventionally physical, chemical and biological remediation techniques are used for the treatment of environmental pollutants (Mishra et al., 2019; Mohamed et al., 2017). Physical techniques include adsorption, electro-dialysis, filtration, ion exchange, sedimentation, coagulation and flocculation, reverse osmosis, floatation and extraction (Werkneh et al., 2019).

However, these techniques have several limitations like lesser sensitivity, more energy consuming, membrane fouling issues, tedious and expensive (Mishra et al., 2019). Chemical remediation techniques include coagulation and oxidation. But in these techniques expensive chemicals are used hence detection of pollutants is compratively expensive (Sharma and Bhattacharya, 2017). Bioremediation is prominently used biological approach for the degradation of pollutants. It mainly involves degradation of pollutants using microbes (Jacob et al., 2018).

Various other bioremediation techniques employed to treat environmental pollutants include phytoremediation, bioventing, biosparging, biofilter, land farming, bioaugmentation, biostimulation etc. (Sharma, 2020). These approaches have been employed for the degradation of harmful pollutants from different sources. But, these methods are time consuming, complicated, expansive, less efficient, sensitive and specific. Non-availability of agricultural land, water resources and several other factors restrict the use of these techniques for environmental pollutant management. In such a scenario, scientific community has made efforts to develop new and more efficient tools for the remediation of environmental pollutants and above mentioned issues have been resolved to a large extent by nanotechnology. Nanoparticles and their related nanostructures have been used as adsorbents and in some cases conjugated magnetic nanoparticles have been used for the sequestration of contaminants from the water and wastewater. The nanoparticles have also been used as catalysts for the removal of pollutants from the contaminated water.

5.1. Nanotools for control/remediation of environmental pollutants

A number of nano based approaches have been used for the removal of wide range of environmental pollutants released from diverse sources (Yang et al., 2019). These approaches include adsorption, catalysis and filtration using nanoadsorbents, nanocatalysts and nanomembranes (Anjum et al., 2019). A detailed account of these approches is given below:

5.1.1. Remediation/removal of the pollutants by nanoadsorbents

Nanoadsorbents are produced from atoms of chemically active elements having better adsorption capacity on their surface (Kyzas and Matis, 2015). Nanoadsorbents can be prepared from a number of nanomaterials including CNTs, silica, clay materials, metal oxides and modified compounds in the form of nanocomposites (Anjum et al., 2019). Nano-particles integration with various adsorbents increase their adsorption capacities significantly. The enhanced surface area consequently accelerate the catalytic and adsorption capacity of nano-particles for the adsorption of metals on their surface. Adsorption of pollutants depends on several factors like pH, temperature, concentration, incubation period (Anjum et al., 2019). Moreover, process of adsorption also relies on adsorption coefficient K_d and partitioning of pollutant in equilibrium conditions (Martínez et al., 2013). Redox reaction starts ionic transformation of persistent inorganic pollutants (Gupta et al., 2015). Most widely used nano-particles for adsorbent preparation are CNTs, manganese oxide, grapheme, zinc oxide, magnesium oxide, titanium oxide and ferric oxides (Gupta et al., 2011). Innate surface and peripheral functionalization are two main properties of nanoadsorbents. External surface configuration, outward size and internal conformation affect their physical, chemical and material properties (Anjum et al., 2019). In the aqueous environment, adsorption process affecting factors are high surface area, adsorption activity, chemical activity, location of atoms on surface, lack of internal diffusion resistance and high surface binding energy (Khajeh et al., 2013).

Anjum et al. (2019) have reported the adsorption of heavy metals from the wastewater. A wide range of nanomaterials including metallic nanoadsorbents such as Fe_3O_2 NPs, ZnO NPs, TiO_2 NPs and CuO NPs, metallic nanoparticles like Au NPs, Ag NPs and Pt NPs, hybrid oxide nanoparticles which includes Fe–Ti NPs, polymeric nanoadsorbents and nanoclays have been used in the fabrication nanoadsorbents (Patanjali et al., 2019). Efforts are on to evaluate the commercial potential of nanoadsorbents for the efficient and safe treatment of wastewater. Nano based approaches are economic and have better efficiency to remove hazardous components from polluted water (Jaleh et al., 2020). Therefore, this improves the health of human as well as associated life cycles of the ecosystem (Nasrollahzadeh et al., 2019).

5.1.2. Remediation of pollutants by nanocatalysis

Nanocatalysts are the chief component of nanocatalysis. They are inorganic materials like semiconductors and metal oxides. Distinct types of nanocatalysts like photocatalysts, electrocatalyst and Fenton based catalysts have been used for the treatment of wastewater (Dutta et al., 2014). Fenton based catalysts have been used for enhancing the redox reaction for organic pollutants and antimicrobial action (Ma et al., 2013). Degradation of organic pollutants in wastewater by photocatalysis is mediated by photocatalytical reactions between metallic nanoparticles and light energy (Akhavan, 2009). Semiconductor metals are acting as photocatalyst for the degradation of dyes, detergents, pesticides, and volatile organic pollutants (Lin et al., 2014). These nanocatalysts have capability to degrade halogenated and non-halogenated organic compounds (Anjum et al., 2019). The principle of photocatalysis involves excitation of electron from the catalyst under the influence of light. For example, TiO_2 NPs when radiated with UV light causes h^+ holes and emit electrons in the conduction part. These h^+ get filled with water molecules and produce OH^- ions in the aqueous media (Akhavan, 2009)).

Use of TiO_2 nanomaterials as a photocatalyst has been more preferred because of unique chemical reactivity and consistency (Anjum et al., 2019). Furthermore, ZnO nanomaterials are also potent photocatalysts as they exhibit broad band gap. The performance of these catalysts depends on various factors like band gap energy, particle size, dose, pollutant concentration and pH. In addition to these degradation efficiency decreased on increasing calcination temperature due to

Table 2
Comparison of various parameters of distinct biosensors developed for the investigation of environmental pollutants.

Type of biosensor		Enzymes/Nanomaterials/Living cells used	Electrode/Substrate used for immobilization	Target Pollutants	Limit of detection (LOD)	Stability	Working range	Application of Biosensor	Reference
Antibiotic detecting biosensors	Amperometric	Pt–Au nanowire array	Au(L-cysteine)-Pt (penicillinase) nanowire array electrode	Penicillin and tetracycline	–	–	–	–	Li et al. (2019)
Pesticides detecting biosensors	Amperometric	Graphene oxide nanosheets	Glassy carbon electrode	Hydrazine (HDZ), ascorbic acid (AA) and hydrogen peroxide (H2O2)	1.04, 0.5 and 4 µM		5–100 µM	Investigation of hazardous components in the environment	Vinodha et al. (2019)
	Optical	Whole-cell *Escherichia coli*	–	3-phenoxybenzoic acid	3 ng/mL	90 days	1.2–1200 ng/mL	Analytical tool to monitor exposure to pyrethroids in environment	Riangrungroj et al. (2019)
	Optical	*Chlamydomonas reinhardtii*	Paper	Nanoencapsulated -atrazine	4pM	21	0.5–200 nM	Help in smart agriculture on site	Scognamiglio et al. (2019)
	Surface plasmon resonance (Piezoelectric)	Oriented immobilization of immunoglobulin on sensor chip	CM5 sensor chip	Chlorpyrifos	0.056 ng/mL	210 cycles	0.25–50.0 ng/mL	Potent device for fast, sensitive, and efficient detection of Chlorpyrifos with wide-ranging uses in The field of environmental monitoring and food safety	Li et al. (2019)
Heavy metallic ions detecting biosensors	Amperometric	DNA-based specific aptamer probes labelled with ferrocene (or methylene blue) and thiol groups at 5′ ad 3′ termini	Screen-printed gold	Hg^{2+} and Pb^{2+} ions	0.1 ng/mL		0.1–1000 ng/mL	Easy, and inexpensive apta-sensors for fast analysis of heavy metals in water samples	(Abu-Ali et al., 2019)
	Amperometric	Horseradish peroxidase-catalyzed noradrenalin and glucose oxidiase enzymes	Platinum	Cr^{3+} and Cr^{6+}	-		-	Investigation of Cr^{3+} and Cr^{6+} ions in real samplesLiu et al. (2019)	(Liu et al., 2019)
	Optical	Recombinant plasmids comprised of merR gene	–	Hg^{2+}	1.0 ppb	–	1–104 ppb	Determination of Hg^{2+} ions in the water samples	Gupta et al. (2019)
	Fluorescence	Aptamer sequence	Magnetic beads	arsenic(III) (As^{3+})	2.0 pM		0-10 µM	Analysis of As^{3+} in real water samples	Zhang et al. (2019)
Enzymatic biosensors	Voltammetric	Nitrogen-doped Ordered Mesoporous Carbon	–	Acetylcholinesterase	0.02 nM		3–24 nM	Effective device for quick and sensitive investigation of organophosphorus pesticides in agri- products	Long et al. (2019)

enlargement of material size by agglomeration. Anjum et al. (2019) have reported that CdS nanoparticles have been employed as photocatalyst for the remediation of dyes in industrial effluents. However, aforesaid photocatalyst are active only in UV radiations not in visible/sunlight. Therefore, researchers have modified the nanocatalysts by dye sensitization, doping metal impurities, hybrid nano-particles or composites using narrow band-gap semiconductors, or anions Anjum et al. (2019). These modified nanocatalysts can emit electrons in the visible light. Modification of nanocatalysts by loading metals reduces the band gap energy and emits electrons to semiconductor in visible light. A number of doped nanocatalysts including ZnO:Co, Ni, ZnS:Mn, ZnS:Cu, CdS:Eu, CdS:Mn, ZnSe:Mn, ZnS:Pb, and Cu for the degradation of pollutants. Doping of nanomaterials has increased the surface area of catalyst and minimized the chances of size reduction and configural alteration of nanocomposites. CuO/ZnO phtocatalysts have been used to degrade Acid Red 88 dye in the waste water in visible light (Sathishkumar et al., 2011). Furthermore, functionalized ZnO nanocomposite using organic homopolymer polyaniline (PANI) has been used for the photocatalytic degradation of methylene blue and malachite green dyes in polluted water (Eskizeybek et al., 2012). Furthermore, TiO_2NPs has been used for the removal of pathogenic bacteria from waste water (Elkodous et al., 2020). Thus these nanocatalysts are potent antimicrobial agent that can be determined by assessing the extracellular polymeric substance (EPS) (Anjum et al., 2019). Mesoporous composite of Ag and TiO_2 film has also exhibited unique antimicrobial activity than commercially available P-25 TiO_2 spinning film.

5.1.3. Removal of the pollutants by filtration using nanomembranes

Nanomaterials such as nano-ribbons, nano-fibres, CNTs etc. have also been used in the synthesis of nanomembranes. These nanomembranes have shown promising applications in the treatment of waste water by removing dyes, heavy metals and other organic pollutants. Researchers have fabricated different types of nanomembranes for the filtration of polluted water including carbon nanotubes membranes, electrospun nanofibre membranes and hybrid nanomembranes (Anjum et al., 2019). Nanomembranes used for the treatment of water have several advantages such as unique catalytic activity, sensitivity and better permeability and fouling resistance (Pendergast and Hoek, 2011). Moreover, treatment of contaminated water by the nanomembranes is cost-effective, require minimum space, effective and simple (Guo et al., 2016). Electrospun nanomembranes prepared from polyvinylidene fluoride (PVDF) have been used for the treatment of wastewater. In addition to this, these membranes have been used in reverse osmosis and for the removal of heavy metals viz. nickel, cadmium, copper and chromium (Anjum et al., 2019). Nanofibre membranes have also been used in desalinaion of contaminated water. Toxic metals such as copper and lead are removed from wastewater by chitosan nanofibre mats (Teng et al., 2011). Moreover, clay nano-particles and PVFD composite membranes have been employed in distillation units. Nowack (2008) has reported that the contaminated water can be treated using nanofiltration by removing metals and organic compounds (Nowack, 2008). Several nanomaterials such as AgNPs, TiO_2 NPs, ZnO NPs, chitosan nanoparticles and carbon nanotubes have been used as disinfectant to handle the pathogenic microorganisms present in water (Werkneh et al., 2019).

Nano zero-valent iron (nZVI) has shown enhanced reactivity than other nanomaterials and thus has been used for the transformation or degradation of pollutants in soils and water (Tosco et al., 2014). nZVI can degrade several hazardous pollutants such as chlorinated compounds, pesticides, chlorinated biphenyls, intensified metallic ions due to their catalytic activity and reduction process (Karn et al., 2009). During degradation process, nZVI's are transformed from Fe^0 to Fe^{2+} and then Fe^{3+}. The chemical reaction involved in degradation of hazardous components of ground and surface water by nZVI has been shown below:

$$2Fe^0\ (s) + 2H_2O\ (l) \rightarrow 2Fe^{2+} + H^2\ (g) + 2OH^{-}.$$

This Fe^{2+} form is further oxidized to Fe^{3+} from that is more stable by involving either of following conversions:

$$2Fe^{2+}\ (s) + 2H^+\ (aq) + 1/2O_2\ (aq) \rightarrow 2Fe^{3+} + H_2O(l)$$

$$2Fe^{2+}\ (s) + 2H_2O\ (l) \rightarrow 2Fe^{3+} + H_2\ (g) + 2OH^-\ (aq)$$ (Crane and Scott, 2012)

The Fe^{2+} ions are hazardous for microbes and invertebrates. However, these Fe^{2+} ions are transformed into Fe^{3+} in neutral and alkaline medium. Aquifers are used in underground water where oxygen is limited. Therefore, Fe^0 state is changed into either Fe_3O_4 (magnetite) or Fe_2O_3 (maghemite) depending upon the oxidative surroundings (Grieger et al., 2010).

Application of nZVI in degradation of heavy metals such as arsenic and chromium and lindane has also been identified (Patil et al., 2016). These nZVI have also been used for the degradation of organic pollutants including DDT and other pesticides (Karn et al., 2009). Inorganic NPs such as Ag/Fe, Ni/Fe and Cu/Fe have played a significant role in reducing the hazardous impact of heavy metals, complex chlorine and benzene containing compounds as well as compounds that are explosive in nature (Koutsospyros et al., 2012; Nie et al., 2013; Yan et al., 2010). For instance, Koutsospyros et al. (2012) prepared bimetallic particles by using either Fe/Cu or Fe/Ni for the remediation of nitramines and nitro-substituted energetic materials found in aqueous effluents. Remediation of these materials was based on reductive technology involoving bimetallic particles and aqueous streams of RDX, HMX, TNT and insensitive-munitions components (NTO, NQ, DNAN). The response time of degradation process was 10 min which depends on solids stacking and initial pH. Degradation process followed first order reaction kinetics. Nie et al. (2013) have prepared silver (Ag)/iron (Fe) particles for the degradation of hexachlorobenzene (HCB). Degradation of HCB was based on dechlorination of Fe that can be enhanced with addition of traces amount of Ag. Rate of degradation of HCB was more in acidic pH at 85 °C. Degradation of HCB using dechlorination pathway produced two important compounds namely 1,2,4,5-tetrachlorobenzene and 1,2,4-trichlorobenzene. This dechlorination pathway took approximately 2 h for PCB degradation. Yan et al. (2010) have revealed the significance of palladized zero-valent (Pd-nZVI) particles for remediation of halogenation compounds. These particles contain metallic iron core and a thin amorphous oxide shell and outer Pd nanoparticles. When water comes in contact with water, Pd-nZVI changes its structural configuration. Thus by *in-situ* remediation involving hydrodechlorination, aging and deactivation based on Pd-nZVI were used to remediate halogenated compounds.

The internal core of metallic nanoparticles such as Fe/Ni and Fe/Pd was confined on polyacrylic acid (PAA)/polyvinylidene fluoridated (PVDF) membrane matrix. These modified membranes have been used for reducing the toxicity caused by chlorinated compounds (Xu and Bhattacharyya, 2005). Preparation of nanoparticles involving PAA was used as chelating agent for exchanging the metallic cations. Reactivity of membrane was assessed by two model compounds namely polychlorinated biphenyl (PCB) congener and trichloroethylene (TCE) via reaction mechanism shift and product distribution.

The removal of DTA using nZVI was mediated by both oxidation and reduction reactions. As a result DTA was converted into amide group by repeated cleavage of two iodides in aerobic conditions. Furthermore, lower pH and elevated nZVI concentration accelerated the decomposition of DTA. Zero valent metals are semiconductor, bi-metallic nanoparticles and acting as nanocatalysts. These nanocatalysts have shown characteristics morphological and catalytic properties (Patanjali et al., 2019). Thus they have been used for the decomposition of environmental pollutants like pesticides, halogenated herbicides, azo dyes, polychlorinated biphenyls and nitroaromatics.

