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Nanoremediation Technologies for sustainable remediation of contaminated environments: Recent advances and challenges

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Abstract

A major and growing concern within society is the lack of innovative and effective solutions to mitigate the challenge of environmental pollution. Uncontrolled release of pollutants into the environment as a result of urbanisation and industrialisation is a staggering problem of global concern. Although, the eco-toxicity of nanotechnology is still an issue of debate, however, nanoremediation is a promising emerging technology to tackle environmental contamination, especially dealing with recalcitrant contaminants. Nanoremediation represents an innovative approach for safe and sustainable remediation of persistent organic compounds such as pesticides, chlorinated solvents, brominated or halogenated chemicals, perfluoroalkyl and polyfluoroalkyl substances (PFAS), and heavy metals. This comprehensive review article provides a critical outlook on the recent advances and future perspectives of nanoremediation technologies such as photocatalysis, nano-sensing etc., applied for environmental decontamination. Moreover, sustainability assessment of nanoremediation technologies was taken into consideration for tackling legacy contamination with special focus on health and environmental impacts. The review further outlines the ecological implications of nanotechnology and provides consensus recommendations on the use of nanotechnology for a better present and sustainable future.

Keywords: Nanoremediation, environmental sustainability, persistent organic pollutants, photocatalysis, nano-sensors

Introduction

Environment sustainability is the responsible and justified interaction between human beings and the environment with judicious use of natural resources that can render the environment safe for present as well as for future generations. The controlled management of natural resources emphasises harmony between ecology and environment and can sustain the ecological/natural balance within the universe (Barrington-Leigh, 2016; Arora et al., 2018). According to United Nations World Summit 2005, sustainable development has social, environmental and economic aspects. Environmental sustainability is intimately related to economic sustainability (Haapanen and Tapio, 2016). According to UN Environment Annual Report 2017, environmental sustainability is essential for global equity, liberty and security. Sustainability is not only holistic, attractive and elastic but imprecise (IUCN, 2006). Among the several agendas, Environmental sustainability and economic security were the main goals highlighted by United Nations Sustainable Development Goals (SDGs), framed on September 15, 2015 (Arora and Mishra, 2019). The Sustainable Remediation Forum for the UK (SuRF-UK) established the consideration of sustainability aspect in remediation of contaminated land and come up with sustainability criteria or checklist for framing a remediation planning. The SuRF-UK indicator checklist provides detailed and comprehensive guidance for checking the sustainability assessment of remediation process. From a decade now, the SuRF-UK sustainability assessment is accepted as crucial to remediation planning and implementation around the world (Bardos et al., 2018).

Despite of its prime importance, the environmental sustainability has remained a non-trivial challenge because of climate change, global warming, resource depletion and disturbances associated with biodiversity. In a recent, Global Sustainable Development Report (GSDR, 2019), it was stated, that both present as well as future of the globe are at risk, no country in the world is at a position to achieve the United Nations Sustainable Development Goals (SDGs)s by 2030 (Sachs et al., 2019). According to World Water Development Report (2019), the water consumption rate has increased by 1% per year from 1980 and is expected to reach 3% by 2050 (World Water Development Report 2019 | UN-Water). The other major setbacks to the environmental sustainability are consumption of fossil fuels and climate change, the consumption of fossil fuels has almost doubled from past 20 years (https://ourworldindata.org/fossil-fuels). The world temperature will raise 3-5ºC by 2050, if uncontrolled release of greenhouse gases had not been checked, as reported by UN World Meteorological Organization. Therefore, there is an urgent need to develop sustainable and eco-friendly approaches for sustaining the viability and sustainability of this planet (Abhilash et al., 2016; Cai et al., 2019; Shields et al., 2019).

A great deal of research is currently underway for developing and designing efficient and reliable techniques to degrade or transform environmental pollutants of concern. Specifically, the use of nanomaterials in environmental remediation have gained much attention due to their unusual characteristics viz cost-effectiveness, sensitivity, excellent electronic properties, high surface to volume ratio and better catalytic properties (Ghasemzadeh et al., 2014; Khan et al., 2019).

Nanoremediation is an innovative remediation technique that relies on the use of nanomaterials. Nanoremediation allows to tackle and address the formidable challenges of 21st century such as pollution crisis, contaminated land management, restoration of environmental imbalance and presents innovative solutions for quick and efficient removal of pollutants from contaminated environment (Das et al., 2019; El-Ramady et al., 2017; Singh and Ambika, 2018). The technologies employing nanostructures has potential not only to reduce the overall costs of cleaning up large scale contaminated, but also to reduce clean-up time, eliminate the need for treatment and disposal of contaminated materials, and reduce contaminant concentration to near zero- all in situ (Corsi et al., 2018; Karn et al., 2009). Nanoremediation technologies entails the applications of reactive nanomaterials such as metal oxides, nanodots, bimetallic nanoparticles, carbon nanotubes, nanoclusters and nanocomposites for the degradation and mineralisation of contaminants (Guerra et al., 2018; Khin et al., 2012; Gehrke et al., 2015; Rajan, 2011). Compared to several traditional remediation methods such as chemical oxidation, solvent co-flushing, pump treat method and thermal decomposition, nanoremediation approaches can provide sustainable solutions to the environmental pollution problems and could depreciate the financial burden for clean-up of contaminated sites (Caliman et al., 2011; Yeung, 2010; Khan et al., 2019; Patil et al., 2016).

According to reports published on the USEPA and environmental nanotechnology website, various contaminated sites have been treated using nanoremediation approaches over the last decade. It has been shown that nanoremediation resulted in drastic reduction in operational costs, by almost 80% and significant reduction of time frame in treating contaminated sites as compared to conventional remediation methods (USEPA 2009, PEN, 2015). The global investment in nano-enabled devices and products have increased nine-fold from $US 432 million to $US 4100 million in only 8-year time span (1997-2005) (Roco, 2005). In recent years, nanotechnology has influenced all fields of science and technology like engineering, medical, electronics, optics, energy and environmental fields, increased number of nanotech products are circulating in the market with 3-4 items added per weak (Bondarenko et al., 2013). In 2015, the nanotechnology market in Asia was estimated to be $14741.6 million and has been expected to reach $55056 million by 2022 with compound annual growth rate (CAGR) increase of 20.7%. According to nanotechnology 2020 market analysis, Asia-pacific is the most attractive market for nanotechnology due to the vast demand for potential nanomaterials. (**Figure 1**)

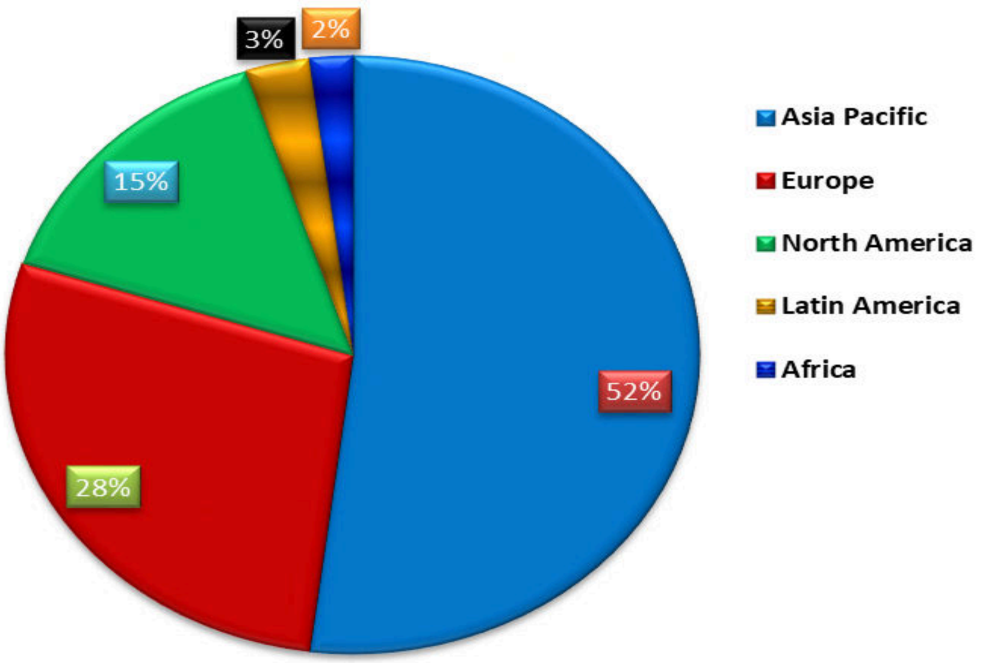

Figure 1. Global nanotechnology market analysis report, 2020, showing the statistics of utilization of nanotech-based products around the globe