The efficiency of fertilizers have also been improved by using metallic nanoparticles which include Al_2O_3NPs, TiO_2NPs, CeO_2NPs, FeONPs and ZnONPs (Prasad et al., 2017). The transformation of dyes, pesticides, pharmaceuticals, and drugs have been mediated by single walled or multi walled CNTs (Yu et al., 2014). These CNTs have detoxified the heavy metallic ions viz. Cr^{3+}, Pb^{2+} and Zn^{2+}, arsenic compounds, bio-contaminations, volatile compounds and dioxins at the affected site (Rao et al., 2007). Avila et al. (2014) also reported the utility of modified E-membranes and platelets for the decomposition of oil spills. Moreover, Zhang et al. (2019) have demonstrated that engineered nanomaterials have degraded the poly- and perfluoroalkyl substances (PFASs) found in contaminated water samples using physical

Table 3
Applications of various nanotools in remediation of various environmental pollutants.

Name of nanotools		Significance of nanotools	Target Pollutants	References
Heavy metals	Fe_3O_4/MnO_2	They act as adsorbent for heavy metals	Investigated Cd^{2+}, Cu^{2+}, Pb^{2+} and Zn^{2+}	Kim et al. (2013)
	TiO_2NPs	These nanomaterials adsorb heavy metals from industrial effluent	Cu(II), Ni(II), Cr(III) and As(III)	Besha et al. (2020)
	$CoFe_2O_4$-reduced graphene oxide	They are used for adsorption of heavy metals	Pb^{2+} and Hg^{2+} ions	Zhang et al. (2014)
	MgONPs	They are used in efficient treatment of polluted water contaminated with heavy metals	Cd^{2+} and Pb^{2+}	Cai et al. (2017)
	CMC-nZVI	Immobilize Cr(VI)	Cr(VI)	Madhavi et al. (2014)
	Al_2O_3NPs, SiO_2NPs, TiO_2NPs	They reduces movement of metals	Zn, Cd, Ni	Peikam and Jalali (2019)
	Nano-Fe/Ca/CaO	They help in immobilization of soil elements like As, Cd and Pb	As, Cd, Pb	Mallampati et al. (2013)
	nZVI	They have been extensively used in elimination of heavy metallic constituents	Cr(VI), Pb^{2+} and As^{3+}	Fu et al. (2014); Mueller et al. (2012)
	Starch-stabilized nZVI, FeSNPs, Fe_3O_4NPs	These nanomaterials lowers both As availability and leachability by elevating Fe/As molar ratio	As	Zhang et al. (2010)
	Functionalized Carbon nanotubes (CNTs)	They help in controlling of foul smell, adsorb heavy metallic ions	Cu^{2+}, Pb^{2+}, Cd^{2+}, Hg^{2+}, Zn^{2+}, Cr^{6+}, Ni^{2+} and Mn^{2+}	Besha et al. (2020); Jung et al. (2017)
	Functionalized Fe_2O_3NPs, Fe_3O_4NPs	They adsorbed heavy metals released from industrial effluents. In sun light they also involved in the process of photo degradation.	Detected heavy metallic ions including Pb^{2+}, Cu^{2+}, Cd^{2+}, Hg^{2+}, Cr^{6+}, Ni^{2+} and As^{5+}	Attia et al. (2013)
	ZnONPs	They detected heavy metallic ions by adsorbption	As^{3+}	Besha et al. (2020)
	Graphene, and its surface modification	They involved in efficient detection of heavy metals	Cr^{6+}, Pb^{2+}, Hg^{2+}, Cd^{2+}, Hg^{2+} and Ni^{2}	Besha et al. (2020)
Antibiotics	Azide-functionalized hollow silica nanospheres	Help in modification of hollow nano forms of silica thereby facilitating the adsorption of antibiotics	Ciprofloxacin hydrochloride	Gao et al. (2015)
	Graphene, and its surface modification	They exhibited potent antibacterial properties. Also used in treatment applications of wastewater contaminated with estrogenic, beta-blockers and other pharmaceuticals	tetracycline, oxytetracycline, chlortetracycline	(Besha et al., 2020)
	TiO_2NPs	They also involved in photo-catalysis for EDCs, antibiotics and elimination of pharmaceutical compounds	Ciprofloxacin, 17b-estradiol	(Besha et al., 2020)
	Functionalized Fe_2O_3NPs, Fe_3O_4NPs	They adsorbed dyes, personal care products (PPCPs), antibiotics and heavy metals released from industrial effluents. In sun light they also involved in the process of photo degradation	diclofenac, naproxen, gemfibrozil and ibuprofen, tetracycline and ciprofloxacin have been detected	Attia et al. (2013)
Dyes	ZnONPs	They are used as phtocatalyst for several organic compounds i.e. dyes	Methylene blue, green and orange	(Besha et al., 2020)
	CdSNPs	These NPs are acting as photocatalyst for the treatment of industrial dyes in polluted water	Azo dye and Congo red	Zhu et al. (2009)
	Functionalized Carbon nanotubes (CNTs)	They help in bio–catalysis	Methyl orange, methylene blue	Besha et al., 2020
	Functionalized Fe_2O_3NPs, Fe_3O_4NPs	They adsorbed dyes. In sun light they also involved in the process of photo degradation.	Red dye, Congo red, Blue 79 azo dye	Attia et al. (2013)
	nZVI	They have been extensively used in elimination of organic compounds like dyes	Methyl orange	Fu et al. (2014); Mueller et al. (2012)
Pesticides and other organic pollutants	ZnONPs	They are used as phtocatalyst for several organic compounds	4-chlorophenol, fungicides, insecticides, herbicides and pesticides	(Besha et al., 2020)
	nZVI	They have been extensively used in elimination of organic compounds like chlorinated and nitoaromatic	Chlorinated ethens, polychlorinated biphynels and phenolics	Fu et al. (2014); Mueller et al. (2012)
	Functionalized Carbon nanotubes (CNTs)	They help in controlling of foul smell and adsorb EDC compound	Phenol derivatives, catechol, aniline, 17b-estradiol and 17a-ethynyl estradiol.	(Besha et al., 2020); Jung et al. (2017)
	CuO NPs	These NPs are acting as an adsorbent	Sulfamethoxazole; bisphenol A	Lata & Samadder (2016)
Bacterial pathogens	MgONPs	They are used in efficient treatment of polluted water contaminated with bacteria	*E. coli*	Cai et al. (2017)
	Functionalized Carbon nanotubes (CNTs)	They help in controlling of foul smell, and EDC compound	*B. cereus*, *S. aureus*, *B. subtilis*, *E. coli* and *P. aeruginosa*	(Besha et al., 2020); Jung et al. (2017)
	Graphene, and its surface modification	They exhibited potent antibacterial properties.	*E. coli* and *B. subtilis*	(Besha et al., 2020)

sorption and photochemical reactions. Zhou et al. (2019) have reported the efficient removal of diatrizoate (DTA) pollutants from water samples in aerobic environment.

Patanjali et al. (2019) reported that silver nanocatalyst N-doped TiO_2NPs and ZrO_2NPs have been used for the degradation of biological entities found in water as they exhibited unique photocatalytical activity, hydrophilicity, reduced toxicity, economic and chemically more stable. Table 3 depicts the different types of nanotools used for degradation of environmental pollutants.

Accumulation of copper either by leaching or some other way leads to severe threats in the ecosystem. Wang et al. (2019) have designed nano $CuAl_2O_4$ spinel by co-precipitation approach. This copper containing spinel exhibited unique antibacterial activity with minimum risk of leaching. Zinatloo et al. (2019) prepared $Nd_2Sn_2O_7{\cdot}SnO_2$ nanocomposites using pineapple extracts. During their fabrication, they are acting as natural reductant and capping agent due to presence of sugar in the extract of pineapple that helps in alteration of shapes. It has been reported that the working of $Nd_2Sn_2O_7{\cdot}SnO_2$ nanocomposites were greatly varied with their size and shape. As these nanocomposites were synthesized by natural procedure therefore they can be easily degraded by photocatalysis mechanism. Nanocomposites of $Nd_2Sn_2O_7{\cdot}SnO_2$ have been found potent visible-light sensing photocatalysts and cost effective mechanism.

Zhou et al. (2019) have developed 'nano kinves', a novel physical technique for the degradation of carboxymethyl cellulose found in organic pollutants. The working of these nano knives involve the cleaving of covalent bonds (β 1–4 glycosidic bonds) acting as a backbone of macromolecular cellulose. The importance of this novel technique is that in contrast to existing technologies, it does not use either chemical or biological agent for the degradation of organic pollutants. it can be inferred from the results that nano knives are cost-effective and eco-friendly technique for the degradation of organic pollutants present in polluted water.

Though, bacteria have been documented for their application in existing degradation approaches like bioremediation. However, owing of limitations of these approaches such as time consuming, less efficient, and expensive and most important non-recovery of microbial cells after degradation of harmful pollutants have been replaced with highly advanced nano based strategies. Zhang et al. (2015) have reported the significance of different groups of microorganisms in recovery of microbial cells after degradation of pollutants. They recovered the bacterial cells using magnetic nanoparticle mediated isolation process (MMI). Authors have reported that MMI were capable to recover uncultured *Burkholderiales* spp., phenol degrading bacteria from biosludge of kitchen waste water. In addition, 5 different phenol degrading bacteria including *Rhodococcus* sp., *Chryseobacterium* sp. and three different *Pseudomonas* spp. have also been isolated from this biosludge. From this work it has been concluded that recovery of physiologically active bacterial cells can be achieved by employing MMI process. Moreover, this approach has also provided a platform to understand a number bacterial essential processes viz. metabolic phenomenon, assembly of genetic constituents, phylogenetic relationship, diversity, adaptation and ecophysiology. Xu et al. (2014) have reported the role of poly-allylamine-hydrochloride (PAAH) NPs in water purification by eradicating the bacteria. These NPs purify the polluted water by electrostatic interaction and magnet capture. They demonstrated the removal of *Escherichia*, *Acinetobacter*, *Pseudomonas* and *Bacillus* bacteria. This demonstration has revealed the removal of bacteria in polluted water by this emerging magnetic NPs technology is economic, efficient and does not cause toxicity to living system. Furthermore, they have also acknowledged that this technology can tackle the bacterial pollution related issues of rural rareas where limited resources are available for the treatment of potable water. Therefore, in near future, researchers can monitor and access the level of water contamination. This will be beneficial for maintaining the quality of water by removing the pathogenic microbes in the water. Fig. 9 depicts the different applications of nanotechnology for achieving sustainable environment.

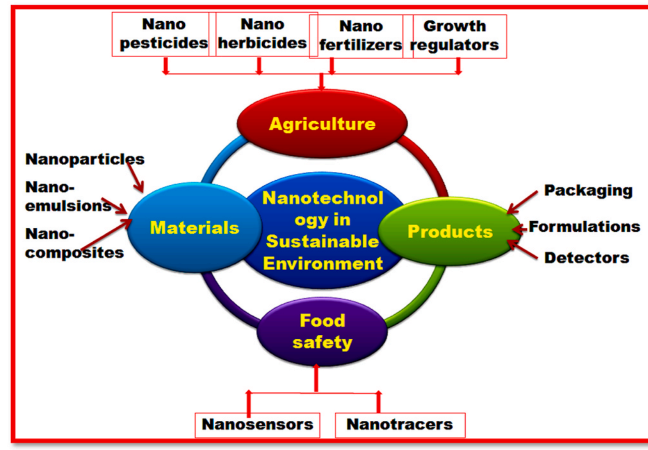

Fig. 9. Applications of nanotechnology in sustainable environment.

Jiang et al. (2018) have reported magnetic NPs (MNPs) can be used for degrading environmentally hazardous components. The characteristics of MNPs like greater surface area, better biocompatibility, rapid degradation process make them a good choice for the treatment of environmental pollution. Furthermore, MNPs can be used for on-site degradation of contaminants released from industries and also effective for the treatment of contaminants found in ground water, soil and air. These MNPs either act adsorbent or catalyst. MNPs have proven to be effective for the treatment of wastewater generated by various industries like tanning, textile, dyeing and painting industries. On the other hand MNPs integrated biosensing devices have also been developed for the investigation of bacteria (Jiang et al., 2018). For example bacteria *P. aeruginosa, M. aeruginosa, D. desulfotomaculum* and *E. coli* have been detected by using MNPs based biosensors (Tang et al., 2013; Lin et al., 2015; Wan et al., 2010. Chen et al. (2014) have also reported the remediation of heavy metallic ions including Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}, Ni^{2+} and As^{3+} by using MNPs. MNPs have also been used for the remediation of radioactive uranium from the contaminated aqueous solution (El-Sherif et al., 2017). Table 4 encapsulates significance of MNPs in remediation of different types of environmental pollutants.

5.2. Role of biochar in the remediation of pollutants

Remediation of environmental pollutants by biochar has been reported by several authors. Biochar is a carbon containing material obtained from solid biomass and sludges by the process of pyrolysis at different temperatures in the range of 300–800 °C (Pan et al., 2020). Before pyrolysis, raw materials are pre-treated using various methods such as dewatering, air drying, crushing, sieving etc. Depending upon time duration, pyrolysis can be slow, medium and fast.

Feedstock → Canning → Pyrolysis → Grinding

Slow pyrolysis process takes more than one h to produce biochar as a main component and small auxiliary components namely syngas (CO, H_2 and CH_4) and bio-oils. While fast pyrolysis takes $<$ 2s and produce biochar (12%), syngas (13%) and bio-oils (75%). Moreover, adsorption and activation efficiency of biochar relies on quantity and quality of feedstock and physico-chemical parameters including temperature, oxygen level, residence time and rate of heating.

Biochar can be a preferred material for the remediation of pollutants due to its high surface area, exceptional adsorption capability and cost-effectiveness. Novel biochar composites have been synthesized by functionalization and incorporation of nanoparticles. Biochar provide effective dispersion and stability to nanoparticles. Functionalization of

Table 4
Application of MNPs in remediation of distinct types of environmental pollutants by adsorption.

Name of target pollutants or adsorbent		Name of magnetic nanoparticles (MNPs)	Reference
Heavy metals	Dy^{3+}, Nd^{3+} and Er^{3+}	Diethylenetriamine-modified chitosan-MNPs	Liu et al. (2017)
	Uranium	CeO_2–TiO_2–Fe_2O_3	El-Sherif et al. (2017)
	Radioactive Cs	Prussian blue MNPs	Jang et al. (2014a)
	Pb^{2+} and Cd^{2+}	Ethylenediamine tetra acetic acid (EDTA)-modified MNPs	Pena et al. (2017)
	Ni^{2+}	Oleate modified MIONs	Magnet et al. (2017)
	Pb(II), Hg(II), Cu(II), and Co (II)	Poly(methyl methacrylate) and superparamagnetic iron oxide nanoparticle	Wanna et al. (2016)
	Cd^{2+}, Cr^{6+}, Cu^{2+}, and Ni^{2+}	Magnetite Fe_3O_4	Shen et al. (2009)
	Pb^{2+}, Cd^{2+}, Cu^{2+}, Zn^{2+}, Ni^{2+} and As^{3+}	EDTA-modified MNPs	Chen et al. (2014)
Dyes	Methylene blue	Anionic sodium dodecyl sulfate (SDS) surfactant-modified $ZnFe_2O_4$ NPs	Zhang et al. (2017)
	Di-anionic azo dye Acid Black 1	Fe_3O_4/γ-Al_2O_3 hybrid composite	Jung et al. (2017a)
Oils	Emulsified oil droplets	Polyoxyallcylated N,N-dimethylethanolamine-Fe_3O_4	Duan et al. (2017)
	Oil	Amine-functionalized MNP	Ko et al. (2017)
	Oil field structure	Multi-shell structure MNPs of ferroferric oxide as core; nonporous silica as inter layer; mesoporous silica as outer layer	Liu et al. (2012)
Pharmaceuticals	Dipyrone	Nickel ferrite	Springer et al. (2016)
	Tetracycline	Chitosan-Fe_3O_4 MNPs	Raeiatbin and Acikel (2017)
	Amoxicillin	Fe_3O_4@C NPs	Kakavandi et al. (2014)
Pesticides	Di-(2-ethylhexyl) phthalate	Magnetic molecularly imprinted polymer NPs	Li et al. (2017a)
	Endrin and dieldrin	Nanocomposites of graphene oxide and MIONs	Shrivas et al. (2017)
	Parathion, fenthion, phoxim, temephos, and paraquat	Liquid-modified MNPs	Latifeh et al., 2016; (Zheng, 2014)
	Nitrate ions	Magnetic activated carbons	Arbabi et al. (2017)

nanoparticles increases the surface active sites to enhance the mechanical and chemical properties of the material. Pan et al. (2020) have revealed the application of biochar and biochar composites in the treatment of wastewater. Treatment of wastewater is based on Fenton-like processes that involve the activation of hydrogen peroxide and persulfate due to oxidation. Biochar prepared from easily available raw materials is a cost-effective process however; Pan et al. (2020) reported reduced adsorption capacity of biochar, poor stability and no reusability. Furthermore, remediation of pollutants depends on raw materials properties, pyrolysis conditions, nature of pollutants and degrading parameters (temperature, oxygen supply etc.) (Angın et al., 2013; Zhao et al., 2020). Therefore, these limitations may restrict the practical application of biochar in wastewater treatment. Development of novel biochar composites may provide a solution to these limitations. Novel biochar can be prepared by incorporating various functional nanoparticles into the biochar. Biochar composites have better physical and chemical properties in comparison to biochar such as large and precise surface area, high porosity, reusability, better stability and catalytical properties. Biochar composites also have better adsorption capacity of multiple pollutants simultaneously from the aquesous sytems (Deng et al., 2019).

Preparation of biochar composites involves pre-treatment and post-treatment techniques. Pre-treatment technique further based on two approaches viz. (i) cultivation of plant seedlings or growing plants in solutions with essential components for prolonged duration to accumulate biomass by bio-concentration process (ii) before pyrolysis biomass is pretreated by impregnating in solutions like $AlCl_3$, $CaCl_2$, $MgCl_2$, $KMnO_4$, and $ZnCl_2$ etc. to form distinct types of nanoparticles including Al_2O_3, AlOOH, CaO, MgO, MnO_x, and ZnO on biochar surface after pyrolysis (Tan et al., 2016). Post-treatment of biochar composites production involves further processing of biochar after pyrolysis of biomass pyrolysis to incorporate other material on biochar. Impregnation, evaporation, and heating are most widely used post-treatment techniques for biochar composites synthesis. Rectorite/sludge derived biochar (RSDBC) loaded with $CuFe_2O_4$ to form $CuFe_2O_4$/RSDBC composite has been used as catalyst to produce active persulphate to remove acid orange 7 (AO7) from polluted water. Performance of catalyst was optimum in solution having pH 7.0 and temperature 25 °C. Remediation efficiency of this acomposite was 95% and it was reuseable for three successive cycles without compromising the efficiency (Guan et al., 2020).

Synthesis of red mud-sewage derived biochar with peroxymonosulfate (PMS) was used for the degradation of sulfamethoxazole (SMX) (Wang et al., 2020). This RSDBC/PMS composite showed 82.5% degradation efficiency. Yin et al. (2019) demonstrated degradation of SMX by synthesizing sludge-derived biochar (SDBC) incorporated with peroxydisulfate (PDS) to form SDBC/PDS. This system exhibited 94.6% degradation efficiency. Huang et al. (2018) have revealed the application of sludge biochar in remediation of bisphenol A, an endocrine disrupting pollutant by advanced oxidation process based on persulfate. Degradation efficiency of pollutant was depending on the performance of catalyst and oxidant generated from persulfate. This biochar system can remove the pollutant up to 80% in 30 min.

5.3. Sustainable solutions based on nanotechnology

Nanotechnology has provided several sustainable solutions to handle the harmful pollutant present in the environment (Tratnyek and Johnson, 2006). Precision farming is one among the significant nano-based approaches that can be used to minimize the release of pollutants from agriculture sector (Cao et al., 2005). Researchers have reported the significance of different types of nanomaterials used for degradation of environmental pollutants as given in Table 5**.** Nanomaterials used for the remediation of pollutants have offered several advantages such as high surface area, better adsorption capacity, rapid and cost-effective (Sadegh et al., 2017). Development of nano-based approaches including nanocatalysis and adsorption have been used for the removal of environmentally hazardous components/chemicals (Guerra et al., 2018a). Nanocatalysis has increased the yield of different reactions. Researchers have fabricated nanofilters and nanomembranes for the decontamination or to maintain the quality of groundwater. Nanomembranes have been used in reverse osmosis for the desalinization and treatment of polluted water (Das et al., 2015). These nanomembranes have shown minimum susceptibility of blocking, better lifetime and cost effectiveness. Nanomaterials used for the remediation of pollutants can be prepared from either chemical or biological materials i.e. microbes, plants, algae etc. However, nanomaterials synthesized from chemicals may cause toxicities that affect vital physiological processes of living systems such reproduction, digestion, respiration and excretion. Moreover, the chemical based nanomaterials may also cause mutations

Table 5
Different types of bionanomaterials for the degradation of environmental pollutants.

Types of living system	Name of Microbes used	Name of nanomaerials/ nanoparticles	Pollutants degraded	References
Bacteria	*C. pasteurianum* BC1 cultures	Pd	Azo dyes, methyl orange and Evans blue	Johnson et al. (2012)
	Desulfovibrio desulfuricans and *Shewanella oneidensis*	Pd	Polychlorinated biphenyls	White et al. (2009)
	Pseudomonas aeruginosa	Nanoscale zerovalent iron (NZVI)	Heavy metal reduction of Cr(VI) and Cd(II)	Singh et al. (2011)
	Geobacillus sp.	Au	Gold-bearing waste	Correa-Llantén et al., 2013
	Veillonella atypica	Selenium	Selenide	Pearce et al. (2008)
	Bacillus subtilis	Co_3O_4	Lithium	Shim et al. (2011)
	Microbacterium sp.	NiO	Ni	Sathyavathi et al. (2014)
	Shewanella algae	Pt	Au (III)	Konishi et al. (2007)
Fungi	*Penicillium oxalicum*	Ag	Methylene blue	Du et al. (2015)
	Flammulina velutipes	Ag	Methylene blue, nitrophenol	Narayanan et al. (2015)
	Gordonia amicalis HS-11	Au and Ag	Hexadecane	Sowani et al. (2016)
	Aspergillus versicolor	CdS	Cadmium ions	Das et al. (2012)
	Fusarium oxysporum	Cu	Electronic waste	Majumber (2012)
Yeast	*R. mucilaginosa*	Cu	Copper-containing wastewater	Farghali et al. (2013)
Plants	*Lantana camara*	Cu	Electronic wastes	Majumber (2012)
	Catharanthus Roseus	Chitosan nanoparticles	Chloramphenicol and ketoconazole	Nagaonkar et al. (2015)
	Aloe vera	α-Fe_2O_3	As(V)	Mukherjee et al. (2016)
	Citrus limon	CuO	Cr(VI)	Mohan et al. (2015)
	Citrus grandis	Cu	Methylene blue	Sinha et al. (2015)
	Phyllanthus emblica	Zero-valent silver nanoadsorbent	Hg(II)	Sundarajan et al. (2013)
	Amaranthus tristis	Ag, Cu and zerovalent iron (ZVI)	Tannery, textile and pharmaceutical wastes	Alsabagh et al. (2015)
	Helicteres isora	Ag	Dyes, such as methyl violet, safranin, eosin methylene blue and methyl orange	Bhakya et al. (2015)
	Pycnoporus sanguineus	Au	4-Nitroaniline	Shi et al. (2015)
	Breynia rhamnoides	Au and Ag	4-Nitrophenol	Gangula et al. (2011)
	Acacia nilotica	Ag	4-Nitrophenol	Karuppiah et al. (2014)

consequently different types of cancers (Kühnel et al., 2017). Therefore, nanoparticles synthesized from biological sources have gained significant attention to overcome the issues of aforesaid chemical based nanomaterials. Therefore, in the following section significance of biological nanomaterials in the remediation of environmental pollutants has been discussed:

5.3.1. Relevance of bio-nanoparticles for the decomposition of environmental pollutants

Biological nanoparticles have been synthesized from lower organisms including bacteria, fungi, actinomycetes, yeasts and algae. Bionanoparticles synthesized from these organisms can effectively degrade the organic compounds at the polluted site (Table 5). It has been found that *C. pasteurianum* BC1 cultures reduced the Pd (II) ions to form metallic Pd nanoparticles (bio-Pd) which is mainly found in the microbial cell wall. These cultures have ability to reduce various organic dyes *viz.* azo dyes, methyl orange and Evans blue (Johnson et al., 2012). Das et al. (2018) have reported the removal of chromium and cadmium ions using nZVI nanoparticles synthesized from *P. aeruginosa* by reduction process.

Eukaryotic organisms such as fungi have also been used for the preparation of nanoparticles (Das et al., 2012). These fungal nanoparticles differ in chemical composition and size. As, one of the potent source of preparation metallic bionanoparticles is fungi; thus fungi have also been referred as ‘‘Nanofactories’’ (Dhillon et al., 2012). Shedbalkar et al. (2014) have reported the preparation of nanoparticles from *Fusarium oxysporum, Aspergillus fumigates* and *F. semitectum*. Kai et al. (2017) have reported the remediation of pollutants using nanoparticles synthesized from white rot fungi (WRF) as these fungi possess enzymes lignin, cellulose and hemicelluloses degradation found in the wood of plant and main constituents of the ecological cycles (Kai et al., 2017).

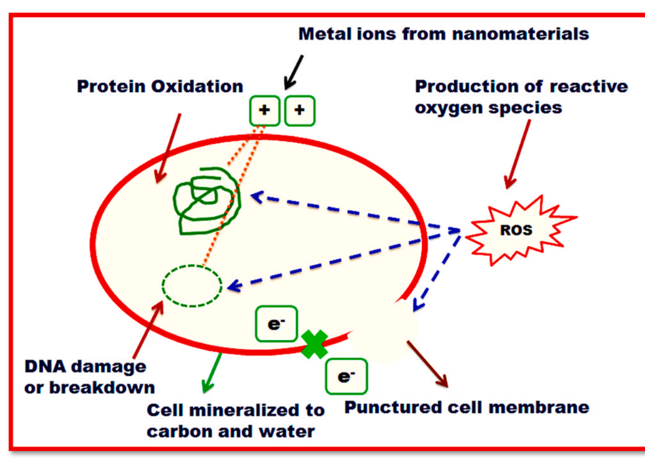

Fig. 10. Toxicological aspect of nanomaterials on entire ecosystem.

Fig. 10 depicts the mechanism of microbial cell death using metallic nanoparticles.

Thus, nano based approaches have provided the sustainable solution for the mitigation of environmental pollutants. Researchers have reported sustainable solutions based on nanomaterials for harvesting the atmosphere CO_2, production of huge amount of biomass for the generation of biofuel, efficient recycling of solid waste into beneficial products and purification of waste water https://www.greenbiz.com/article/3-ways-nanomaterials-can-combat-pollution.

5.3.1.1. Degradation of pollutants using emulsified zero-valent iron.

Emulsified zero-valent iron (E-ZVI) is another ecofriendly strategy for the degradation of environmental pollutants (Dong et al., 2015). E-ZVI is the modified form of nZVI. E-ZVI is prepared by encapsulation of iron particles by biodegradable oil membrane. This biodegradable membrane has ability to absorb pollutants which cannot dissolve and lyses into nontoxic compounds (Liu et al., 2010; Mathew et al., 2017). Hence, these E-ZVIs can be used for degradation of pollutants as well as for purification of groundwater (Mathew et al., 2017). Dong et al. (2015) have revealed the application of E-ZVI in degradation of nitrobenzene in ground water. They prepared E-ZVI by coating iron nanoparticles using emulsified vegetable oil membrane. Optimum concentration of oil used for EZVI preparation was 1–2%. Kinetics of nitrobenzene reduction in anaerobic environment was evaluated by performing batch experiments. Reduction of nitropbenzene during degradation followed pseudo first-order kinetics and 0.0942 min^{-1} was the rate constant of nitrobenzene. Furthermore, degradation rate of nitrobenzene and production of aniline was directly proportional to iron content. One more study by Dong et al. (2018) have also revealed the remediation of nitrobenzene. Zhang et al. (2019) have reported the degradation of nitrobenzene by synthesizing E-ZVI. The stability and activity of E-ZVI was enhanced by using xanthine. Removal of nitrobenzene was based on reduction process during batch experiments.

5.3.1.2. Engineering approach based on nanotechnology for clean and green environment. Existing nanotechniques do not provide an effective knowledge for the fabrication of such analytical tools that can be used for the risk assessment. Available analytical devices are less in number, costly, time taking and incompetent to assess nanomaterials in environment (Montaño et al., 2014). So far, there are no standard methods for detection of nanoparticles in environment. In addition to these, existing nano approaches are less efficient and reliable for making clean and green environment. Hence, it is requisite to design such eco-friendly nano tools or devices which can mitigate the problems associated with different types of pollution (Garner and Keller, 2014). (Patil et al., 2016) have reported the use of permeable iron barriers (PIBs) to capture nZVI after degradation of pollutants at the target site. These PIBs degrade the pollutants by reduction process. Beside this other approach for preparation of smart/engineered nanomaterials that can be used for the abatement of pollutants involves modification of nanomaterials with novel coatings or functional groups. These smart nanomaterials have offered many advantages such as improved stability, moving ability and performance of nanoparticles (Thatai et al., 2014). Fig. 11 depicts the mechanism of remediation of environmental pollutants using nanoparticles. Thus, engineering of nanomaterials has become quite essential for making green environment by enhancing capabilities of nano tools for the effective remediation of environmental pollutants.

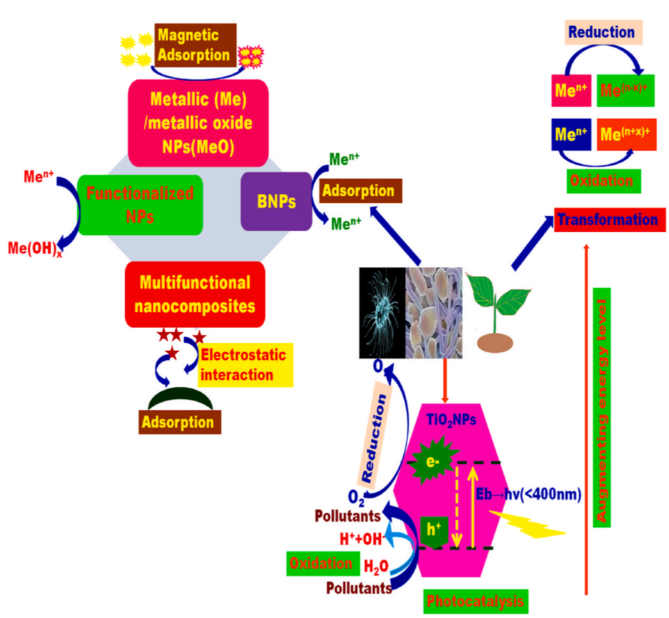

Fig. 11. Diagrammatic representation of mechanism of remediation of pollutants using nanoparticles.

5.3.2. Applications of green nanoparticles

Synthesis of green nanoparticles is simple, eco-friendly and economic, improve degrading capabilities, minimized release of hazardous products and byproducts in nature (Shah et al., 2015). Plants are major source for the synthesis of green nanoparticles. These green nanoparticles have shown profound impact in reducing the ecotoxicity. Earlier, 'Eco-friendly' approaches were based on use of green tea leaves, oak, pomegranate plants for the synthesis of nZVI. These aforementioned plants have shown unique anti-oxidant properties (Machado et al., 2013a, 2013b; Hoag et al., 2009; Nadagouda et al., 2010; Kharissova et al., 2013). Machado et al. (2013b) have reported the detection of ibuprofen in soil by using nZVI. These nZVI were prepared from leaves of grape marc, black tea and vine (Machado et al., 2013b). Nadagouda et al. (2010) have synthesized the eco-friendly nZVIs using polyphenolic components extracted from tea plants. They used borohydride method for the preparation of green nZVI. These green nZVI were found to be hazardless than the control samples prepared by using borohydride reduction protocols. In vitro assessment of biocompatibility was carried out on human keratinocyte cell (HaCaT) line. Determination of cytotoxicity effects of green nZVI was based on methyl tetrazolium, (3-(4, 5-dimethylthilthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulfophenyl)-2H-tetrazolium)) and lactate dehydrogenase assays. Furthermore, assessment of mitochondrial function and integrity of membrane in human keratinocytes revealed non-toxicity impacts of these green nZVI. (Das et al.,2018) have reported remediation of electronic waste by synthesizing copper nanoparticles from leaves extract of *Lantana camara*. Furthermore, they also reported that leaves extract of *Catharanthus roseus* was used for the degradation of chloramphenicol and ketoconazole. Besides these a number of plants have been used for the preparation of green nanoparticles for the remediation of distinct types of environmental pollutants as depicted in Table 5.

Fig. 12 depicts the preparation of green nanoparticles with the help of plant extracts.

Distinct types of green nanoparticles have been used for the detection and degradation of organic pollutants dyes, antibiotics, heavy metallic ions and microbial pathogens. Various applications of green nanoparticles are encapsulated in Table 6.