Nanotechnology enables the manipulation of matter at nano-dimensions where unique phenomena enable novel applications (Shafi et al., 2020a; Omar, 2018; Vikesland, 2018). Nanotechnology ensures the *in-situ* remediation of contaminated media without adding further chemicals (Karn et al., 2009). The technology at nano level involves the use of reactive nanomaterials with high surface area, lower reduction potential and quantum confinement which makes them versatile entities for degradation, detoxification and transformation of hazardous recalcitrant pollutants in the environmental medias (Fajardo et al., 2020; Gil-Díaz et al., 2019; Patil et al., 2016; Tosco et al., 2014). These nanomaterials in form of catalysts, chemical oxidants, nanosensors, adsorbents ensure rapid detection and simultaneous detoxification of contaminants such as chlorinated biphenyls, pesticides, drugs, aromatic heterocycles, volatile organic compounds, heavy metals, inorganic ions from water, air and contaminated land sites (Chaudhry et al., 2008; Cui et al., 2001). Environmental applications of nano-based materials have received public attention and needs to be elaborated with special focus on sustainability assessment of remediation proposal (Thangavel and Sridevi, 2015; Bouqellah et al., 2019; Das and Chatterjee, 2019; Khan et al., 2015).

This review outlines the application of nanotechnology in 1) photocatalytic processes for energy production and environmental restoration, 2) detection and quantification of trace contaminants from environment using nanosensors, 3) groundwater, wastewater and contaminated soil remediation using nanoadsorbents and nanocatalysts. Furthermore, the sustainability assessment was taken into consideration for tackling contamination legacy with special focus to health and environmental impacts.

2. Nano-Photocatalysis in environmental remediation: A sustainable approach

Persistent organic pollutants in the environment are not readily degraded and therefore persist for long times and ultimately find their way into the food chain, thus causing severe detrimental effects to human beings (Ashraf, 2017). Due to inability of conventional treatment technologies to degrade recalcitrant organic compounds completely, the level of pollutants in the environment is rising day by day. Researchers in collaboration with governmental and non-governmental agencies have devoted their constant efforts to mitigate the increasing pollution level by developing smarter and eco-friendly techniques (Anjaneyulu et al., 2005; Bates et al., 2016; Ludlow and Roux, 2012). Photocatalytic technique is one among them, by which the use of highly reactive hydroxyl and superoxide radicals can convert the hazardous materials into environmental benign products. Photocatalysts speeds up the chemical reaction in ample presence of solar radiations. In general, Photocatalysis is a redox reaction on the surface of photocatalyst brought about by valence band (holes, h^+) and conduction band (electrons, e^-) produced by the absorption of photons. Upon irradiation holes are generated in valence band (VB) and electrons in conduction band (CB) of a photocatalyst, such photogenerated electron-hole pairs (e^-/h^+) induces the formation of highly energetic and reactive species such as hydroxyl (OH^-) and superoxide radicals (O_2^-). The reactive species are enough potent to oxidize organic pollutants, decompose the air pollutants such as NO_2, CO and NH_3, degrade the waste plastics and destruct all water borne microbes. Photocatalysis has been considered as a productive procedure for the mineralization of hazardous chemical substances, unsafe inorganic materials and microbial disinfection because of the generation of highly energetic radicals which act as powerful oxidizing agent (Ajmal et al., 2014; Khin et al., 2012). The diagrammatic representation of photocatalytic mechanism is depicted in **Figure 2**.

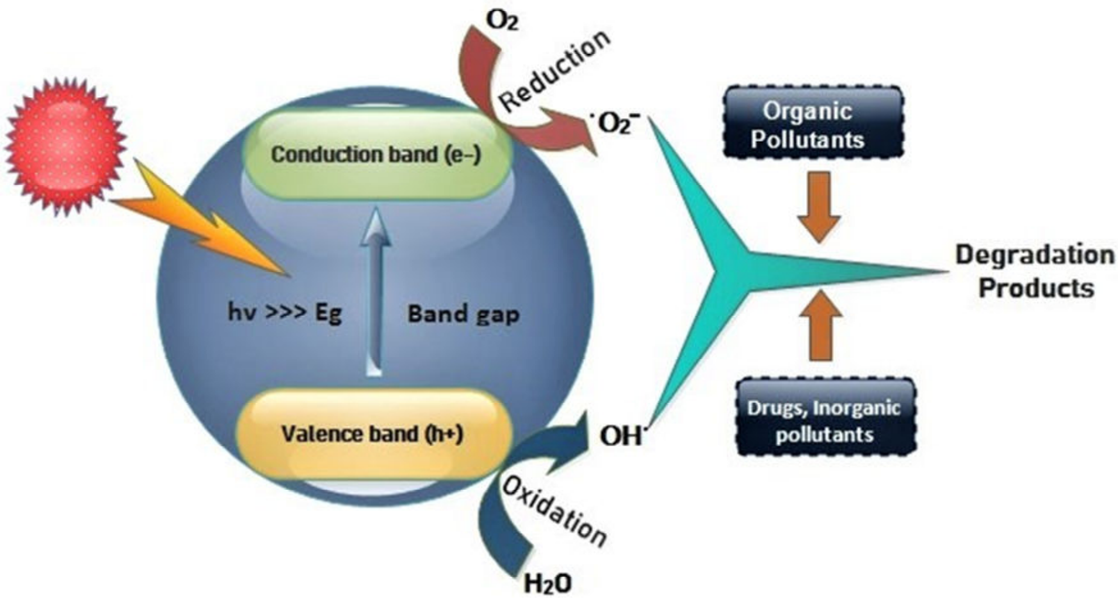

Figure 2. General Mechanism of photocatalysis, depicting the generation of holes (h^+) and electrons (e^-) and subsequent degradation of pollutants by utilizing solar light.

The photo catalytic oxidation of hydrocarbons, phenols, aldehydes, halo-compounds, surfactants, dyes, drugs, pesticides, etc demonstrates the efficient clean-up process for maintaining the health of environment (Charanpahari et al., 2018; Hoffmann et al., 1995). From the last decade extensive research has been focussed on nanomaterial photocatalysis for environmental clean-up. A vast number of photocatalysts in their nanoform have been developed like metal oxides, metal sulphides, composite oxides, carbon nanotubes, dendrimers, polymeric nanocomposites etc. to decontaminate soil, purify air and detoxify wastewater (Das et al., 2015; Khan et al., 2015; Krishnan et al., 2017; Mahlambi et al., 2015).

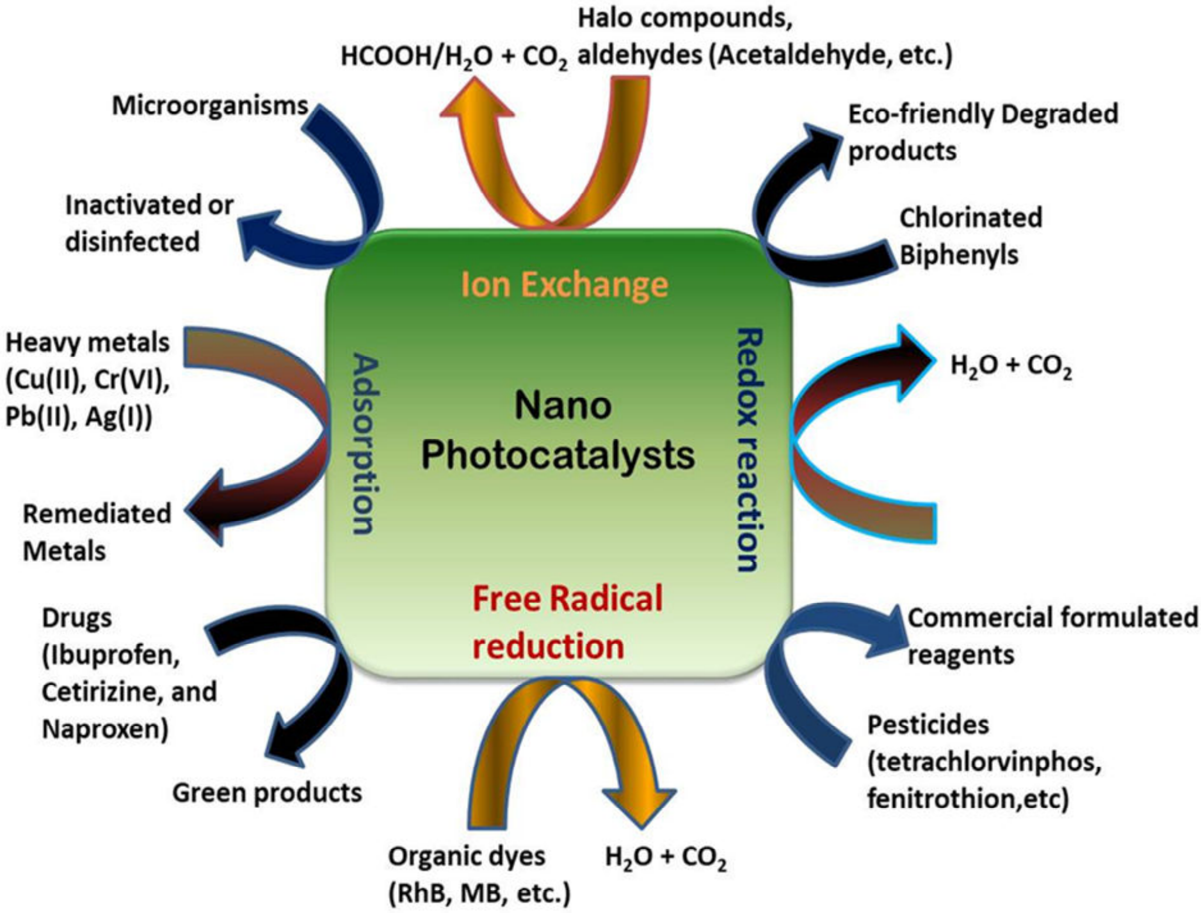

Figure 3. Photocatalytic degradation of various pollutants by sustainable approaches using metallic nanoparticles

Photocatalysis is a photochemical process based on redox reactions of electron/hole pairs upon irradiation (Guo et al., 2018; Kiriakidis and Binas, 2014). Photocatalysis has the potential to degrade plethora of recalcitrant pollutants as depicted in **Figure 3** and is considered as an efficient remediation technique as per sustainability perspective of the environment (Arora et al., 2016; Khan et al., 2015). This technique is considered as a potential advanced oxidation technology (AOP) to culminate demanding problems of air contamination, energy restoration and water disinfection. Due to rapid degradation rates, complete conversion of organic compounds to green products and simultaneous treatment of multiple contaminants, AOPs such as photocatalysts proved to be smart alternatives to mitigate environmental problems in comparison to conventional treatment methods (Jiang et al., 2012; Krishnan et al., 2017).

Furthermore, photo catalytic water splitting has proved to be safer, cleaner and sustainable approaches to generate molecular hydrogen. Hydrogen is considered as the promising and sustainable alternate for consumption of fossil fuels as the only product that it forms during combustion is water (Rosen and Koohi-Fayegh, 2016; Takata and Domen, 2019; Wolff et al., 2018). Research on formation of molecular oxygen or molecular hydrogen through photocatalytic water splitting is at the cutting edge to mitigate the burning problem of energy crisis. Several photocatalysts have been investigated for molecular hydrogen production or oxygen evolution reactions but most of the photocatalysts suffer a severe drawback of low efficiency. Metal oxides, sulphides, nitrides, conjugated organic polymers, carbon based photocatalysts are seen as an efficient photocatalysts for water splitting or hydrogen production (CdSe, CdS, Ta_3N_5, TaON, C_3N_4, SiC, $BiVO_4$, WO_3, Cu_2O, Fe_2O_3, g-C_3N_4 nanosphere, TFPT-covalent organic framework, Polymer P7) (Landman et al., 2017; Y. Li et al., 2019; N. Liu et al., 2015). However, the efficiency can be somewhat less due to electron-hole recombination and photocorrosion. Therefore, modified photocatalysts such as bimetallic nanoparticles, hierarchical nanostructures, nanocomposites, oxynitrides and functionalized nanoparticles can prove excellent candidates for water splitting reactions because of better charge separation and synergism for photoabsorption (Wang et al., 2019). The mechanism of photo catalytic water splitting along with generation and recombination of photo-induced charge carriers is depicted in **Figure 4.**

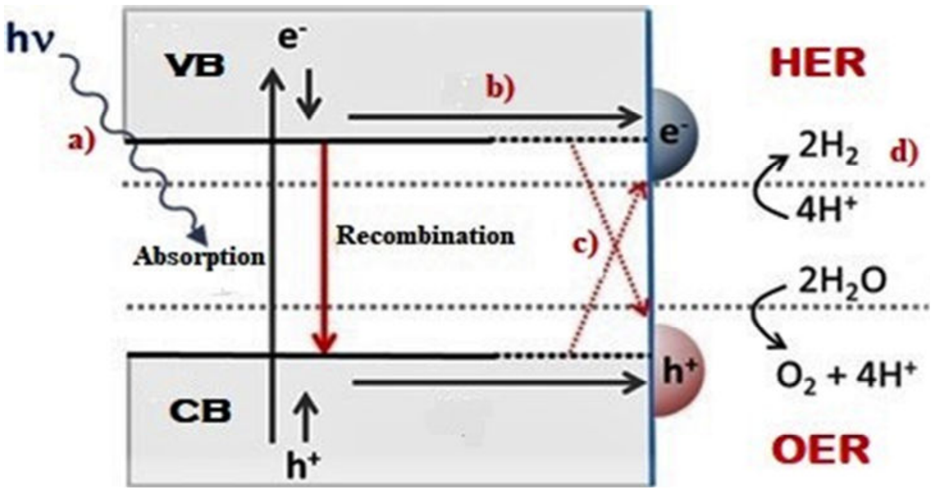

Figure 4. Reaction scheme of photocatalytic water-splitting on the surface of heterogeneous photocatalyst: a) absorption b) charge transfer c) redox reactions d) charge recombination. Reproduced From (Axet et al., 2019)

Recently, a new finding based on the interaction between photocatalysts and microorganisms has opened a general pathway for sustainable remediation of environmental pollutants and has explored the sustainable growth of photocatalysts as well (Deng et al., 2020). Based on the extensive literature, three types of interactions were established between photocatalysts and microorganisms as follows: 1) photocatalytic damage to microorganisms which includes sterilisation of microorganisms and disinfection of public environment. 2) Synergistic effect of photocatalysts on microorganism which includes altruistic collaboration for degradation of pollutants and generation of energy in a sustainable manner. 3) Preparation of photocatalysts with the aid of microorganisms as a greener and sustainable approach. The coupling of photocatalytic technology (photoanode) with bio-electrochemical systems (biocathode) can degrade the organic pollutants in a sustainable manner and enhance the production of hydrogen and generation of electricity. Du et al., (2017) reported the combination of photocatalytic anode with biocathode, CNT/TiO_2 was fabricated by decorating CNT with TiO_2 nanoparticles. This biocathode coupled photochemical battery (Bio-PEC) shows efficient degradation of methylene blue (0.0120 min^{-1}) and excellent power density of

(211.32 mW m^{-2}). Sakimoto et al., (2016) investigated the coupling of highly specific biocatalysts with the efficient photocatalytic semiconductor. The study involves the use of cadmium sulphide (CdS) nanoparticles to autosensitise *Moorella thermoacetica,* thus producing acetic acid with the utilisation of carbon dioxide in photosynthesis. The photoelectrons transferred from photocatalyst to the bacteria add to CO_2 and undergoes several reaction pathways inside the bacteria to produce acetic acid. Marsolek et al., (2008) proposed the concept of coupling of photodegradation to biodegradation (ICPB). This Photo catalytic coupled microorganism system is a novel remediation method for treatment of refractory wastewater in a sustainable manner. Moreover, the microbial assisted photocatalytic preparation involves the use of electrochemical active biofilms (EAB) to facilitate efficient electron transfer and improves the photocatalytic performances (Khan et al., 2014). The possible interactions between photocatalysts and microorganisms are also shown in **Figure 5**.