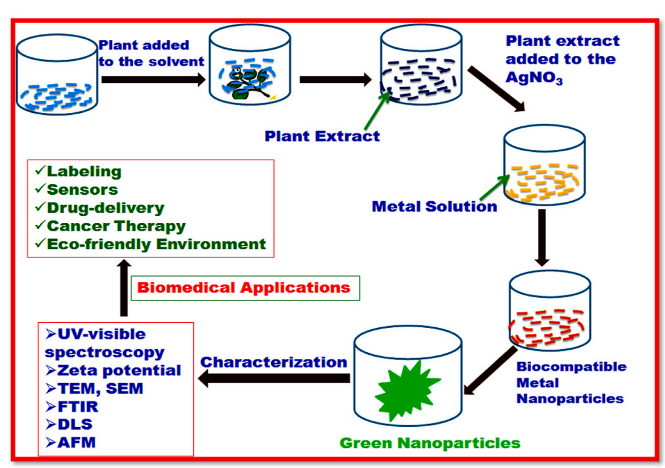

Fig. 12. Diagrammatic illustration of biological synthesis of nanoparticles using plant extracts.

Table 6
Applications of green nanoparticles in detection of environmental pollutants.

Name of green nanomaterials/ nanoparticles	Name of plants	Target pollutants	Analytical performance	Advantages	Reference
CuO NPs	Peels of *Punica gra natum* L	Methyl orange (MO) and Bacteria namely *S. aureus*-MRSA-33591, *S. aureus*-25923) and *E. coli*-K12, *P. vulgaris*- ATCC-49132	Minimum concentration of CuO NPs for degradation was 5–10 mg mL^{-1} in 90 min	These NPs were acting as efficient catalyst for the photodegradation of MO and showed unique antimicrobial activity against pathogenic bacteria	Fuku et al. (2018)
AgNPs	*Convolvulus arvensis*	Azo dyes	–	Economic, safe, and effective catalysts for the efficient degradation of organic pollutants like azo dyes	Rasheed et al. (2018)
AuNPs & AgNPs	Leaf extract of *Mussaenda glabrata*	Rhodamine B and methyl orange showed antimicrobial activity against *Bacillus pumilus*, *Staphylococcus aureus*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Aspergillus niger*, and *Penicillium chrysogenum*.	Degradation of these pollutants takes 5–9 min and catalytic rate was 0.7250 and 0.4464 min^{-1}	Simple, fast, user friendly and efficient approach of degradation of organic pollutants	Francis et al. (2017)
TiO_2NPs	*Jatropha curcas*	Chromium (Cr)	76% removal of Cr from tannery waste water	Simple and eco-friendly	Goutam (2018)
Iron hexacyaanoferrate NPs	Sapindus-mukorossi	Anthracene, phenanthrene, chrysene, fluorene, and benzo (a) pyrene	Minimum catalytic concentration 25 mg	Rapid, efficient, green approach for the degradation of targeted pollutants	Shanker (2017)
AuNPs	Leaf extract of Sansevieria roxburghiana	4-nitrophenol, acridine orange, congo red, bromothymol blue, phenol red and methylene blue	Degraded upto 87.8%, 40.4%, 93%, 88.1%, 85.88%, 49.6% respectively	Simple, facile, green approach of degradation	Kumar et al. (2019)
Dysprosium stannate ($Dy_2Sn_2O_7$ NPs)	*Ficus carica*	Acid Violet 7 and crystal violet	–	Visible-light-sensitive photocatalyst for efficient removal and destruction of organic contaminants in water	Zinatloo et al. (2020)
CuONPs	Leaves extract of *Citrofortunella microcarpa*	Rhodamin B	This approach removed the organic dye upto 98.31%	This approach was simple, reliable, stable, and eco-friendly for the degradation of target pollutant	Rafique et al. (2020)
AgNPs	Rhizome extract *of Zingiber officinale*	Methylene blue, methyl red, and safranin O.	Degrading efficiency of targeted pollutants were 14.25×10^{-3} s^{-1}, 9.68×10^{-3} s^{-1} and $4.72 \times 10^{-3}$$sec^{-1}$ respectively	Simple, economic, efficient and recommended for the treatment of waste water from industries	Barman et al. (2020)

5.4. Gaps/challenges and future prospects of present environmental nanotechnology

There is an essential need to develop nano-based innovative devices and materials for the detection and remediation of all sorts of pollutants existing in the nature. Nano tools and devices used for detection and remediation of pollutants should exhibit unique sensitivity, consistency, economic, ecofriendly, require only traces amount of chemicals and minimum energy consumption. Presently available nano devices need further modifications/improvements for the better analytical performances in comparison to conventional strategies. These devices must be facile, robust, user-friendly, portable and functional in harsh environmental conditions . Furthermore, environmental nanotechniques must have capability to work continuously without any interruption and require minimum monitoring by the technicians. Emerging pollutant detecting systems design such that they can easily collect the samples from atmosphere, water and soil. Currently most of nano tools and devices are being used in laboratory set-up, so they must need their commercialization so that hazardous components of environment can be detected and degraded in-fields for the prevention of harmful effects to living systems.

6. Conclusion and discussion

Increasing growth rate of human population and rapid industrialization have damaged the environment which is a very serious concern globally. Sustainable environment can be achieved only if atmosphere, hydrosphere and lithosphere are free from hazardous constituents. These hazardous components have destroyed the several interlinked food chains of ecosystem and significantly affected all types of ecosystems. Nanotechnology has provided a platform for clean, green and safe environment to all. Different types of nanoparticles such as AuNPs, CuONPs, AgNPs and nanocomposites have been used in the fabrication of biosensors for the detection of pollutants in the real water, soil, crops samples. Nanoparticles such as TiO_2NPs, AgNPs, ZnONPs and chitosan NPs have been used for the detection of pathogenic microorganisms. CNTs integrated biosensing devices have detected several organic, chlorinated and carcinogenic pollutants. Nanotechniques including SERS and SPR have revealed the analysis of aromatic and chlorinated compounds, POPs, heavy metals, and herbicides. Furthermore, sensitivity of biosensing devices have been enhanced by combing with SPR. Researchers have given more emphasis on electrochemical biosensors for the detection of different types of pollutants as they exhibit several advantages including sensitivity, specificity, rapidity, economic and simple. These electrochemical biosensors have been employed for the efficient detection of heavy metallic ions like Pb^{2+}, Cd^{2+}, Cu^{2+}, Hg^{2+}, Zn^{2+}, As^{3+} etc. and organic compounds such as parathion, diazinon, chlorpyrifos, p-nitrophenol, hydroquinone, paracetamol, penicillin and tetracycline. SPR integrated optical biosensors were also used for the detection of pathogenic bacterium such as *S. typhimurium,* several fungal toxins and heavy metallic ions including Hg^{2+}, Zn^{2+}, Al^{3+} and many more. Nanotechnology has remarkably contributed in remediation of diverse range of environmental pollutants. Scientific communities have used a group of nanomaterials like nZVI, CdS NPs, SiO_2NPs, CuO NPs for the degradation of chlorinated compounds, dyes, phenolics etc. Several nanocomposites namely Fe_3O_4/MnO_2, CO Fe_2O_4-reduced graphene oxide, CMC-nZVI, nano-Fe/Ca/CaO etc. have facilitated the controlled release of pollutants into surroundings by acting as adsorbent or photocatalyst. However, nanomaterials synthesized from chemical sources have caused toxicities to living organisms and their by causes distinct types of ailments related to digestive system, hepatic system, cardiovascular system, nervous system and reproductive system. These nanomaterials have also increased the pulmonary diseases, dermatic problems and asthmatic issues in humans. Therefore, researchers have synthesized green nanoparticles from plants to prevent the aforesaid harmful effects. Hence, environmental nanotechnology has provided an innovative frontier to combat the issues of sustainable environment for making clean and green environment that is need of the hour. Moreover, in future scientific efforts will lead to development of highly advanced nano tools and devices that will definitely beneficial for the quick, sensitive, specific, simple, economic, portable, ecofriendly and reliable to combat all the existing issues of sustainable environment by efficient removal and remediation of environmental pollutants. Hence, this review article will certainly provide a future outlook to scientific communities for the development of advanced nanotechniques that will indeed overcome the issues of existing technology.

Clean and green environment is essential for healthy ecosystem. Though, nanotechnology has offered pivotal platform for attaining eco-friendly environment. However, development of nano based techniques used for environment purposes are still in their zygotic phase. Therefore, further improvement is necessary to improve the efficiency of existing nano integrated approaches for the detection and remediation of hazardous components of environment. Furthermore, future research must be implicated on development of innovative nanotechniques which must use renewable sources of energy such as solar system, wind, hydro energy based installed softwares, require minimum power; and rechargeable batteries (Kumar et al., 2020). In spite of development of several innovative nanotechniques, current nanotechniques have shown less stability and poor efficiency in detection and degradation of pollutants like pesticides, heavy metallics, phenolics etc. residing in varying environment including air, water and soil. Biosensors have also attracted the interest of environmentalist for the analysis of hazardous component of environment. Though, present biosensing technologies also need more improvement as they are not capable of simultaneous detection of multiple pollutants at a time and difficulty to differentiate between natural ingredients and pollutants (Kumar et al., 2020). Moreover, they are non-transportable; their applications mostly confined to laboratory experiments and thus limited commercial applications. Hence, futuristic nanodevices fabrication used for investigation of pollutants must be unique in simplicity, user-friendly, selectivity, sensitivity, quick, and miniaturized for on-site and multifaceted detection of pollutants in the real environment. Moreover, microfluidic system has also promising applications for the monitoring of diverse range of environmental pollutants. These lab-on-chip devices have shown many benefits including ease in portability, miniaturized, cost-effective, simple and ease in fields detection of pollutants. Analytical performance of biosensing devices can be enhanced further by fabrication procedures involving distinct types of nanomaterials or nanocomposites. Beside this, future efforts will facilitate the development of automated, continuous, and real-time sensors for better throughput investigation of hazardous components of environment and this is the urgent need of the hour (Nigam and Shukla, 2015).

Inspite of immense applications of nanotechnology in the field of environment, there are several unresolved issues that must be addressed (Kumar et al., 2020). Therefore future implications must resolve following challenges:

- Researchers should search proper conjugation of techniques for efficient degradation and treatment of distinct types of pollutants in different environments.
- Long term evaluation of toxic effects on living systems caused by nanomaterials or nanocomposites used for the detection, remediation or treatment procedures.
- Assessments of bionanomaterials used in place of nanomaterials of chemical origin to analyse the degradation capacity or any conversion into less toxic forms. It also necessitate to understand the structural integrity as well as physiological processes such as their mechanism of action and effects of reactions on community and surrounding organisms, generated during degradation of pollutants at the contaminated site.
- Assessment of extent of practical restoration of natural tendency of soil after several times of remediation of pollutants by natural modifications using microorganisms is also very important.
- It is also essential to find the extent of modifications of conventional and advanced techniques to produce a viable nano integrated technology for eco-friendly environment by reducing the existence and dispersion of harmful components.
- Search efficient nano integrated strategies for degradation of evolving (emerging) pollutants released from pharmaceuticals, cosmetics, hormones, antibiotics, functionalized nanoparticles and many more.

Therefore, aforesaid discussed issues vitally need further scientific efforts to prevent the fatal consequences of pollutants on entire flora and fauna. Therefore, futuristic scientific contribution, governmental and no-governmental agencies of all over the universe will definitely establish a benchmark for all the existing challenges in the coming years.

Ethical issues

No.

Declaration of competing interest

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

Acknowledgement

Dr. Neelam thankfully acknowledges the UGC-Dr. D. S. Kothari Post-Doctoral Fellowship for financial assistance.

References

Abu-Ali, H.F., Nabok, A., Smith, T., Al-Shanawa, M.A., 2019. Electrochemical inhibition biosensor array for rapid detection of water pollution based on bacteria immobilized on screen-printed gold electrodes. Europ. Chem. Bullet. 7 (10), 307–314.

Akhavan, O, 2009. Lasting antibacterial activities of Ag–TiO_2/Ag/a-TiO_2 nanocomposite thin film photocatalysts under solar light irradiation. J. Coll. Interf. Sci. 336, 117–124. https://doi.org/10.1016/j.jcis.2009.03.018.

Al-Rubaye, A.G.G., 2019. Development of Optical Biosensors Based on Metal Nanostructures for Pollution (Mycotoxins) Detection (Doctoral Dissertation, Sheffield Hallam University).

Alsabagh, A.M., Fathy, M., Morsi, R.E., 2015. Preparation and characterization of chitosan/silver nanoparticle/copper nanoparticle/carbon nanotube multifunctional nano-composite for water treatment: heavy metals removal; kinetics, isotherms and competitive studies. Rsc Advanc 5 (69), 55774–55783.

Amine, A., Mohammadi, H., Bourais, I., Palleschi, G., 2006. Enzyme inhibition-based biosensors for food safety and environmental monitoring. Biosens. Bioelectron. 21 (8), 1405–1423.

Angın, D., Köse, T.E., Selengil, U., 2013. Production and characterization of activated carbon prepared from safflower seed cake biochar and its ability to absorb reactive dyestuff. Appl. Surf. Sci. 280, 705–710.

Anjum, M., Miandad, R., Waqas, M., Gehany, F., Barakat, M.A., 2019. Remediation of wastewater using various nano-materials. Arab J Chem. 12 (8), 4897–4919.

Arbabi, M., Hemati, S., Shamsizadeh, Z., Arbabi, A., 2017. Nitrate removal from aqueous solution by almond shells activated with magnetic nanoparticles. Desalinat Water Treat 80, 344–351.

Attia, T.M.S., Hu, X.L., 2013. Synthesized magnetic nanoparticles coated zeolite for the adsorption of pharmaceutical compounds from aqueous solution using batch and column studies. Chemos 93 (9), 2076–2085.

Avila, A.F., Munhoz, V.C., de Oliveira, A.M., Santos Mayara, C.G., Lacerda, Glenda R.B. S., Gonçalves, C.P., 2014. Nano-based systems for oil spills control and cleanup. J. Hazard Mater. 27, 20–27.

Ayodhya, D., Veerabhadram, G., 2018. Highly efficient sunlight-driven photocatalytic degradation of organic pollutants and fluorescence detection of Hg2+ using multifunctional GO-Bi2S3 nanostructures. J Photochem Photobiol A: Inside Chem. 356, 545–555.

Balasurya, S., Syed, A., Thomas, A.M., Marraiki, N., Elgorban, A.M., Raju, L.L., Khan, S. S., 2020. Rapid colorimetric detection of mercury using silver nanoparticles in the presence of methionine. Spectrochim. Acta Mol. Biomol. Spectrosc. 228, 117712.

Balram, D., Lian, K.Y., Sebastian, N., 2020. Ultrasound-assisted synthesis of 3D flower-like zinc oxide decorated fMWCNTs for sensitive detection of toxic environmental pollutant 4-nitrophenol. Ultrason. Sonochem. 60, 104798.