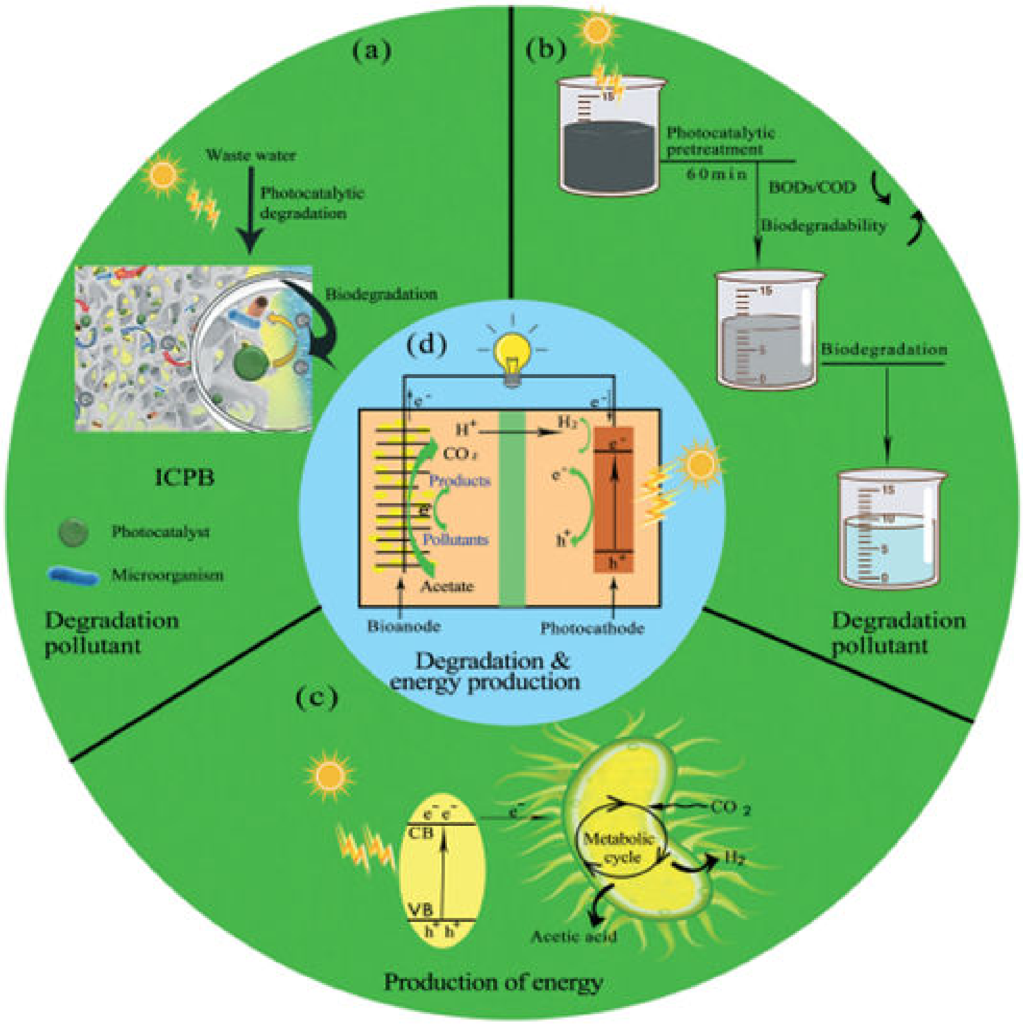

Figure 5. (a) Photocatalytic coupling of microbial degradation of pollutants (ICPB). (b) Photocatalytic retreatment of pollutants in wastewater enhances the biodegradability of refractory materials. (c) Microbes use photogenic electrons to make valuable chemicals through their own metabolic cycles. (d) Photocatalysts as electrode materials to improve the degradation of pollutants and power generation performance of bioelectrochemical systems. Reproduced from (Deng et al., 2020)

An ideal photocatalyst should possess high surface to volume ratio, proper band gap, high porosity, quantum confinement, reliability and long term stability. Nanomaterials which are depicted in **Table 1** are considered as ideal photocatalysts because of desired features viz high surface area, high reactivity, rapid diffusion, easy dispersibility and sustainable environmental remediation approach. Titanium dioxide (TiO_2) is considered as an efficient photocatalyst because of its potential catalytic activity, chemical stability and non-toxicity (Diamandescu et al., 2008; Fujishima et al., 2000; Gupta and Tripathi, 2011). To date, several research articles have been published on TiO_2, explaining its fascinating characteristics in photocatalytic hydrogen production, air purification, and water disinfection. Kato and Mashio, (1964) reported photocatalytic oxidation of tetralin (1,2,3,4-tetrahydronaphthalene), a potent human mutagen and toxic chemical by a TiO_2 suspension. Sonawane et al., (2004) investigated Fe-doped TiO_2 for photodegradation of methyl orange and it was found to degrade 95% of methyl orange after 2-3 hours exposure of sunlight. Rocha et al., (2010) carried out efficient degradation and mineralisation of organic matter in oil sludge by heterogeneous catalysis of H_2O_2/UV/TiO_2, indicating the catalytic behaviour of TiO_2. Yang and Yang, (2018) carried out complete degradation of rhodamine B dye, almost 99% through the photocatalytic behaviour of anatase TiO_2. Mahmoodi et al., (2007b), (2007a) reported the efficient catalytic behaviour of immobilized TiO_2 nanoparticles in decomposition of agricultural pollutants such as diazonin, Butachlor (N- butoxymethyl-2-chloro-2,6-diethylacetanilide), imidacloprid as N-heterocyclic aromatics In addition to TiO_2, several metallic nanomaterials are investigated for potential photocatalytic applications like ZnO (Rajamanickam and Shanthi, 2016), ZnS (Ahmadi et al., 2020), ZrO_2 (Botta et al., 1999), MoS_2 (Li et al., 2013), WO_3 (Dong et al., 2017), CdS (Su et al., 2018), Fe_2O_3 (Rincón Joya et al., 2019), Cu_2O (Bhargava and Khan, 2018), 2D $PbMoO_4$ (Datta et al., 2018), $NaNbO_3$ (Shi et al., 2011), $CdIn_2S_4$ (Huang et al., 2014), $ZnIn_2S_4$ (Huang et al., 2014). ZnO being inexpensive and non-toxic shares the same photodegradation mechanism as TiO_2 and is considered as potential photocatalyst for environmental remediation. ZnO is an n-type semiconductor with excellent electronic properties and exhibits better absorption efficiency compared to TiO_2 (Bai et al., 2013; Wang et al., 2011). Tian et al (2012) performed the photodegradation of methylene orange by two photocatalysts, Degussa P25 TiO_2 and ZnO and it was reported that the degrading power of ZnO was 4 times more than that of P25. However, the photocatalytic activity of ZnO is somehow affected because of its large band gap energy. Therefore, several efforts have been taken to mitigate the limitation and enhance the absorption efficiency of ZnO viz, incorporation of dopants, composite formation, dye sensitization and surface decoration with active materials. It has been investigated that the dopants such as silver, aluminium, tin, cobalt, reduced graphene oxide, graphite like g-C_3N_4 can increase the photocatalytic activity of ZnO by measurable factors and can improve its practical application in multiple fields (Nguyen et al., 2019; Wu et al., 2011). Furthermore, composites of carbon source (GO, g-C_3N_4) with Ag, Zn and other transition metals exhibited promising properties for mineralization of organic pollutant. Reduced GO have the capability of lowering band gaps and prevent agglomeration of nanoparticles because of its excellent electron transfer properties, thus boosts the photocatalytic activity (Wang et al., 2011). Xu et al., (2018) designed quaternary composites of ZnO nanorod/RGO/$CuInS_2$ quantum dots which exhibit enhanced photocatalytic activity under visible light irradiation. Divya et al., (2017) synthesized TiO_2/ZnO/RGO/Ag quaternary nanocomposites which can photodegrade almost 99% of organic pollutant (Rhodamine B) under visible light with excellent recyclability. It has also been reported, that ZnO/RGO@NF showed high photocatalytic efficiency for the degradation of Malachite green (MG) and efficient photocatalytic performance for continuous operations, showing its great potential as stable and promising catalyst for the efficient removal of MG in seawater (N. Liu et al., 2015).

The investigation of synthetic route and potential application of various other nanomaterials have been reviewed and are shown in **Table 1**. The applicability of various photocatalysts is restricted by their wide band gap and fast recombination of photogenerated electron-hole pairs. To overcome this difficulty, various approaches were employed to tailor the band gap of photocatalysts such as doping, dye-sensitization, formation of heterojunctions and capping, etc. It has been reported that that doping a photocatalyst with suitable dopant can inhibit the electron–hole pair recombination resulting in separation of photogenerated species and thus enhance the photocatalytic activity (Akir et al., 2017; He et al., 2018).

Table 1. List of metal-based nano-photocatalysts and their use in environmental remediation

NM type	Synthetic Method	Light used for Irradiation	Environmental Applications	Literature
Ag_2S/Bi_2WO_6	Hydrothermal method	Visible light	RhB Degradation	(Mehraj et al., 2015b)
CuS/ZnS	Hydrothermal method	Visible light	H_2 Production, Acid-Blue degradation	(Harish et al., 2017)
SnO_2 Nanospheres	Microwave assisted Solvothermal method	Visible light	Photo-oxidation of RhB	(Parthibavarman et al., 2018)
CdS Nanowire	Solvothermal method	Visible light	Degradation of methylene blue and RhB	(Ganesh et al., 2017)
CdS Nanoparticles	Chemical precipitation method	Visible light	Acid Blue-29 degradation	(Qutub et al., 2016)
Fe_2O_3/BiOI	Hydrolysis method	Visible light	RhB degradation	(Mehraj et al., 2016)
TiO_2/ZrO_2	Sol-gel method	UV light	Degradation of Ponceau BS	(Pirzada et al., 2015b)
BiOBr/Cd(OH)$_2$	Chemical bath method	Visible light	RhB degradation	(Pirzada et al., 2015a)
AgBr/Ag_2CO_3	Ion Exchange Reaction	Visible light	Degradation of Ponceau BS	(Mehraj et al., 2014)
ZnO/ZrO_2	Sol-gel method	UV light	Acid Blue-25 degradation, antibacterial activity	(Aghabeygi and Khademi-Shamami, 2018)
SnO_2/SrO	Hydrothermal method	UV light	Degradation of azo-dye, drug and pesticide	(Sultana et al., 2015)
Ag_3PO_4/BiOBr	Precipitation method	UV light	Degradation of RhB and Phenol	(Mehraj et al., 2015a)
Fe_3O_4/TiO_2/Ag NC	Sol-gel, hydrothermal method	Visible light	Photoreduction of ampicillin	(Y. Zhao et al., 2016)
TiO_2/ZnS-In_2S_3 NC	Electrospinning method	Visible light	RhB Degradation	(C. Liu et al., 2015)
TiO_2-MWCNT/Al_2O_3 NC	Sol-gel method	Visible light	Photodegradation of Methyl Orange	(W. Zhang et al., 2015)
Cu_2O/TiO_2	Electrospinning procedure	UV and Visible light	Photocatalysis of p-nitro phenol	(Yang et al., 2010)
ZnO/Zn(OH)F	Microfluidic Chemical Method	UV light	Photodegradation of MB	(D. Zhao et al., 2016)
Ag_3PO_4/TiO_2	Electrospinning and solution process	Visible light	RhB Degradation	(Yao et al., 2012)
SiO_2/Bi_2WO_6	Hydrothermal and calcination method	UV and Visible light	RhB and Ponceau BS degradation	(Liao et al., 2015)

$Ce\text{-}ZrO_2/SiO_2$	Template assisted thermal method	UV light	Methylene blue degradation	(Schneider and Naumann, 2014)
SiO_2/CuO	Electrospinning soaking and calcination method	UV and Visible light	Degradation of RhB and Phenol	(Hu et al., 2015)
$TiO_2/ZnFe_2O_4$	Hydrothermal method	UV and Visible light	Photocatalytic and photo-electrochemical activity	(Wang et al., 2013)
$BiOCl/Bi_4Ti_3O_{12}$	Solvothermal method	Visible light	Photodegradation of methyl orange and p-nitrophenol	(M. Zhang et al., 2015)
Co_3O_4/Fe_2O_3	Low-Temperature Method	UV Light	Degradation of Acridine Orange and Brilliant Cresyl Blue	(M. Zhang et al., 2015)
TiO_2/WO_3	Hydrothermal method	Visible light	Degradation of diclofenac	(Mugunthan et al., 2018)
$SnO_2\text{-}\alpha\text{-}Fe_2O_3$	Grinding method	Visible light	Degradation of Phenol	(Devi and Shyamala, 2018)
$Ag/BiVO_4$	Microwave hydrothermal method	Visible light	Degradation of bisphenol A, RhB, MB	(Regmi et al., 2018a)
Au/CeO_2	Ligand-assisted impregnation	Visible light	Reduction of nitrobenzene, Acetophenone,	(Ke et al., 2013)
Au/ZrO_2	Ligand assisted impregnation	Visible light	Reduction of Nitro aromatic compounds	(Zhu et al., 2010)
$WO_3/BiVO_4/TiO_2$ NC	hydrothermal, spin coating and electrodeposition methods	Visible light	Photoelectrochemical water splitting	(Kalanur et al., 2017)
$Ag_2S/NiO\text{-}ZnO$ NC	Precipitation method	Visible light	Degradation of RhB, Acetone sensing	(Shafi et al., 2019)

*NM = Nanomaterials, UV = Ultraviolet. RhB = Rhodamine B, NC = Nanocomposite

3. Nanosensors in trace contaminant detection in environmental mediums

A nanosensor is a miniaturized device, which converts a chemical interaction into electrically useful signal. The information obtained from the chemical interaction quantifies the composition and detects the presence or absence of particular element or ion, activity, concentration etc (Shafi et al., 2019). Excessive use of natural resources and environmental pollution has received a paramount attention and its monitoring is of prime concern for human welfare. Sensors for detection of hazardous pollutants, ecological VOCs and trace impurities in environment are indispensible for sustainable development of environment and human welfare (Hernandez-Vargas et al., 2018; Jalal et al., 2018). Recently, tremendous efforts have presented a leap-forward in the development of metal oxide nanosensors which are proving efficient materials in the remediation of the environment. Metal oxide nanostructures are peculiar materials which have intrigued the whole scientific community by their novel features. The remarkable features of these tiny structures are assessed for detection and quantification of several hazardous gases, poisonous chemicals and biochemicals in the environment. Metal oxide nanostructures in the form of chemical, gas, biological, optical and humidity sensors have been extensively researched to detect the ecological pollutants and VOCs present in the environment (Das et al., 2015; Z. Li et al., 2019; Solanki et al., 2011).

Till now, several sensing techniques have been developed, but due to their high cost, insensitivity and time-consuming nature, those techniques are unsuitable for environmental pollutant detection. Therefore, a facile and low-cost method of environmental remediation was based on fabrication of metal oxide (MO) nano-sensors. MO nano-sensors are easy to prepare, economical and efficient in function and operation. Although, metal oxide nanostructures exhibit excellent sensing properties, but the sensitivity and selectivity has always been a question of debate. To improve the stability, sensitivity and response time of these MO nanosensors, they are combined with other organic counterparts to form a nanocomposite which not only improves stability but also exhibit synergistic effect for desirable sensing application (Ganie et al., 2021; Shang et al., 2019). From recent past, several efforts have been devoted to manufacture MO nanocomposites with graphene (RGO-MO) for highly effective, sensitive and selective sensing performance. Graphene, due its fascinating properties are deal material for trace quantity detection (Wang et al., 2016). The sensing property of metal oxide decorated carbon materials are due to intriguing structural features which could provide large number of active sites on the surface, enhance the surface interaction of nanosensor with the target gas and thereby increases the sensing performance of the nanomaterial.