Bao, J., Huang, T., Wang, Z., Yang, H., Geng, X., Xu, G., Hou, C., 2019. 3D graphene/copper oxide nano-flowers based acetylcholinesterase biosensor for sensitive detection of organophosphate pesticides. Sens. Actuat. B: Inside Chem. 279, 95–101.
Barman, K., Chowdhury, D., Baruah, P.K., 2020. Bio-synthesized silver nanoparticles using Zingiber officinale rhizome extract as efficient catalyst for the degradation of environmental pollutants. Inorganic and Nano-Metal Chem. 50 (2), 57–65.
Baruah, S., Dutta, J., 2009. Nanotechnology applications in pollution sensing and degradation in agriculture: a review. Environ. Chem. Lett. 7, 191–204. https://doi.org/10.1007/s10311-009-0228-8.
Besha, A.T., Liu, Y., Fang, C., Bekele, D.N., Naidu, R., 2020. Assessing the interactions between micropollutants and nanoparticles in engineered and natural aquatic environments. Crit. Rev. Environ. Sci. Technol. 50 (2), 135–215.
Bhakya, S., Muthukrishnan, S., Sukumaran, M., Muthukumar, M., Kumar, S.T., Rao, M. V., 2015. Catalytic degradation of organic dyes using synthesized silver nanoparticles: a green approach. J Bioremed Biodegred 6 (5), 1.
Bontidean, I., Mortari, A., Leth, S., Brown, N.L., Karlson, U., Larsen, M.M., Csöregi, E., 2004. Biosensors for detection of mercury in contaminated soils. Environ. Pollut. 131 (2), 255–262.
Brito de Figueiredo, M.C., Rodrigues, G.S., Caldeira, P.A., Morsyleide, de F.R., Antônio, S.A.F., et al., 2010. Environmental performance evaluation of agro-industrial innovations e Part 2: methodological approach for performing vulnerability analysis of watersheds. J. Clean. Prod. 18, 1376–1385.
Cai, Y., Li, C., Wu, D., Wang, W., Tan, F., Wang, X., Wong, P.K., Qiao, X., 2017. Highly active MgO nanoparticles for simultaneous bacterial inactivation and heavy metal removal from aqueous solution. Chem. Eng. J. 312, 158–166.
Cao, Y., Huang, L., Chen, J., Liang, J., Long, S., Lu, Y., 2005. Development of a controlled release formulation based on a starch matrix system. Int. J. Pharm. (Amst.) 298 (1), 108–116.
Cao, Y., Jin, R., Mirkin, C.A., 2001. DNA-modified core-shell Ag/Au nanoparticles. J Americ. Chem. Soc. 23, 7961–7962.
Cargnello, M., Grzelczak, M., Rodríguez González, B., Syrgiannis, Z., Bakhmutsky, K., La Parola, V., Fornasiero, P., 2012. Multiwalled carbon nanotubes drive the activity of metal@ oxide core–shell catalysts in modular nanocomposites. J. Am. Chem. Soc. 134 (28), 11760–11766.
Cesewski, Ellen, Johnson N, Blake, 2020. Electrochemical biosensors for pathogen detection. Biosens. Bioelectron. 159 https://doi.org/10.1016/j.bios.2020.112214.
Chang C., S., Adriaens, P., 2007. Nano-immunodetection and quantification of mycobacteria in metalworking fluids. Environ. Eng. Sci. 24, 58–72.
Chaudhery MustansarHussainRüstemKeçili, 2020. Chapter 1-Environmental pollution and environmental analysis. Modern Environmental Analysis Techniques for Pollutants 2020, 1–36.
Chen, C., Wang, J., 2020. Optical biosensors: an exhaustive and comprehensive review. Analyst 145 (5), 1605–1628.
Chen, H.M., Liu, R.S., Tsai, D.P., 2009. A versatile route to the controlled synthesis of gold nanostructures. Cryst. Growth Des. 9 (5), 2079–2087.
Chen, J., Hao, Y., Chen, M., 2014. Rapid and efficient removal of Ni 2+ from aqueous solution by the one-pot synthesized EDTA-modified magnetic nanoparticles. Environ. Sci. Pollut. Res. 21 (3), 1671–1679.
Chen, K., Lu, G., Chang, J., Mao, S., Yu, K., Cui, S., Chen, J., 2012. Hg (II) ion detection using thermally reduced graphene oxide decorated with functionalized gold nanoparticles. Anal. Chem. 84 (9), 4057–4062.
Chen, K.J., Lee, C.F., Rick, J., Wang, S.H., Liu, C.C., Hwang, B.J., 2012. Fabrication and application of amperometric glucose biosensor based on a novel PtPd bimetallic nanoparticle decorated multi-walled carbon nanotube catalyst. Biosens. Bioelectron. 33 (1), 75–81.
Chua, C.K., Pumera, M., 2013. Covalent chemistry on graphene. Chem. Soc. Rev. 42 (8), 3222–3233.
Correa-Llantén, D.N., Muñoz-Ibacache, S.A., Castro, M.E., Muñoz, P.A., Blamey, J.M., 2013. Gold nanoparticles synthesized by Geobacillus sp. strain ID17 a thermophilic bacterium isolated from Deception Island, Antarctica. Microb. Cell Factories 12 (1), 1–6.
Crane, R.A., Scott, T.B., 2012. Nanoscale zero-valent iron: future prospects for an emerging water treatment technology. J. Hazard Mater. 211–212, 112–125.
Dai, L., Soundarrajan, P., Kim, T., 2012. Sensors and sensor array based on conjugated polymers and carbon nanotubes. Pure Appl. Chem. 74, 1753–1772.
Damiati, S., Küpcü, S., Peacock, M., Eilenberger, C., Zamzami, M., Qadri, I., Schuster, B., 2017. Acoustic and hybrid 3D-printed electrochemical biosensors for the real-time immunodetection of liver cancer cells (HepG2). Biosens. Bioelectron. 94, 500–506.
Daoudi, K., Gaidi, M., Columbus, S., Shameer, M., Alawadhi, H., 2021. Highly sensitive silver decorated-graphene oxide-silicon nanowires hybrid SERS sensors for trace level detection of environmental pollutants. arXiv preprint arXiv 2101, 07955.
Das, S., Sen, B., Debnath, N., 2015. Recent trends in nanomaterials applications in environmental monitoring and remediation. Environ. Sci. Pollut. Res. 22 (23), 18333–18344.
Das, S.K., Shome, I., Guha, A.K., 2012. Surface functionalization of Aspergillus versicolor mycelia: in situ fabrication of cadmium sulphide nanoparticles and removal of cadmium ions from aqueous solution. RSC Adv. 2 (7), 3000–3007.
Das, S., Chakraborty, J., Chatterjee, S., et al., 2018. Prospects of biosynthesized nanomaterials for the remediation of organic and inorganic environmental contaminants. Environ. Sci. Nano 5 (12), 2784–2808.
De Stefano, L., Moretti, L., Rendina, I., Rotiroti, L., 2005. Pesticides detection in water and humic solutions using porous silicon technology. Sensor. Actuator. B 111–112, 522–525. https://doi.org/10.1016/j.snb.2005.03.047.
Deng, R., Huang, D., Zeng, G., et al., 2019. Decontamination of lead and tetracycline from aqueous solution by a promising carbonaceous nanocomposite: Interaction and mechanisms insight. Bio. Resour. Technol. 283, 277–285.
Dhand, C., Dwivedi, N., Loh, X.J., Ying, A.N.J., Verma, N.K., Beuerman, R.W., Ramakrishna, S., 2015. Methods and strategies for the synthesis of diverse nanoparticles and their applications: a comprehensive overview. RSC Adv. 5 (127), 105003–105037.
Dhillon, G.S., Brar, S.K., Kaur, S., Verma, M., 2012. Green approach for nanoparticle biosynthesis by fungi: current trends and applications. Crit. Rev. Biotechnol. 32, 49–73.
Ding, J., Zhang, D., Liu, Y., Zhan, X., Lu, Y., Zhou, P., Zhang, D., 2021. An electrochemical aptasensor for Pb2+ detection based on metal–organic-framework-derived hybrid carbon. Biosensors 11 (1), 1.
Dong, J., Wen, C., Liu, D., Zhang, W., Li, J., Jiang, H., Hong, M., 2015. Study on degradation of nitrobenzene in groundwater using emulsified nano-zero-valent iron. J. Nanoparticle Res. 17 (1), 1–11.
Dong, J., Wen, C., Gao, S., 2018. A 2D tank test on remediation of nitrobenzene-contaminated aquifer using in-situ reactive zone with emulsified nanoscale zero-valent iron. Chemos. 20, 766–776.
Du, L., Xu, Q., Huang, M., Xian, L., Feng, J.X., 2015. Synthesis of small silver nanoparticles under light radiation by fungus Penicillium oxalicum and its application for the catalytic reduction of methylene blue. Mater. Chem. Phys. 160, 40–47.
Duan, M., Xu, Z., Zhang, Y., Fang, S., Song, X., Xiong, Y., 2017. Core-shell composite nanoparticles with magnetic and temperature dual stimuli-responsive properties for removing emulsified oil. Adv. Powder Technol. 28 (5), 1291–1297.
Dutta Kumar, Amit, Maji Kumar, Swarup, Adhikary, Bibhutosh, 2014. γ-Fe_2O_3 nanoparticles: An easily recoverable effective photo-catalyst for the degradation of rose bengal and methylene blue dyes in the waste-water treatment plant. Mat. Res. Bullet. 49, 28–34. https://doi.org/10.1016/j.materresbull.2013.08.024.
Eksin, E., Erdem, A., Fafal, T., Kıvçak, B., 2019. Eco-friendly sensors developed by herbal based silver nanoparticles for electrochemical detection of mercury (II) ion. Electroanalysis 31 (6), 1075–1082.
Elkodous, Abd, El-Sayyad, M, Youssry, G.S., Nada, S.M., et al., 2020. Carbon-dot-loaded Co x Ni 1− x Fe 2 O 4; x= 0.9/SiO 2/TiO 2 nanocomposite with enhanced photocatalytic and antimicrobial potential: An engineered nanocomposite for wastewater treatment. Sci. Rep. 10 (1), 1–22.
El-Sherif, R.M., Lasheen, T.A., Jebril, E.A., 2017. Fabrication and characterization of CeO2-TiO2-Fe2O3 magnetic nanoparticles for rapid removal of uranium ions from industrial waste solutions. J. Mol. Liq. 241, 260–269.
Enfrin, M., Lee, J., Gibert, Y., Basheer, F., Kong, L., Dumée, L.F., 2020. Release of hazardous nanoplastic contaminants due to microplastics fragmentation under shear stress forces. J. Hazard Mater. 384, 121393.
Eskizeybek, Volkan, Sarı, Fahriye, Gülce, Handan, et al., 2012. Preparation of the new polyaniline/ZnO nanocomposite and its photocatalytic activity for degradation of methylene blue and malachite green dyes under UV and natural sun lights irradiations. Appl. Catal. B Environ. 119-120, 197–206.
Estrela, P., Stewart, A.G., Yan, F., Migliorato, P., 2005. Field effect detection of biomolecular interactions. Electrochim. Acta 50, 4995–5000. https://doi.org/10.1016/j.electacta.2005.02.075.
Fallah, H., Asadishad, T., Shafiei, M., Shokri, B., Javadianaghezi, S., Mohammed, W.S., Hamidi, S.M., 2020. Utilizing ZnO Nanorods for CO gas detection by SPR technique. Opt Commun. 463, 125490.
Farghali, A.A., Bahgat, M., Allah, A.E., Khedr, M.H., 2013. Adsorption of Pb (II) ions from aqueous solutions using copper oxide nanostructures. Beni-Suef University J Basic and Appl Sci 2 (2), 61–71.
Fleeger, J.W., Carman, K.R., Nisbet, R.M., 2003. Indirect effects of contaminants in aquatic ecosystems: a review. Sci. Total Environ. 317, 207–233.
Francis, S., Joseph, S., Koshy, E.P., Mathew, B., 2017. Green synthesis and characterization of gold and silver nanoparticles using Mussaenda glabrata leaf extract and their environmental applications to dye degradation. Environ. Sci. Pollut. Res. 24 (21), 17347–17357.
Fu, F., Dionysiou, D.D., Liu, H., 2014. The use of zero-valent iron for groundwater remediation and wastewater treatment: a review. J. Hazard Mater. 267, 194–205.
Fuku, X., Thovhogi, N., Maaza, M., 2018, May. Photocatalytic effect of green synthesised CuO nanoparticles on selected environmental pollutants and pathogens. In AIP Conference Proceedings 1962 (1), 040006 (AIP Publishing LLC).
Gangula, A., Podila, R., Karanam, L., Janardhana, C., Rao, A.M., 2011. Catalytic reduction of 4-nitrophenol using biogenic gold and silver nanoparticles derived from *Breynia rhamnoides*. Langmuir 27 (24), 15268–15274.
Gao, J., Chen, J., Li, X., Wang, M., Zhang, X., Tan, F., Xu, S., Liu, J., 2015. Azide-functionalized hollow silica nanospheres for removal of antibiotics. J. Colloid Interface Sci. 444, 38–41.
Garg, N., Bera, S., Ballal, A., 2020. SPR responsive xylenol orange functionalized gold nanoparticles-optical sensor for estimation of Al3+ in water. Spectrochimic. Act. Part A: Mol. Biomol. Spectroscopy 228, 117701.
Garner, K.L., Keller, A.A., 2014. Emerging patterns for engineered nanomaterials in the environment: a review of fate and toxicity studies. J. Nanopart. Res. 16, 2503.
Gaviria-Arroyave, M.I., Cano, J.B., Peñuela, G.A., 2020. Nanomaterial-based fluorescent biosensors for monitoring environmental pollutants: a critical review. Talanta Open, 100006.
Gebre, S.H., Sendeku, M.G., 2019. New frontiers in the biosynthesis of metal oxide nanoparticles and their environmental applications: an overview. SN Appl. Sci. 1 (8), 1–28. https://doi.org/10.1007/s42452-019-0931-4.
Goutam, Surya Pratap, Gaurav Saxena, Varunika Singh, Anil Yadav, 2018. Green synthesis of TiO2 nanoparticles using leaf extract of Jatropha curcas L. for photocatalytic degradation of tannery wastewater. Chem. Eng. J. 336, 386–396. https://doi.org/10.1016/j.cej.2017.12.029.

Grieger, K.D., Fjordøge, A., Hartmann, N.B., Eriksson, E., Bjerg, P.L., Baun, A., 2010. Environmental benefits and risks of zero-valent iron particles (nZVI) for in situ remediation: risk mitigation or trade-off? J. Contam. Hydrol. 118, 165–183.

Guan, K., Zhou, P., Zhang, J., Zhu, L., 2020. Catalytic degradation of acid orange 7 in water by persulfate activated with CuFe2O4@ RSDBC. Material res exp 7(1), 016529.

Guerra, F.D., Attia, M.F., Whitehead, D.C., Alexis, F., 2018. Nanotechnology for environmental remediation: materials and applications. Molecules 23 (7), 1760.

Guo, X., He, M., Chen, B., Hu, B., 2012. Solidified floating organic drop microextraction combined with ETV-ICP-MS for the determination of trace heavy metals in environmental water samples. Talanta 94, 70–76.

Guo, Jie, Zhang, Qing, Cai, Zhijiang, 2016. Preparation and dye filtration property of electrospun polyhydroxybutyrate–calcium alginate/carbon nanotubes composite nanofibrous filtration membrane. Separat. Purificat. Technol. 161, 69–79. https://doi.org/10.1016/j.seppur.2016.01.036.

Gupta K, V, Agarwal, S, Saleh A., T, 2011. Synthesis and characterization of alumina-coated carbon nanotubes and their application for lead removal. J. Hazard. Mat. 185, 17–23. https://doi.org/10.1016/j.jhazmat.2010.08.053.

Gupta, S., Sarkar, S., Katranidis, A., Bhattacharya, J., 2019. Development of a cell-free optical biosensor for detection of a broad range of mercury contaminants in water: a plasmid DNA-based approach. ACS Omega 4 (5), 9480–9487.

Habte, G., Choi, J.Y., Nho, E.Y., Oh, S.Y., Khan, N., Choi, H., Kim, K.S., 2015. Determination of toxic heavy metal levels in commonly consumed species of shrimp and shellfish using ICP-MS/OES. Food Sci Biotechnol 24 (1), 373–378.

Haes, A.J., Van Duyne, R.P., 2002. A nanoscale optical biosensor: sensitivity and selectivity of an approach based on the localized surface plasmon resonance spectroscopy of triangular silver nanoparticles. J. Americ. Chem. Soc. 124, 10596–10604. https://doi.org/10.1021/ja020393xS0002-7863(02)00393-1.

Hanif, F., Tahir, A., Akhtar, M., Waseem, M., Haider, S., Aboud, M.F.A., Warsi, M.F., 2019. Ultra-selective detection of Cd2+ and Pb2+ using glycine functionalized reduced graphene oxide/polyaniline nanocomposite electrode. Synth. Met. 257, 116185.

Hashim Suhaila, Hazwani, Fen Wing, Yap, Omar Nur Alia, Sheh, et al., 2020. Structural, optical and potential sensing properties of tyrosinase immobilized graphene oxide thin film on gold surface. Optik 212, 164786. https://doi.org/10.1016/j.ijleo.2020.164786.

He, Y., Wang, Z., Ma, L., Zhou, L., Jiang, Y., Gao, J., 2020. Synthesis of bismuth nanoparticle-loaded cobalt ferrite for electrochemical detection of heavy metal ions. RSC Adv. 10 (46), 27697–27705.

Hernandez-Vargas, G., Sosa-Hernández, J.E., Saldarriaga-Hernandez, S., Villalba-Rodríguez, A.M., Parra-Saldivar, R., Iqbal, H., 2018. Electrochemical biosensors: a solution to pollution detection with reference to environmental contaminants. Biosensors 8 (2), 29.

Hoag, G.E., Collins, J.B., Holcomb, J.L., Hoag, J.R., Nadgouda, M.N., Varma, R.S., 2009. Degradation of bromothymol blue by 'greener' nano-scale zero-valent iron synthesized using tea polyphenols. J. Math. Chem. 19, 8671–8677. https://commons.wikimedia.org/wiki/File%3AHealth_effects_of_pollution.png. https://commons.wikimedia.org/wiki/File%3AHealth_effects_of_pollution.png. https://commons.wikimedia.org/wiki/File%3AHealth_effects_of_pollution.png.

Hu, R., Zhang, X., Chi, K.N., Yang, T., Yang, Y.H., 2020. Bifunctional MOFs-based ratiometric electrochemical sensor for multiplex heavy metal ions. ACS Appl. Mater. Interfaces 12 (27), 30770–30778.

Huang, B.C., Jiang, J., Huang, G.X., Yu, H.Q., 2018. Sludge biochar-based catalysts for improved pollutant degradation by activating peroxymonosulfate. J. Mater. Chem. A 6 (19), 8978–8985.