Metal oxide gas sensors have been introduced in 1960s; When Seiyama et al., (1962) reported the operation of gas sensors on basis of chemical interaction or resistance changes of the MOS layer and the analyte gas molecule. Since then, several MO nano architectures in form of nanotubes, nanofibers, nanoflowers, nanorods, nanospheres, nanosheets, nanowires and nanodots have been fabricated for gas sensor application. Cretu et al., (2016) developed hydrogen gas sensor based on zinc doped copper oxide nanomaterials which exhibited excellent sensor response with faster response time and good sensitivity. Sankar ganesh et al., (2017) investigated the effect of Al doping into the ZnO matrix for detection of ammonia and found that Al doped ZnO turns out to be suitable sensor for the quantification of trace amount of ammonia. It was also pointed out that activity of the fabricated sensor was improved due to catalytic effect which henceforth, demonstrated a strong link between gas sensing and heterogeneous catalysis. Han et al., (2016) reported the fabrication of NO_2 sensor using synergistic effects of ZnO/PMMA and CuPc/pentacene heterojunctions. The fabricated OFET sensors showed good sensitivity and lower detection limit. This study demonstrates that the synergistic effect of dielectrics and organic semiconductors can be utilized to develop reliable and accurate gas sensors. Li et al., (2017) synthesized formaldehyde sensor by using facile hydrothermal method. The formaldehyde sensor based on SnO_2 microspheres showed high sensitivity, good stability and response recovery at 200^{o}C temperature.

Chemiresistive gas sensors based on MO nanostructures have been remarkably used for detection of volatile organic compounds (VOCs). The VOCs are widely used in industries and household products, causing deleterious effects on human health even in ppm concentrations. The detection of VOCs such as acetone, methanol, NH_3, HCHO, benzene and toluene is necessary due to their long-term health effects (Moseley, 2017). Chemiresistive gas sensors represent a major class of gas sensors, whose electrical resistance changes on exposure to target analyte (either oxidising or reducing) and showed fast response and recovery times towards several VOCs (methanol, toluene, acetone, propanol etc.). Joseph et al., (2004) reported the crosslinking of gold and platinum nanoparticles with nonanedithiol which showed CO and NH_3 detection up to 500 ppm concentration. Feng et al., (2019) developed a methanol sensor based on NiO fibres which can detect methanol up to 500 ppm level. The sensor possesses high selectivity, high response time and operates at room temperature. The sensing performance of VOCs can be explained on basis of ionosorption model. When a metal oxide nanostructure is exposed to air, oxygen molecules are adsorbed on surface of metal oxide. The adsorption of oxygen molecules is facilitated by cationic vacancies on metal oxide.

$$O_{2\,(g)} + 2\,e^- \longrightarrow 2\,O^-_{(ads)} + 2\,h^+ \qquad (1)$$

After that, when metal oxide nano-sensor is exposed to target analyte (e.g., methanol), the methanol molecules react with ionosorbed oxygen species, to produce electrons. These electrons are returned to metal oxide, thus increasing the resistance of sensor. Thus, the operation of metal oxide nano-sensor is based on resistance change upon exposure to target analyte.

$$CH_3OH + 3\,O^- \longrightarrow CO_2 + 2\,H_2O + 3e^- \qquad (2)$$

Another recently developed cost effective and facile gas sensor based on cellulose fibres present within paper by exploiting intrinsic hygroscopic properties of cellulose fibres. Cellulose fibres within paper inherently contains substantial amount of moisture enabling the use of wet chemical method for sensing without manually adding water to the substrate. The sensor exhibits high sensitivity to water soluble gases with fast and reversible response. The sensor shows comparable or better performance than most commercial ammonia sensors. This sensor can be integrated into food packaging's to monitor freshness and to reduce food waste or can be implemented into near field communication to tag functions as wireless, battery-less gas sensors that can be interrogated with smartphones. Moreover, this sensor has specifically shown higher sensitivity, lower detection limits and rapid response time for ammonia detection as it is highly soluble with high humidity, RH> 60% (Chiu et al., 2019).

3.1. Electrochemical Sensors for detection of refractory organics

Contamination of soil and water bodies by uncontrolled disposal of solid and liquid waste drawn from innumerable sources like waste-water discharges from oil field, different types of industrial waste from chemical, textiles, petrochemical, food and beverages industries and hospital discharges have shown negative impact on the present ecosystem. These wastes largely contain inorganic pollutants like excessive discharges of metal ions and organic pollutants like phenol, benzene, alkanes, polycyclic aromatic hydrocarbons (PAHs) and many more pollutants. The constituent analysis, quantification, detection and determination play a pivotal role in assessing and close monitoring of the toxic elements and are of prime importance as they supposedly causes severe ailments and diseases resulting in damaging of lungs, kidneys, liver, thus interfering body metabolism.

In order to determine and detect these toxic pollutants, various techniques like HPLC, AAS, FID, liquid chromatography, colorimetry, isotopic-dilution mass spectrometry, chemiluminescence, and devices based on varieties of electro-analytical techniques mainly potentiometry, differential pulse voltammetry have been used so far. However, eelectrochemical techniques are very efficient for real time detection of pollutants as well as for addressing serious environmental problems (Jang et al., 2018). The application of electrochemical/chemical sensor is based on the deduction of chemical composition of surrounding environment, giving reliable information about the environmental health. The main feature of the electrochemical sensors is quick and reversible response without the perturbation of sample. Chemical sensors based on nanostructured semiconductor materials for the detection of refractory organics, such as nitrophenol, hydrazine and phenyl hydrazine, have been recognized as a very promising approach, which has attracted intensive attention from both academic and industrial fields in the past few years. These electrochemical techniques have several advantages over other method because of their remarkable sensitivity, portability and lower cost. Electrochemical sensors fall into various categories like voltammetric, potentiometric and amperometric sensors. Besides these kinds of sensors, SWASV (Square wave anodic stripping voltammetry), DPASV (Differential pulse anodic stripping voltammetry) techniques are very fast, highly reliable, most accurate and highly sensitive. These evolved techniques are important for analysing real samples for real time detection (Veerakumar et al., 2015).

3.2. Detection of various solvents and toxic organic pollutants

The detection of various toxic solvents, drugs or other interfering materials are most easily done by using various modes of electrochemical techniques like cyclic voltammetry, amperometry, linear sweep voltammetry and differential pulse voltammetry. These techniques are most widely exploited for the detection of toxic solvents in the environment, biosensing of glucose, dopamine, and ascorbic acid along with many drugs like acetophenone, aspirin, ciprofloxacin, sulfamaxole etc. These techniques proved to be highly sensitive and reliable by utilising varieties of modified nanoparticles and nanocomposites ranging from metal oxides to different carbon nanomaterial including graphene oxide, carbon nanotubes, activated carbon platforms and conducting polymers like (PANI, Ppy, PTh). The nanocomposites based electrochemical sensors have shown excellent stability, high specific surface area, high conductivity, high thermal stability, and increased electron conductivity and has been extensively investigated for the detection and quantification of various hazardous and toxic solvents from the environment (Sayfa et al., 2019). Considering the ideal parameters into view, various metallic, bimetallic, conducting polymers based or derived nanocomposites have been investigated and utilised as chemical sensors. The detection of the target analyte depends on many factors like electro-activity of the composite catalyst, types of electrode, electrolytic solution and working conditions (temperature, concentration and pH). Varieties of nanocomposites have been synthesized for obtaining the best suitable electrocatalyst in order to analyse and detect the toxic contaminants. Qin et al., (2014) has reported zircon-based carbon paste electrode as amperometric sensor for determination of phenol using phosphate buffer as electrolyte. The fabricated sensor was found to show efficient electroanalytic response towards detection of phenol with 9 μM LOD at an S/N ratio of 3. Another group of researchers has developed hybrid materials based on single walled carbon nanotubes (SWCNT) and poly (3,4-ethylenedioxythiophene). The screen-printed electrodes (SPE) has been modified using these nanocomposites and has been utilized for simultaneous determination of phenol and chlorophenol derivatives. The modified SPE has shown better response than enzymatic and non-enzymatic sensor with much wider and dynamic linear range of detection. It can most widely be used as disposable electrochemical sensor for determination of trace level of pollutants and toxic compounds in environment and biological real samples. Rehman et al., (2011) reported the hydrothermal fabrication of CuO co-doped ZnO nanostructured material for detection of ammonia sensing as target analyte using silver electrodes. The developed electrodes displayed good sensitivity, stability, and reproducibility with corresponding detection limits of 8.9 μM with short response time. Another group of researchers fabricated ZnO nanosheets based screen printed electrodes by electrodeposition method and studied the electrochemical responses for the detection of phenol and o-cresol by using cyclic voltammetry and linear sweep voltammetry. The fabricated sensor has shown better electro-catalytic oxidation of phenol and o-cresol in real wastewater sample. Moreover, the sensor has shown 4.1nM and 5.5nM detection limits for phenol and o-cresol respectively, for wide linear range of 0.01μM to 50 μM (Liu et al., 2016). Nithya, (2015) has reported the determination of ascorbic acid using zinc decorated graphene oxide based on glassy carbon electrode using differential pulse voltammetry. The nanocomposites have shown high surface area with efficient electrocatalytic response in the wide linear range (1 μM to 1000 μM) having sensitivity and detection limit of 0.178 $\mu A/\mu M/cm^2$ and 0.01 μM respectively. In this study the comparison of colorimetry and voltammetry has also been shown, indicating that voltammetric sensors produce more reproducible results. Since early development on glucose detection was based on enzymatic biosensor which certainly suffers from various operating drawbacks. In order to overcome these limitations, various nanostructured materials (non-enzymatic chemical sensor) have been used as glucose sensors (Al-mokaram et al., 2017). Recent studies have been focussed on developing peptide-based hybrid compounds using metallic electrode materials mainly gold, as biosensors. Bianchi et al., (2014) has reported peptide based non- enzymatic biosensor for estimating ammonia and urea oxidation by using peptide microstructure onto the thiolate gold electrodes. The developed assemblies possess different functional group which considerably interacts with target species via cationic-Π-receptors and hydrogen bonding. The biosensor under optimal conditions has shown excellent catalytic response for both ammonia and urea within concentration range of 0.1 mM to 1 mM. The calculated sensitivity was found to be 2.83 and 81.3$\mu A/mM/cm^2$ for ammonia and urea respectively at applied potential of +0.4 V vs SCE suggesting it as a highly sensitive sensor capable of detecting ammonia even below physiological levels of 1-100 mM.

3.3. Early discrimination of heavy metal ions

Among the various techniques used for heavy metal ions detection, the most effective and facile among them are colorimetry and cyclic voltammetry. Both techniques offer simple and facile procedure for the determination of metal ions and various pharmaceutical products. Colorimetry uses masking agent like EDTA, glutathione, and imidazole for simultaneous determination of metal ions. Zhang et al., (2012) has developed peptide modified gold nanoparticles(P-AuNPs) for determination and quantification of metal ions like Cd^{2+}, Ni^{2+} and Co^{2+} in wastewater samples The tests were carried out by monitoring the change in colouration of the probe upon mixing with metal ions solution. The method shows relatively good selectivity for Cd^{2+}, Ni^{2+} and Co^{2+} over other metal ions. Cd^{2+} shows the most obvious colour change over Ni^{2+} and Co^{2+} while using EDTA (masking Co^{2+}), glutathione (masking Cd^{2+}), and imidazole (masking Ni^{2+}) as masking agents. This novel gold (P-AuNPs) based probe offers several advantages like simplicity of preparation and rapid detection of heavy metal ions with high sensitivity. Different gold nanoparticles are investigated in colorimetric determination due to their colour change attributing properties. Gold nanoparticles modified with multifunctional graphene prepared by one pot redox reaction have been investigated for colorimetric determination of Hg^{2+} in water samples, exhibiting detection limits up to 0.16 nM (Yan et al., 2014). Mehta et al., (2013) has demonstrated the real water sample analysis for detection of copper (Cu^{2+}) ions using dopamine dithiocarbamate-functionalized gold nanoparticles. The decorated gold nanoparticles exhibit characteristic colour change with lower detection limit of 14.9 µM and linear range of 1-10 mM. Since, metal ions are most harmful toxics pollutants present in water and soil bodies, but on the other hand, these metal ions are essential for normal functioning of human body. However, the presence of metal ions beyond threshold level can cause severe health problems which can have significant negative impact on human welfare (Li et al., 2018).

Z. Guo et al., (2017) has reported the utilisation of DPASV technique for determination of Cd, Cu, and Pb using chitosan-poly-L-lysine nanocomposites modified glassy carbon electrode (GCE). The detection limits for Cd, Cu, and Pb were found to be 0.01 µg /L, 0.02

μg/L and 0.02 μg/L respectively. Veerakumar et al., (2016) has analysed the electrochemical detection of Cd, Pb, Cu, and Hg using palladium nanoparticles supported on porous activated carbon. The porous activated carbon nanoparticles were synthesized by green synthesis from biomass feedstock. The Pd/PAC modified GCE exhibit excellent results for simultaneous determination of metal ions with wide linear range of concentration, high sensitivity and low detection limits. Another group has investigated the Ce-Zr oxide nanospheres for electrochemical determination of Hg, Cd, Cu and Zn by using SWASV technique. The efficient redox behaviour of nanospheres has resulted in the quantification of metal ions with lower LOD and sensitivity of 0.006 μM and 1662.02 μM/cm^2 respectively (Li et al., 2018). Ni nanoparticles decorated on activated carbons have been used for electrochemical detection of Hg ions by using GCE as working in the cyclic voltammetric experiment. The fabricated sensor has shown selective and sensitive detection of metal ions with detection limits up to 10 nM (Veerakumar et al., 2015).

Moreover, the versatile applications of MOF in different sensing application have opened a new gateway in electrochemical detection by increasing the electrocatalytic activity of the developed nanoparticles by substantial amount. Zhao et al., (2019) reported a modified MOF by using a conducting polymer (PANI) as self-doped polyaniline (SPAN) modified metal organic framework (SPAN@UIO-66-NH_2). The developed materials have shown excellent electrical conductivity with rapid electron transfer rate for detection of Cd^{2+} by using SWASV technique. The MOF based electrochemical sensor has shown faster response time with corresponding detection limit of 0.17ug/L in real sample analysis. This suggests the utilisation of fabricated MOF based electrochemical sensor in real water sample analysis and urine samples for detection of cadmium ions. Another group developed a MOF based on zeolite materials and examined it for detection of Pb (II) ions using DPASV techniques. The electrocatalyst has shown synergistic features of MOFs and zeolites such as high surface area, crystallinity, better thermal and chemical stability and highly ordered structure. The combined properties of both have led to the development of efficient electrochemical sensor for selective detection of lead ions in aqueous solution. Moreover, the electrochemical response of the sensor shows lower detection limit of Pb ions (4.12-12.50 ppb) with optimized reaction parameters and wide linear range from 12 ppb to 100 ppb (Khieu et al., 2018).

Other toxic metal ions like Cd, As, Pd, Co, Ag, Zn, Cr and Ni are also being monitored in the environment by using newly developed techniques. Zhou et al., (2016) has reported DNA based MoS_2/Au hybrid FET sensor for ultrasensitive detection of Hg ions in aqueous solution. The sensor performance was investigated using specific DNA as the capture probe for the label free detection by monitoring the electrical characteristics of FET device. This sensor shows a rapid response to Hg ions with ultra-low detection limits of 0.1nM, which was found to be lower than maximum limits for Hg ions in drinking water (9.9 nM) as recommended by USEPA, along with high sensitivity to Hg ions as compared with other ions like As, Cd, and Pb. The applications of several electrochemical techniques in the detection of trace amounts of pollutants in the environment have been reviewed and are shown in **Table 2**.

Table. 2. Application of various nanomaterial based electrochemical sensors in detection and quantification of Hazardous pollutants.