Hussain, C.M., Kecili, R., 2020. Modern Environmental Analysis Techniques for Pollutants. Elsevier, pp. 1–426. https://doi.org/10.1016/C2018-0-01639-4.

Hwa, K.Y., Sharma, T.S.K., Ganguly, A., 2020. Design strategy of rGO–HNT–AgNPs based hybrid nanocomposite with enhanced performance for electrochemical detection of 4-nitrophenol. Inorg Chem Front 7 (10), 1981–1994.

Hyeon, S.H., Lim, W.K., Shin, H.J., 2020. Novel surface plasmon resonance biosensor that uses full-length Det7 phage tail protein for rapid and selective detection of Salmonella enterica serovar Typhimurium. Biotechnol. Appl. Biochem. 1–8.

Jackson, T., Mansfield, K., Saafi, M., Colman, T., Romine, P., 2007. Measuring soil temperature and moisture using wireless MEMS sensors. Measure 41 (4), 381–390. https://doi.org/10.1016/j.measurement.2007.02.009.

Jacob, J.M., Karthik, C., Saratale, R.G., Kumar, S.S., Prabakar, D., Kadirvelu, K., Pugazhendhi, A., 2018. Biological approaches to tackle heavy metal pollution: a survey of literature. J. Environ. Manag. 217, 56–70.

Jadhav, S.D., Jadhav, M.S., Jawale, R.W., 2013. Study of chloride and nitrate concentration of MulaMutha River in Pune city (Maharashtra). Int. J. Chem. Life Sci. 2, 1140–1142.

Jaleh, B., Karami, S., Sajjadi, M., Mohazzab, B.F., Azizian, S., Nasrollahzadeh, M., Varma, R.S., 2020. Laser-assisted preparation of Pd nanoparticles on carbon cloth for the degradation of environmental pollutants in aqueous medium. Chemosphere 246, 125755.

Jang, M., Yoon, Y.I., Kwon, Y.S., Yoon, T.J., Lee, H.J., Hwang, S.I., Kim, S.M., 2014. Trastuzumab-conjugated liposome-coated fluorescent magnetic nanoparticles to target breast cancer. Korean J. Radiol. 15 (4), 411.

Jeevanandam, J., Barhoum, A., Chan, Y.S., Dufresne, A., Danquah, M.K., 2018. Review on nanoparticles and nanostructured materials: history, sources, toxicity and regulations. Beilstein J. Nanotechnology 9 (1), 1050–1074.

Jia, J., Li, H., Zong, S., et al., 2016. Magnet bioreporter device for ecological toxicity assessment on heavy metal contamination of coal cinder sites. Sens. Actuat. B Chem. 222, 290–299.

Jiang, B., Lian, L., Xing, Y., Zhang, N., Chen, Y., Lu, P., Zhang, D., 2018. Advances of magnetic nanoparticles in environmental application: environmental remediation and (bio) sensors as case studies. Environ. Sci. Pollut. Res. 25 (31), 30863–30879.

Jiang, B., Song, Y., Liu, Z., et al., 2020. Whole-cell bioreporters for evaluating petroleum hydrocarbon contamination. Critical Reviews in Environmental Science and Technology, 51, 1–-51. https://doi.org/10.1080/10643389.2020.1717907.

Johnson, A, Merilis, G, Hastings, J, Palmer, M E, Fitts, J P, Chidambaram, D, 2012. Reductive degradation of organic compounds using microbial nanotechnology. J. Electrochem. Soc. 160, G27 https://doi.org/10.1149/2.053301jes.

Jung, K.W., Choi, B.H., Ahn, K.H., Lee, S.H., 2017. Synthesis of a novel magnetic Fe3O4/γ-Al2O3 hybrid composite using electrode-alternation technique for the removal of an azo dye. Appl. Surf. Sci. 423, 383–393.

Kai, H., Guiqiu, C., Guangming, Z., Zhenzhen, H., Zhi, G., Tiantian, H., Min, P., Jiangbo, S., Liang, H., 2017. Applications of white rot fungi in bioremediation with nanoparticles and biosynthesis of metallic nanoparticles. Appl. Microbiol. Biotechnol. 101, 4853–4862.

Kakavandi, B., Esrafili, A., Mohseni-Bandpi, A., Jonidi Jafari, A., Rezaei Kalantary, R., 2014. Magnetic Fe3O4@ C nanoparticles as adsorbents for removal of amoxicillin from aqueous solution. Water Sci. Technol. 69 (1), 147–155.

Karn, B., Kuiken, T., Otto, M., 2009. Nanotechnology and in situ remediation: a review of the benefits and potential risks. Environ. Healt. Perspect 117, 1823–1831.

Karousis, N., Tagmatarchis, N., Tasis, D., 2010. Current progress on the chemical modification of carbon nanotubes. Chemical review 110 (9), 5366–5397.

Karuppiah, C., Palanisamy, S., Chen, S.M., Emmanuel, R., Ali, M.A., Muthukrishnan, P., Al-Hemaid, F.M., 2014. Green biosynthesis of silver nanoparticles and nanomolar detection of p-nitrophenol. J. Solid State Electrochem. 18 (7), 1847–1854.

Kaur, J., Singh, P.K., 2020. Enzyme-based optical biosensors for organophosphate class of pesticide detection. Phys. Chem. Chem. Phys. 22 (27), 15105–15119.

Khajeh, Mostafa, Yamini, Yadollah, Miri, Ramin, et al., 2013. Nanoadsorbents: Classification, preparation, and applications (with emphasis on aqueous media). Chem. Rev. 113 (10), 7728–7768. https://doi.org/10.1021/cr400086v.

Khan, I., Saeed, K., Khan, I., 2019. Nanoparticles: properties, applications and toxicities. Arabian J. Inside Chem. 12 (7), 908–931.

Khanmohammadi, A., Ghazizadeh, A.J., Hashemi, P., Afkhami, A., Arduini, F., Bagheri, H., 2020. An overview to electrochemical biosensors and sensors for the detection of environmental contaminants. J. Iran. Chem. Soc. 1–19.

Kharissova, O.V., Dias, Rasika H.V., Kharisov, B.I., Pérez, B.O., Pérez Jiménez, V.M., 2013. The greener synthesis of nanoparticles. Trends Biotechnol. 31, 240–248.

Kim, E.J., Lee, C.S., Chang, Y.Y., Chang, Y.S., 2013. Hierarchically structured manganese oxide-coated magnetic nanocomposites for the efficient removal of heavy metal ions from aqueous systems. ACS Appl. Mater. Interfaces 5 (19), 9628–9634.

Ko, S., Kim, E.S., Park, S., Daigle, H., Milner, T.E., Huh, C., Geremia, G.A., 2017. Amine functionalized magnetic nanoparticles for removal of oil droplets from produced water and accelerated magnetic separation. J. Nano Res. 19 (4), 132.

Kołątaj, K., Krajczewski, J., Kudelski, A., 2019. Nanosensors for Environmental Analysis Based on Plasmonic Nanoparticles. In Environ. In: Mental Nanotechnology. Springer, pp. 255–287. Cham 2019.

Koutsospyros, A., Pavlov, J., Fawcett, J., Strickland, D., Smolinski, B., Braida, W., 2012. Degradation of high energetic and insensitive munitions compounds by Fe/Cu bimetal reduction. J. Hazard Mater 219–220, 75–81.

Konishi, Y., Ohno, K., Saitoh, N., et al., 2007. Bioreductive deposition of platinum nanoparticles on the bacterium Shewanella algae. J. Biotechnol. 128 (3), 648–653.

Kucherenko, I.S., Soldatkin, O.O., Kucherenko, D.Y., Soldatkina, O.V., Dzyadevych, S.V., 2019. Advances in nanomaterial application in enzyme-based electrochemical biosensors: a review. Nanoscale Advanc 1 (12), 4560–4577.

Kühnel, D., Marquard, C., Nau, K., Krug, H.F., Paul, F., Steinbach, C., 2017. Environmental benefits and concerns on safety: communicating latest results on nanotechnology safety research—the project DaNa$^{2.0}$. Environ. Sci. Pollut. Res. 24, 11120–11125.

Kumar, H., Kumari, N., Sharma, R., 2020. Nanocomposites (conducting polymer and nanoparticles) based electrochemical biosensor for the detection of environment pollutant: its issues and challenges. Environ. Impact Assess. Rev. 85, 106438.

Kyzas Z., George, Matis A., Kostas, 2015. Nanoadsorbents for pollutants removal: A review. J. Mol. Liquid. 203, 159–168. https://doi.org/10.1016/j.molliq.2015.01.004.

Langer, J., Jimenez de Aberasturi, D., Aizpurua, J., Alvarez-Puebla, R.A., Auguié, B., Baumberg, J.J., Liz-Marzán, L.M., 2019. Present and future of surface-enhanced Raman scattering. ACS Nano 14 (1), 28–117.

Lata, S., Samadder, S.R., 2016. Removal of arsenic from water using nano adsorbents and challenges: a review. J. Environ. Manag. 166, 387–406.

Latifeh, F., Yamini, Y., Seidi, S., 2016. Ionic liquid-modified silica-coated magnetic nanoparticles: promising adsorbents for ultra-fast extraction of paraquat from aqueous solution. Environ. Sci. Pollut. Res. 23 (5), 4411–4421.

Lefevre, F., Chalifour, A., Yu, L., Chodavarapu, V., Juneau, P., Izquierdo, R., 2012. Algal fluorescence sensor integrated into a microfluidic chip for water pollutant detection. Lab Chip 12 (4), 787–793.

Li, M., Zhang, G., Feng, C., Wu, H., Mei, H., 2020. Highly sensitive detection of chromium (VI) by photoelectrochemical sensor under visible light based on Bi SPR-promoted BiPO4/BiOI heterojunction. Sensor. Actuator. B Chem. 305, 127449.

Li, Q., Dou, X., Zhang, L., Zhao, X., Luo, J., Yang, M., 2019. Oriented assembly of surface plasmon resonance biosensor through staphylococcal protein A for the chlorpyrifos detection. Anal. Bioanal. Chem. 411 (23), 6057–6066.

Li, Z., Liu, C., Sarpong, V., Gu, Z., 2019. Multisegment nanowire/nanoparticle hybrid arrays as electrochemical biosensors for simultaneous detection of antibiotics. Biosens. Bioelectron. 126, 632–639.

Lin Shi, Tsung, Thirumavalavan, Munusamy, Yan, Ting, Jiunn-FwuLee, 2014. Synthesis of ZnO/Zn nano photocatalyst using modified polysaccharides for photodegradation of dyes. Carbohyd. Polym 105, 1–9. https://doi.org/10.1016/j.carbpol.2014.01.017.
Lin, Z., Xu, Y., Zhen, Z., Fu, Y., Liu, Y., Li, W., Zhang, D., 2015. Application and reactivation of magnetic nanoparticles in Microcystis aeruginosa harvesting. Bioresour. Technol. 190, 82–88.
Liu, E., Zheng, X., Xu, X., Zhang, F., Liu, E., Wang, Y., Yan, Y., 2017. Preparation of diethylenetriamine-modified magnetic chitosan nanoparticles for adsorption of rare-earth metal ions. New J. Chem. 41 (15), 7739–7750.
Liu, L., Chen, C., Chen, C., Kang, X., Zhang, H., Tao, Y., Yao, S., 2019. Poly (noradrenalin) based bi-enzyme biosensor for ultrasensitive multi-analyte determination. Talanta 194, 343–349.
Liu, T., Zhao, L., Sun, D., Tan, X., 2010. Entrapment of nanoscale zero-valent iron in chitosan beads for hexavalent chromium removal from wastewater. J. Hazard Mater. 184 (1–3), 724–730.
Liu, Z., Yang, H., Zhang, H., Huang, C., Li, L., 2012. Oil-field wastewater purification by magnetic separation technique using a novel magnetic nanoparticle. Cryogenics 52 (12), 699–703.
Long, B., Tang, L., Peng, B., Zeng, G., Zhou, Y., Mo, D., Yu, J., 2019. Voltammetric biosensor based on nitrogen-doped ordered mesoporous carbon for detection of organophosphorus pesticides in vegetables. Curr. Anal. Chem. 15 (1), 92–100.
Long, C., Li, X., Jiang, Z., Zhang, P., Qing, Z., Qing, T., Feng, B., 2021. Adsorption-improved $MoSe_2$ nanosheet by heteroatom doping and its application for simultaneous detection and removal of mercury (II). J. Hazard Mater. 413, 125470.
Lu, Z., Zhao, W., Wu, L., He, J., Dai, W., Zhou, C., Ye, J., 2021. Tunable electrochemical of electrosynthesized layer-by-layer multilayer films based on multi-walled carbon nanotubes and metal-organic framework as high-performance electrochemical sensor for simultaneous determination cadmium and lead. Sensor. Actuator. B Chem. 326, 128957.
Lukyanenko, K.A., Denisov, I.A., Sorokin, V.V., Yakimov, A.S., Esimbekova, E.N., Belobrov, P.I., 2019. Handheld enzymatic luminescent biosensor for rapid detection of heavy metals in water samples. Chemosensors 7 (1), 16.
Ma, X., Gurung, A., Deng, Y., 2013. Phytotoxicity and uptake of nanoscale zero-valent iron (nZVI) by two plant species. Sci. Total Environ. 443, 844–849.
Machado, S., Pinto, S.L., Grosso, J.P., Nouws, H.P.A., Albergaria, J.T., Delerue-Matos, C., 2013a. Green production of zero-valent iron nanoparticles using tree leaf extracts. Sci. Total Environ. 445–446, 1–8.
Machado, S., Stawiński, W., Slonina, P., Pinto, A.R., Grosso, J.P., Nouws, H.P.A., Albergaria, J.T., Matos-Delerue, C., 2013b. Application of green zero-valent iron nanoparticles to the remediation of soils contaminated with ibuprofen. Sci. Total Environ. 461–462, 323–329.
Madhavi, V., Prasad, T.N.V.K.V., Reddy, B.R., Reddy, A.V.B., Gajulapalle, M., 2014. Conjunctive effect of CMC–zero-valent iron nanoparticles and FYM in the remediation of chromium-contaminated soils. Appl. Nanosci. 4 (4), 477–484.
Madou, M., 1997. Fundamentals of Microfabrication. CRC Press, New York.
Magnet, C., Lomenech, C., Hurel, C., Reilhac, P., Giulieri, F., Chaze, A.M., Kuzhir, P., 2017. Adsorption of nickel ions by oleate-modified magnetic iron oxide nanoparticles. Environ. Sci. Pollut. Res. 24 (8), 7423–7435.
Mahdavian, L., Mousavi E., S., 2019. Diameter of single-walled carbon nanotubes (SWCNTs) as an effective factor in the detection and degradation of PCBs. Polycyc. Aromat. Compound. 39, 14–22.
Mahmoudpour, M., Dolatabadi, J.E.N., Torbati, M., Homayouni-Rad, A., 2019a. Nanomaterials based surface plasmon resonance signal enhancement for detection of environmental pollution. Biosens. Bioelectron. 127, 72–84.
Majumder, D.R., 2012. Bioremediation: copper nanoparticles from electronic-waste. Int. J. Eng. Sci. Technol. 4 (10).
Malhotra Dhar, Bansi, Ali Azahar, Md., 2018. Plasmonic nanostructures: Fiber-optic biosensors. Nanomat. Biosens. Nanomat. Biosens. Fundamentals and Applications Micro and Nano Technologies 161–181. https://doi.org/10.1016/B978-0-323-44923-6.00006-6.
Mallampati, S.R., Mitoma, Y., Okuda, T., Sakita, S., Kakeda, M., 2013. Total immobilization of soil heavy metals with nano-Fe/Ca/CaO dispersion mixtures. Environ. Chem. Lett. 11 (2), 119–125.
Manisalidis, I., Stavropoulou, E., Stavropoulos, A., Bezirtzoglou, E., 2020. Environmental and health impacts of air pollution: a review. Front in Pub Health, *8*.
Martínez, F., Muñoz M.J., López-, Aguado, J., et al., 2013. Coupling membrane separation and photocatalytic oxidation processes for the degradation of pharmaceutical pollutants. Water Res. 47 (15), 5647–5658. https://doi.org/10.1016/j.watres.2013.06.045.
Mathew, B.B., Singh, H., Biju, V.G., Krishnamurthy, N.B., 2017. Classification, source, and effect of environmental pollutants and their biodegradation. J. Environ. Pathol. Toxicol. Oncol 36 (1).
Mauter, M.S., Zucker, I., Perreault, F., Werber, J.R., Kim, J.H., Elimelech, M., 2018. The role of nanotechnology in tackling global water challenges. Nature Sustainability 1 (4), 166–175.
Mehrvar, Mehrab, Abdi, Mustafe, 2004. 2004. "Recent developments, characteristics, and potential applications of electrochemical biosensors.". Anal. Sci. 20.8, 1113–1126.
Menon, S., Mathew, M.R., Sam, S., Keerthi, K., Kumar, K.G., 2020. Recent advances and challenges in electrochemical biosensors for emerging and re-emerging infectious diseases. J. Electroanal. Chem., 114596
Merkoci, A., 2006. Carbon nanotubes in analytical sciences. Microchim. Act 152, 157–174.
Mishra, S., Chowdhary, P., Bharagava, R.N., 2019. Conventional methods for the removal of industrial pollutants, their merits and demerits. In: Emerging and Eco-Friendly Approaches for Waste Management. Springer, Singapore, pp. 1–31.
Mitra, R., Saha, A., 2017. Reduced graphene oxide based "turn-on" fluorescence sensor for highly reproducible and sensitive detection of small organic pollutants. ACS Sustain. Chem. Eng. 5 (1), 604–615.
Mohamed, C.N., Borhane, M., Olfa, M., Mika, S., 2017. Remediation of emerging pollutants in contaminated wastewater and aquatic environments: biomass-based technologies. Clean – soil, air. Water 45 (5), 1–19.
Mohan, S., Singh, Y., Verma, D.K., Hasan, S.H., 2015. Synthesis of CuO nanoparticles through green route using Citrus limon juice and its application as nanosorbent for Cr (VI) remediation: process optimization with RSM and ANN-GA based model. Process Saf. Environ. Protect. 96, 156–166.
Mondal, S., 2020. Potential of nanotechnology for rural applications. Arabian J. Sci. Eng. 1–32.
Montaño, M., Lowry, G., von der Kammer, F., Blue, J., Ranville, J., 2014. Current status and future direction for examining engineered nanoparticles in natural systems. Environ. Chem. 11, 351–366.
Moskovits, M., Srnová-Šloufová, I., Vlčková, B., 2002. Bimetallic Ag–Au nanoparticles: extracting meaningful optical constants from the surface-plasmon extinction spectrum. The J. Chem. Phys. 116 (23), 10435–10446.
Mourdikoudis, S., Pallares, R.M., Thanh, N.T., 2018. Characterization techniques for nanoparticles: comparison and complementarity upon studying nanoparticle properties. Nanoscale 10 (27), 12871–12934.
Mueller, N.C., Braun, J., Bruns, J., Černík, M., Rissing, P., Rickerby, D., Nowack, B., 2012. Application of nanoscale zero valent iron (NZVI) for groundwater remediation in Europe. Environ. Sci. Pollut. Res. 19 (2), 550–558.
Mukherjee, D., Ghosh, S., Majumdar, S., Annapurna, K., 2016. Green synthesis of α-Fe2O3 nanoparticles for arsenic (V) remediation with a novel aspect for sludge management. J Environ Chem Eng 4 (1), 639–650.
Munonde, T.S., Nomngongo, P.N., 2021. Nanocomposites for electrochemical sensors and their applications on the detection of trace metals in environmental water samples. Sensors 21 (1), 131.
Nadagouda, M.N., Castle, A.B., Murdock, R.C., Hussain, S.M., Varma, R.S., 2010. In vitro biocompatibility of nano scale zero valent iron particles (NZVI) synthesized using tea polyphenols. Green Chem. 12, 114–122.
Nagaonkar, D., Gaikwad, S., Rai, M., 2015. Catharanthus roseus leaf extract-synthesized chitosan nanoparticles for controlled in vitro release of chloramphenicol and ketoconazole. Colloid Polym. Sci. 293 (5), 1465–1473.
Narayanan, K.B., Park, H.H., Han, S.S., 2015. Synthesis and characterization of biomatrixed-gold nanoparticles by the mushroom Flammulina velutipes and its heterogeneous catalytic potential. Chemosphere 141, 169–175.
Nasrollahzadeh, M., Sajadi, S.M., Sajjadi, M., Issaabadi, Z., 2019. Applications of nanotechnology in daily life. Int. Sci. Technol. 28, 113–143.
Naveed Ul Haq, A., Nadhman, A., Ullah, I., Mustafa, G., Yasinzai, M., Khan, I., 2017. Synthesis approaches of zinc oxide nanoparticles: the dilemma of ecotoxicity. J. Nanomaterial 1–15. https://doi.org/10.1155/2017/8510342, 8510342.
Neelam, Chhillar A.K., Rana, J.S., 2019. Enzyme nanoparticles and their biosensing applications: a review. Analyt. Biochem 581 (1–12), 113345.
Nie, X., Liu, J., Zeng, X., Yue, D., 2013. Rapid degradation of hexachlorobenzene bymicron Ag/Fe bimetal particles. J. Environ. Sci. 25, 473–478.
Nigam, V.K., Shukla, P., 2015a. Enzyme based biosensors for detection of environmental pollutants-a review. J. Microbiol. Biotechnol. 25 (11), 1773–1781.
Nigam, V.K., Shukla, P., 2015b. Enzyme based biosensors for detection of environmental pollutants-A review. J. Microbiol. Biotechnol. 25 (11), 1773–1781.
Nile, S.H., Baskar, V., Selvaraj, D., Nile, A., Xiao, J., Kai, G., 2020. Nanotechnologies in food science: applications, recent trends, and future perspectives. Nano-Micro Lett. 12 (1), 45.
Nowack, B., 2008. Harald krug copyright © volume 2. In: Aspects, Environmental (Ed.), WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.
Nsibande, S.A., Forbes, P.B.C., 2016. Fluorescence detection of pesticides using quantum dot materials–a review. Anal Chim Act 945, 9–22.
Ong, T.T., Blanch, E.W., Jones, O.A., 2020. Surface Enhanced Raman Spectroscopy in environmental analysis, monitoring and assessment. Sci. Total Environ, 137601.
Pan, X., Gu, Z., Chen, W., Li, Q., 2020. Preparation of biochar and biochar composites and the application in a Fenton-like process for wastewater decontamination: a review. Sci. Total Environ., 142104
Pandey P., Veda, Swati Singh, Rupinder Singh, Upendra N. Dwivedi, 2012. Purification and characterization of peroxidase from papaya (Carica papaya) fruit. Appl. Biochem. Biotechnol. 167, 367–376. https://doi.org/10.1007/s12010-012-9672-1.
Pandey, G., 2018. Challenges and future prospects of agri-nanotechnology for sustainable agriculture in India. Environ. Technol. Innovation 11, 299–307.
Patanjali, P., Singh, R., Kumar, A., Chaudhary, P., 2019. Nanotechnology for Water Treatment: A Green Approach. In Green Synthesis, Characterization and Applications of Nanoparticles. Elsevier, pp. 485–512.
Patil, S.S., Shedbalkar, U.U., Truskewycz, A., Chopade, B.A., Ball, A.S., 2016. Nanoparticles for environmental clean-up: a review of potential risks and emerging solutions. Environ Technol Innovat 5, 10–21.
Pearce, C.I., Coker, V.S., Charnock, J.M., Pattrick, R.A., Mosselmans, J.F.W., Law, N., Lloyd, J.R., 2008. Microbial manufacture of chalcogenide-based nanoparticles via the reduction of selenite using Veillonella atypica: an in situ EXAFS study. Nanotechnology 19 (15), 155603.
Peikam, E.N., Jalali, M., 2019. Application of three nanoparticles (Al 2 O 3, SiO 2 and TiO 2) for metal-contaminated soil remediation (measuring and modeling). Int. J. Environ. Sci. Technol. 16 (11), 7207–7220.
Pena, R.C., Cornejo, L., Bertotti, M., 2017. Removal of heavy-metal ions from wastewater samples using magnetic nanoparticles modified with ethylenediaminetetraacetic acid. Desalination Water Treat 84, 271–278.

Pendergast M., MaryTheresa, Hoek M.V., Eric, 2011. A review of water treatment membrane nanotechnologies. Energy Env. Sci. 4, 1946–1971. https://doi.org/10.1039/C0EE00541J.
Peng, X., Zou, J., Liu, Z., Guo, Y., 2019. Electrochemical sensor for facile detection of trace N-nitrosodiphenylamine based on poly (diallyldimethylammonium chloride)-stabilized graphene/platinum nanoparticles. New J. Inside Chem. 43 (2), 820–826.
Polukarova, M., Markiewicz, A., Björklund, K., Strömvall, A.M., Galfi, H., Sköld, Y.A., Aronsson, M., 2020. Organic pollutants, nano-and microparticles in street sweeping road dust and washwater. Environ. Int. 135, 105337.
Prakashan, V.P., George, G., Sanu, M.S., Sajna, M.S., Saritha, A.C., Sudarsanakumar, C., Unnikrishnan, N.V., 2020. Investigations on SPR induced Cu@ Ag core shell doped SiO2-TiO2-ZrO2 fiber optic sensor for mercury detection. Appl. Surf. Sci. 507, 144957.
Prasad, R., Bhattacharyya, A., Nguyen, Q.D., 2017. Nanotechnology in sustainable agriculture: recent developments, challenges, and perspectives. Front. Microbiol. 8, 2017.
Pundir, C.S., Yadav, N., Chhillar, A.K., 2019. Occurrence, synthesis, toxicity and detection methods for acrylamide determination in processed foods with special reference to biosensors: a review. Trend. Food Sci. Technol. 85, 211–225.
Qi, J., Li, B., Wang, X., Fu, L., Luo, L., Chen, L., 2018. Rotational paper-based microfluidic-chip device for multiplexed and simultaneous fluorescence detection of phenolic pollutants based on a molecular-imprinting technique. Anal. Chem. 90 (20), 11827–11834.
Raeiatbina, P., Açıkelb, Y.S., 2017. Removal of tetracycline by magnetic chitosan nanoparticles from medical wastewaters. Desalination Wter Treat 73, 380–388.
Rafique, M., Shafiq, F., Gillani, S.S.A., Shakil, M., Tahir, M.B., Sadaf, I., 2020. Eco-friendly green and biosynthesis of copper oxide nanoparticles using Citrofortunella microcarpa leaves extract for efficient photocatalytic degradation of Rhodamin B dye form textile wastewater. Optik 208, 164053.
Ramnani, P., Saucedo, N.M., Mulchandani, A., 2016. Carbon nanomaterial-based electrochemical biosensors for label-free sensing of environmental pollutants. Chemosphere 143, 85–98.
Rao, G.P., Lu, C., Su, F., 2007. Sorption of divalent metal ions from aqueous solutions by carbon nanotubes: a review. Sep. Purif. Technol. 58, 224–231.
Rasheed, T., Bilal, M., Li, C., Nabeel, F., Khalid, M., Iqbal, H.M., 2018a. Catalytic potential of bio-synthesized silver nanoparticles using Convolvulus arvensis extract for the degradation of environmental pollutants. J. Photochem. Photobiol. B Biol. 181, 44–52.
Rasheed, T., Li, C., Bilal, M., Yu, C., Iqbal, H.M., 2018b. Potentially toxic elements and environmentally-related pollutants recognition using colorimetric and ratiometric fluorescent probes. Sci. Total Environ. 640, 174–193.
Raul, R.G., Irineo, T.P., Gerardo, G.G.R., Miguel, C.M.L., 2016. Biosensors used for quantification of nitrates in plants. J. Sensor 1–12.
Razack, S.A., Duraiarasan, S., 2020. A Way to Create a Sustainable Environment: Green Nanotechnology–With an Emphasis on Noble Metals. The ESLI Handbook of Nanotechnology. Risk, Safety, ESLI and Commercialization, p. 359.
Riangrungroj, P., Bever, C.S., Hammock, B.D., Polizzi, K.M., 2019. A label-free optical whole-cell Escherichia coli biosensor for the detection of pyrethroid insecticide exposure. Sci. Rep. 9 (1), 1–9.
Sablok, K., Bhalla, V., Sharma, P., Kaushal, R., Chaudhary, S., Suri, C.R., 2013. Amine functionalized graphene oxide/CNT nanocomposite for ultrasensitive electrochemical detection of trinitrotoluene. J. Hazard Mater. 248, 322–328.
Sadegh, H., Ali, G.A., Gupta, V.K., Makhlouf, A.S.H., Shahryari-ghoshekandi, R., Nadagouda, M.N., Megiel, E., 2017. The role of nanomaterials as effective adsorbents and their applications in wastewater treatment. J Nanostructure Chem. 7 (1), 1–14.
Sakthinathan, S., Kubendhiran, S., Chen, S.M., Govindasamy, M., Al-Hemaid, F.M., Ajmal Ali, M., Sivasanker, S., 2017. Metallated porphyrin noncovalent interaction with reduced graphene oxide-modified electrode for amperometric detection of environmental pollutant hydrazine. Appl. Organomet. Chem. 31 (9), e3703.
Sangaonkar, G.M., Desai, M.P., Dongale, T.D., Pawar, K.D., 2020. Selective interaction between phytomediated anionic silver nanoparticles and mercury leading to amalgam formation enables highly sensitive, colorimetric and memristor-based detection of mercury. Scientific report 10 (1), 1–12.
Sano, N., Ohtsuki, F., 2007. Gas sensor using single-wall carbon nanohorns. Adv. Powder Technol. 18, 455–466. https://doi.org/10.1163/156855207781389447.
Sathishkumar, Panneerselvam, Sweena, Ramaswamy, Wu J, Jerry, et al., 2011. Synthesis of CuO-ZnO nanophotocatalyst for visible light assisted degradation of a textile dye in aqueous solution. Chem. Eng. J. 171 (1), 136–140. https://doi.org/10.1016/j.cej.2011.03.074.
Sathyavathi, S., Manjula, A., Rajendhran, J., Gunasekaran, P., 2014. Extracellular synthesis and characterization of nickel oxide nanoparticles from Microbacterium sp. MRS-1 towards bioremediation of nickel electroplating industrial effluent. Bioresour. Technol. 165, 270–273.
Schnorr, J.M., van der Zwaag, D., Walish, J.J., Weizmann, Y., Swager, T.M., 2013. Sensory arrays of covalently functionalized single-walled carbon nanotubes for explosive detection. Adv. Funct. Mater. 23 (42), 5285–5291.
Schroeder, Vera, et al., 2018. "Carbon nanotube chemical sensors.". Chem. Rev. 119.1, 599–663.
Scognamiglio, V., Antonacci, A., Arduini, F., Moscone, D., Campos, E.V., Fraceto, L.F., Palleschi, G., 2019. An eco-designed paper-based algal biosensor for nanoformulated herbicide optical detection. J. Hazard Mater. 373, 483–492.
Sedki, M., Zhao, G., Ma, S., Jassby, D., Mulchandani, A., 2021. Linker-free magnetite-decorated gold nanoparticles (Fe3O4-Au): synthesis, characterization, and application for electrochemical detection of arsenic (III). Sensors 21 (3), 883.
Shah, M., Fawcett, D., Sharma, S., Tripathy, S.K., Poinern, G.E.J., 2015. Green synthesis of metallic nanoparticles via biological entities. Mater 8 (11), 7278–7308.
Shah, Z., Gul, T., Khan, S.A., Shaheen, K., Anwar, Y., Suo, H., Salman, S.M., 2021. Synthesis of high surface area AgNPs from Dodonaea viscosa plant for the removal of pathogenic microbes and persistent organic pollutants. Mater. Sci. Eng., B 263, 114770.
Shanker, Uma, Vidhisha Jassal , Manviri Rani, 2017. Degradation of toxic PAHs in water and soil using potassium zinc hexacyanoferrate nanocubes. J. Environ. Manage. 337–348. https://doi.org/10.1016/j.jenvman.2017.09.015.
Sharma, I., 2020. Bioremediation Techniques for Polluted Environment: Concept, Advantages, Limitations, and Prospects. In Trace Metals in the Environment-New Approaches and Recent Advances. IntechOpen.
Sharma, S., Bhattacharya, A., 2017. Drinking water contamination and treatment techniques. Appl Water Sci 7 (3), 1043–1067.
Shedbalkar, U., Singh, R., Wadhwani, S., Gaidhani, S., Chopade, B.A., 2014. Microbial synthesis of gold nanoparticles: current status and future prospects. Adv. Colloid Interface Sci. 209, 40–48.
Shen, Y.F., Tang, J., Nie, Z.H., Wang, Y.D., Ren, Y., Zuo, L., 2009. Tailoring size and structural distortion of Fe3O4 nanoparticles for the purification of contaminated water. Bioresour. Technol. 100 (18), 4139–4146.
Shi, C., Zhu, N., Cao, Y., Wu, P., 2015. Biosynthesis of gold nanoparticles assisted by the intracellular protein extract of Pycnoporus sanguineus and its catalysis in degradation of 4-nitroaniline. Nanoscale Res Letter 10 (1), 1–8.
Shim, H.W., Jin, Y.H., Seo, S.D., Lee, S.H., Kim, D.W., 2011. Highly reversible lithium storage in bacillus subtilis-directed porous Co3O4 nanostructures. ACS Nano 5 (1), 443–449.
Shrivas, K., Ghosale, A., Nirmalkar, N., Srivastava, A., Singh, S.K., Shinde, S.S., 2017. Removal of endrin and dieldrin isomeric pesticides through stereoselective adsorption behavior on the graphene oxide-magnetic nanoparticles. Environ. Sci. Pollut. Res. 24 (32), 24980–24988.
Shufang, Ren, Junling, Zeng, Zhixiang, Zheng, et al., 2021. Perspective and application of modified electrode material technology in electrochemical voltammetric sensors for analysis and detection of illicit drugs. Sens. Actuat. A Phy. 329 https://doi.org/10.1016/j.sna.2021.112821.
Singh, S., Barick, K.C., Bahadur, D., 2011. Surface engineered magnetic nanoparticles for removal of toxic metal ions and bacterial pathogens. J. Hazard Mater. 192 (3), 1539–1547.
Singh, S., Halder, A., Sinha, O., Sarkar, P.K., Singh, P., Banerjee, A., Mitra, A., 2020. Nanoparticle-based 'turn-on'scattering and post-sample fluorescence for ultrasensitive detection of water pollution in wider window. PloS One 15 (1), e0227584.
Sinha, T., Ahmaruzzaman, M., 2015. Biogenic synthesis of Cu nanoparticles and its degradation behavior for methyl red. Mater. Lett. 159, 168–171.
Sneddon, J., Vincent, M.D., 2008. ICP-OES and ICP-MS for the determination of metals: application to oysters. Anal. Lett. 41 (8), 1291–1303.
So, H.M., Won, K., Kim, Y.H., Kim, B.K., Ryu, B.H., Na, P.S., Lee, J.O., 2005. Single-walled carbon nanotube biosensors using aptamers as molecular recognition elements. J Americ Chem Soc 127 (34), 11906–11907.
Sowani, H., Mohite, P., Munot, H., Shouche, Y., Bapat, T., Kumar, A.R., Zinjarde, S., 2016. Green synthesis of gold and silver nanoparticles by an actinomycete Gordonia amicalis HS-11: mechanistic aspects and biological application. Process Biochem. 51 (3), 374–383.
Springer, V., Pecini, E., Avena, M., 2016. Magnetic nickel ferrite nanoparticles for removal of dipyrone from aqueous solutions. J Environ Chem Eng 4 (4), 3882–3890.
Srinivasan, B., Tung, S., 2015. Development and applications of portable biosensors. J. Laborat. Autom 20 (4), 365–389.
Su, Shao, Chem, Shimou, Fan, Chunhai, 2018. Recent advances in two-dimensional nanomaterials-based electrochemical sensors for environmental analysis. Green Energy Environ. 3, 97–106. https://doi.org/10.1016/j.gee.2017.08.005.
Su, Y., Xia, S., Wang, R., Xiao, L., 2017. Phytohormonal quantification based on biological principles. Hormone metabolism and signaling in plants 13, 431–470.
Sugunan, A., Thanachayanont, C., Dutta, J., Hilborn, J.G., 2005. Heavy metal ion sensors using chitosan-capped gold nanoparticles. Sci. Technol. Adv. Mat 6, 335–340. https://doi.org/10.1016/j.stam.2005.03.007.
Sundarajan, S., Sameem, S.M., Sankaranarayanan, S., Ramaraj, S., 2013. Synthesis, characterization and application of zero-valent silver nano adsorbents. Organization 2 (12).
Syam, R., Davis, K.J., Pratheesh, M., Anoopraj, R., Joseph, B.S., 2012. Biosensors: a novel approach for pathogen detection. Vetscan 7 (1), 14–18.
Tang, Y., Zou, J., Ma, C., Ali, Z., Li, Z., Li, X., He, N., 2013. Highly sensitive and rapid detection of Pseudomonas aeruginosa based on magnetic enrichment and magnetic separation. Theranostic 3 (2), 85.
Taton, T.A., Lu, G., Mirkin, C.A., 2001. Two-color labeling of oligonucleotide arrays via size-selective scattering of nanoparticles probes. J. Americ. Chem. Soc. 123, 5164–5165.
Taurozzi, J.S., Tarabara, V.V., 2007. Silver nanoparticle arrays on track etch membrane support as flow-through optical sensors for water quality control. Environ. Eng. Sci. 24, 122–137.
Tan, X., Liu, Y., Gu, Y., et al., 2016. Biochar-based nano-composites for the decontamination of wastewater: a review. 212, 318–333. Bioresour. Technol. 212, 318–333.
Teng, Minmin, Wang, Hongtao, Li, Fengting, et al., 2011. Thioether-functionalized mesoporous fiber membranes: Sol–gel combined electrospun fabrication and their applications for Hg^{2+} removal. J. Coll. Int. Sci. 355 (1), 23–28. https://doi.org/10.1016/j.jcis.2010.11.008.
Thatai, S., Khurana, P., Boken, J., et al., 2014. Nanoparticles and core–shell nanocomposite based new generation water remediation materials and analytical techniques: a review. Microchem. J. 116, 62–76.

Tiwari, N., Santhiya, D., Sharma, J.G., 2020. Microbial remediation of micro-nano plastics: current knowledge and future trends. Environ. Pollut., 115044
Tosco, T., Papini, M.P., Viggi, C.C., Sethi, R., 2014. Nanoscale zero valent iron particles for groundwater remediation: a review. J. Clean. Prod. 1–12.
Tratnyek, P.G., Johnson, R.L., 2006. Nanotechnologies for environmental cleanup. Nano Today 1, 44–48.
Trojanowicz, M., 2006. Analytical applications of carbon nanotubes: a review. Trends Anal. Chem. 25, 480–489. https://doi.org/10.1016/j.trac.2005.11.008.
Uniyal, S., Sharma, R.K., 2018. Technological advancement in electrochemical biosensor based detection of organophosphate pesticide chlorpyrifos in the environment: a review of status and prospects. Biosens. Bioelectron. 116, 37–50.
Valcarcel, M., Simonet, B.M., Cardenas, S., 2008. Analytical nanoscience and nanotechnology today and tomorrow. Anal. Bioanal. Chem. 391 (5), 1881–1887. https://doi.org/10.1007/s00216-008-2130-9.
Vidic, J., Manzano, M., Chang, C.M., Jaffrezic, R.N., 2017. Advanced biosensors for detection of pathogens related to livestock and poultry. Veterin. Res. 2017 48 (1), 11.
Vinodha, G., Cindrella, L., Shima, P.D., 2019. Graphene oxide based highly sensitive electrochemical sensor for detection of environmental pollutants and biomolecules. Mater. Res. Express 6 (8), 085548.
Virkutyte, J., Varma, R., 2010. Treatment of Micropollutants in Water and Wastewater. IWA Publishing.
Wan, Y., Zhang, D., Hou, B., 2010. Determination of sulphate-reducing bacteria based on vancomycin-functionalised magnetic nanoparticles using a modification-free quartz crystal microbalance. Biosens. Bioelectron. 25 (7), 1847–1850.
Wang, J., 2005. Carbon-Nanotube based electrochemical biosensors: a review. Electroanalysis 17, 7–14. https://doi.org/10.1002/elan.200403113.
Wang, Z., Liang, K., Chan, S.W., et al., 2019. Fabrication of nano CuAl2O4 spinel for copper stabilization and antibacterial application. J. Hazard. Mat. 371, 550–557.
Wang, J., Qiu, C., Mu, X., Pang, H., Chen, X., Liu, D., 2020a. Ultrasensitive SERS detection of rhodamine 6G and p-nitrophenol based on electrochemically roughened nano-Au film. Talanta 210, 120631.
Wang, J., Shen, M., Wang, H., Du, Y., Zhou, X., Liao, Z., Chen, Z., 2020b. Red mud modified sludge biochar for the activation of peroxymonosulfate: singlet oxygen dominated mechanism and toxicity prediction. Sci. Total Environ. 740, 140388.
Wanna, Y., Chindaduang, A., Tumcharern, G., Phromyothin, D., Porntheerapat, S., Nukeaw, J., Pratontep, S., 2016. Efficiency of SPIONs functionalized with polyethylene glycol bis (amine) for heavy metal removal. J. Magn. Magn Mater. 414, 32–37.
Wei, L., Lu, D., Wang, J., Wei, H., Zhao, J., Geng, H., Zhang, Y., 2014. Highly sensitive detection of trinitrotoluene in water by chemiresistive sensor based on noncovalently amino functionalized single-walled carbon nanotube. Sensors and Actuator B. Inside Chem. 190, 529–534.
Werkneh, A.A., Rene, E.R., 2019. Applications of Nanotechnology and Biotechnology for Sustainable Water and Wastewater Treatment. In Wat. In: Er and Wastewater Treatment Technologies. Springer, Singapore, pp. 405–430.
White, B.R., Stackhouse, B.T., Holcombe, J.A., 2009. Magnetic γ-Fe2O3 nanoparticles coated with poly-l-cysteine for chelation of as (III), Cu (II), Cd (II), Ni (II), Pb (II) and Zn (II). J. Hazard Mater. 161 (2–3), 848–853.
Willner, M.R., Vikesland, P.J., 2018. Nanomaterial enabled sensors for environmental contaminants. J. Nanobiotechnol. 16 (1), 1–16.
Xia, Y., Wang, K., Shi, Y., Gui, X., Lv, C., Tao, H., 2021. Reduced graphene oxide cross-linked L-cysteine modified glassy carbon electrode for detection of environmental pollutant of hydroquinone. FlatChem 25, 100214.
Xu, J., Bhattacharyya, S.D., 2005. Membrane based bimetallic nanoparticles for environmental remediation: synthesis and reactive properties. Environ. Prog. 24, 358–366.
Xu, W., Zhang, J., Zhang, L., Hu, X., Cao, X., 2009. Ultrasensitive detection using surface enhanced Raman scattering from silver nanowire arrays in anodic alumina membranes. J. Nanosci. Nanotechnol. 9 (8), 4812–4816.
Xu, Y., Li, C., Zhu, X., et al., 2014. Application of magnetic nanoparticles in drinking water purification. Environ. Eng. Managem. J. 13 (8), 2023–2029. https://doi.org/10.30638/eemj.2014.224.
Yadav, N., Chhillar, A.K., Yadav, S.S., 2019. Relevance of nomaterials-based biosensors for detection of pathogens in. Foods. Biochem. Cell. Arch. 19 (1), 7–12.
Yadav, N., Chhillar, A.K., Pundir, C.S., 2018. Preparation, characterization and application of haemoglobin nanoparticles for detection of acrylamide in processed foods. Int. J. Biol. Macromol. 107, 1000–1013.
Yan, W., Herzing, A.A., Li, X.Q., Kiely, C.J., Zhang, W.X., 2010. Structural evolution of Pd-Doped nanoscale zero-valent iron (nZVI) in aqueous media and implications for particle ageing and reactivity. Environ. Sci. Technol. 44, 4288–4294.
Yang, L., Yang, L., Ding, L., Deng, F., Luo, X.B., Luo, S.L., 2019. Principles for the application of nanomaterials in environmental pollution control and resource reutilization. In: Nanomaterials for the Removal of Pollutants and Resource Reutilization. Elsevier, pp. 1–23.
Yajun, Y, Meng, G, 2010. Ag dendritic nanostructures for rapid detection of polychlorinated biphenyls based on surface-enhanced Raman scattering effect. J Applied Physics 107, 044315. https://doi.org/10.1063/1.3298473.
Yin, R., Guo, W., Wang, H., Du, J., Wu, Q., Chang, J.S., Ren, N., 2019. Singlet oxygen-dominated peroxydisulfate activation by sludge-derived biochar for sulfamethoxazole degradation through a nonradical oxidation pathway: performance and mechanism. Chem. Eng. J. 357, 589–599.
Yu, L., Zhang, P., Dai, H., Chen, L., Ma, H., Lin, M., Shen, D., 2017. An electrochemical sensor based on Co 3 O 4 nanosheets for lead ions determination. RSC Adv. 7 (63), 39611–39616.
Yu, W., Sisi, L., Haiyan, Y., Jie, L., 2020. Progress in the functional modification of graphene/graphene oxide: a review. RSC Adv. 10 (26), 15328–15345.
Yu, J.G., Zhao, X.H., Yang, H., Chen, X.H., Yang, Q., Yu, L.Y., Jiang, J.H., Chen, X.Q., 2014. Aqueous adsorption and removal of organic contaminants by carbon nanotubes. Sci. Total Environ. 482–483, 241–251.
Zhang, C., Jiang, S.Z., Huo, Y.Y., Liu, A.H., Xu, S.C., Liu, X.Y., Man, B.Y., 2015. SERS detection of R6G based on a novel graphene oxide/silver nanoparticles/silicon pyramid arrays structure. Optic express 23 (19), 24811–24821.
Zhang, L.D., Fang, X.S., 2008. Controlled growth and characterization methods of semiconductor nanomaterials. J. Nanosci. Nanotechnol. 8 (1), 149–201.
Zhang, M., Dong, Y., Gao, S., Cai, P., Dong, J., 2019. Effective stabilization and distribution of emulsified nanoscale zero-valent iron by xanthan for enhanced nitrobenzene removal. Chemosphere 223, 375–382.
Zhang, M., Wang, Y., Zhao, D., Pan, G., 2010. Immobilization of arsenic in soils by stabilized nanoscale zero-valent iron, iron sulfide (FeS), and magnetite (Fe3O4) particles. Chin. Sci. Bull. 55 (4–5), 365–372.
Zhang, P., Lo, I., O`Connor, D., Pehkonen, S., Cheng, H., Hou, D., 2017. High efficiency removal of methylene blue using SDS surface-modified ZnFe2O4 nanoparticles. J. Colloid Interface Sci. 508, 39–48.
Zhang, W., Asiri, A.M., Liu, D., Du, D., Lin, Y., 2014. Nanomaterial-based biosensors for environmental and biological monitoring of organophosphorus pesticides and nerve agents. Trends Anal. Chem. 54, 1–10.
Zhang, W., Sprafke, J.K., Ma, M., Tsui, E.Y., Sydlik, S.A., Rutledge, G.C., Swager, T.M., 2009. Modular functionalization of carbon nanotubes and fullerenes. J Americ Chem Soc. 131 (24), 8446–8454.
Zhao, J., Jiaojiao, L., Duo, J., Yan, G., Yukun, C., Wei, W., et al., 2020. Removal of atrazine by biochar-supported zero-valent iron catalyzed persulfate oxidation: reactivity, radical production and transformation pathway. Environ. Res. 184, 109260.
Zhao, H., Ma, H., Li, X., Liu, B., Liu, R., Komarneni, S., 2021. Nanocomposite of halloysite nanotubes/multi-walled carbon nanotubes for methyl parathion electrochemical sensor application. Appl. Clay Sci. 200, 105907.
Zheng, X., He, L., Duan, Y., Jiang, X., Xiang, G., Zhao, W., Zhang, S., 2014. Poly (ionic liquid) immobilized magnetic nanoparticles as new adsorbent for extraction and enrichment of organophosphorus pesticides from tea drinks. J. Chromatogr. A 1358, 39–45. https://doi.org/10.1016/j.chroma.2014.06.078.
Zheng, Z., Yu, H., Geng, W.C., Hu, X.Y., Wang, Y.Y., Li, Z., Guo, D.S., 2019. Guanidinocalix [5] arene for sensitive fluorescence detection and magnetic removal of perfluorinated pollutants. Nature communication 10 (1), 1–9.
Zhou, G.N., He, C.S., Wang, Y.X., He, P.P., Liu, J., Mu, Y., Zhang, L.S., 2019. Aerobic removal of iodinated contrast medium by nano-sized zero-valent iron: a combination of oxidation and reduction. J. Hazard Mater. 373, 417–424.
Zhu, H., Jiang, R., Xiao, L., Chang, Y., Guan, Y., Li, X., Zeng, G., 2009. Photocatalytic decolorization and degradation of Congo Red on innovative crosslinked chitosan/nano-CdS composite catalyst under visible light irradiation. J. Hazard Mater. 169 (1–3), 933–940.
Zinatloo S.,, Ajabshir, Morassaei S.,, M., Salavati M., Niasari, 2019. Facile synthesis of Nd2Sn2O7-SnO2 nanostructures by novel and environment-friendly approach for the photodegradation and removal of organic pollutants in water. j. Environ. Mang. 233, 107–119.
Zinatloo-Ajabshir, S., Morassaei, M.S., Amiri, O., Salavati-Niasari, M., 2020. Green synthesis of dysprosium stannate nanoparticles using Ficus carica extract as photocatalyst for the degradation of organic pollutants under visible irradiation. Ceram. Int. 46 (5), 6095–6107.