Nanostructured materials	Electrochemical techniques	Target analyte	Limit of detection (µM)	Concentration linear range (µM)	Sensitivity ($\mu A/\mu M/cm^2$)	References
Ni(II)-based metal–organic frameworks	Square wave anodic stripping voltammetry	Pb^{2+}	0.508	0.5-6.0	-	(Guo et al., 2017)

Graphene Oxide/Cobalt Oxide Nanocomposite	Amperometry	Insulin	0.12×10^{-9}	0.00046 to 0.1	686.6	(Razmi et al., 2019)
γ-Fe_2O_3 nanoflower	Stripping voltammetry	Pb^{2+}	-	0.0001 to 0.001	0.19782	(S. Li et al., 2016)
Acetyl-cholinesterase biosensor based on gold NPs	Amperometry	Paraoxon	0.0007	0.005 to 1.0	-	(Lang et al., 2016)
		Dimethoate	0.0039	0.005 to 1.0	-	
3D Copper Foam-Supported $CuCo_2O_4$ Nanosheet	Amperometry	Glucose	1000	0 to 1000	2.09×10^3	(Liu et al., 2018)
Au–Pt alloy nanocatalysts	Amperometry	Methanol	100	1000–11000	43	(Guo et al., 2014)
CuO-NPs/3DGR	Differential Pulse Voltammetry	Malathion	1×10^{-5}	3×10^{-5}– 0.0015	-	(Xie et al., 2018)
Core–Shell CeO_2 nanoparticles@Cross-linked PANI	Gas sensor	NH_3 gas sensor	-	6.5 to 50 ppm	-	(Wang et al., 2014)

1

4. Nanoadsorbents and Nanocatalysts for wastewater and soil remediation: Added benefits and challenge for nanoremediation

4.1. Water, groundwater and wastewater treatment and remediation

With the advancement in horticultural, agricultural, industrial and urban activities, the quality of ground water is deteriorated and the level of pollution is increasing day by day (Belal and El-Ramady, 2016). The seepage of numerous inorganic and organic pollutants above their permissible limits into the groundwater has deleterious effects on its quality, standard and composition. Nowadays natural water bodies have been used as dumping sites which has reduced the quality of ground water. Excessive use of fertilisers, pesticides and weedicides has posed a serious threat to the quality and composition of ground water (Andreozzi et al., 1999; Sharma and Bhattacharya, 2017). Furthermore, water has been enriched by most harmful chemicals such as organochlorines, organophosphorus, heavy metals, and various carcinogenic agents. Prolonged persistence of organic chemicals in water has resulted in bioaccumulation of these pollutants which has severe and hazardous effects on human beings. It has been reported that lindane (hexachlorocyclohexane), an organopesticide has bio-accumulated into the human food chain disturbing the normal functioning of endocrine system and causing cancer in humans (Jayaraj et al., 2016). Cultural Eutrophication of water bodies has become a serious problem and has shown a range of devastating effects. One major effect is algal bloom, which can deplete dissolved oxygen content of the water bodies, affecting marine life as shown in **Figure 6**. Cultural eutrophication is not only detrimental to marine life but it can affect the terrestrial life as well due to the harmful toxins released by algae such as anatoxin-a, domoic acid, brevotoxin, saxitoxin, microcystin, geosmin (Paerl et al., 2018).

Nanoremediation as compared to other remediation techniques proved to be an efficient technique for groundwater decontamination. Nanoremediation has been applied for the remediation of variety of contaminants present in water such as chlorinated compounds, heavy metals, hydrocarbons or organic compounds, pesticides and inorganic ions (X. Liu et al., 2019; Y. Liu et al., 2019; Rajan, 2011; Teow and Mohammad, 2019; Zhang and Liu, 2020). The application of *in situ* nanoremediation in Water, groundwater and wastewater treatment relies on the use of nanoadsorbents, membrane systems based on nanocomposites and nanocatalysts. The efficient adsorption properties and excellent membrane permeability of nanomaterials allows rapid waste-water treatment and complete removal of organic pollutants, heavy metals and antibiotic-resistance bacteria. Photocatalytic nanomaterials can play a potential role in degrading harmful algal blooms in water hence maintain the natural quality of water.

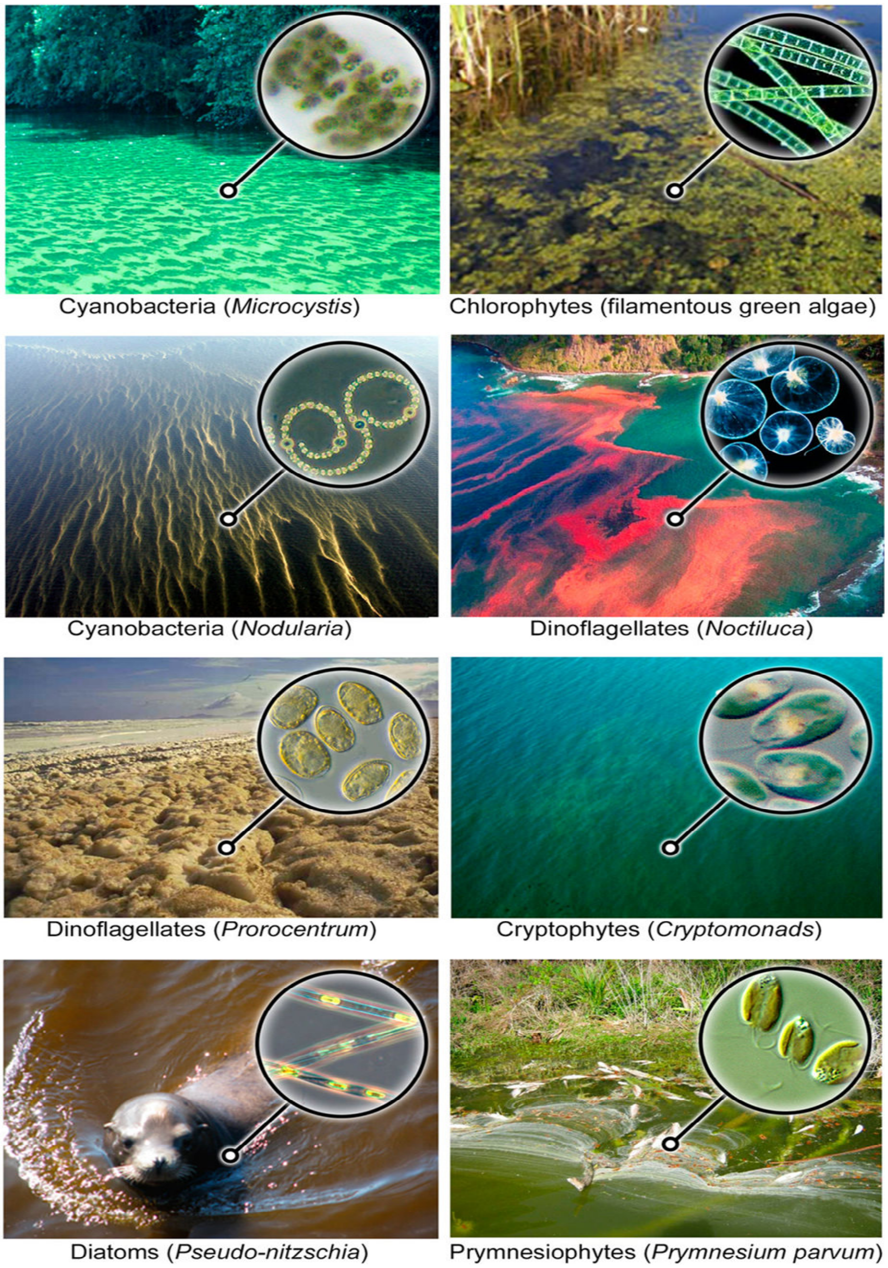

Figure 6. Harmful bloom formation depicting cultural eutrophication of water along the fresh water to marine continuum, Reproduced from **(**Paerl et al., 2018)

It has been reported that Ni doped $BiVO_4$ nanocomposite can cause the inactivation of algae under visible light irradiation and retard the formation and proliferation of algal bloom (Regmi et al., 2017b). Co-doped $BiVO_4$ have been utilized for the effective degradation of malachite green and has also shown efficient activity towards inactivation of green tides caused by the prelevance of *Escherichia coli* and *chlamydomonas pulsatilla* in wastewater (Regmi et al., 2017a). Moreover, the efficiency of Ag-TiO_2 and MoS_2/Bi_2WO_6 heterostructures has been studied for the elimination of blooms and detoxification of pollutants in wastewater. The application of integrated nano-biotechnique by utilising Pd/Fe^0 bimetallic nanoparticle in complete degradation of recalcitrant environmental pollutant lindane (hexachlorocyclohexane) has also been reported in literature (Regmi et al., 2018a).

The usefulness of photocatalysis in disintegration of harmful recalcitrant micro-organisms (bacteria, virus, fungi and protozoa) can be explained on basis of generation of highly reactive radicals which can degrade these micro pollutants present in water. Several mechanistic pathways for the inactivation and degradation of pollutants in water have been reported in literature. The main step in all the pathways involves the reduction of molecular oxygen (O_2) by the nanomaterials, thereby generating reactive oxygen species (ROS), which induce a type of stress in the normal functioning of the cell as shown in **Figure 7**. The cell integrity and hence the metabolism of the cell got disrupted by oxidative damage of its components which ultimately leads to inactivation or sometimes death of cell (Regmi et al., 2018b).

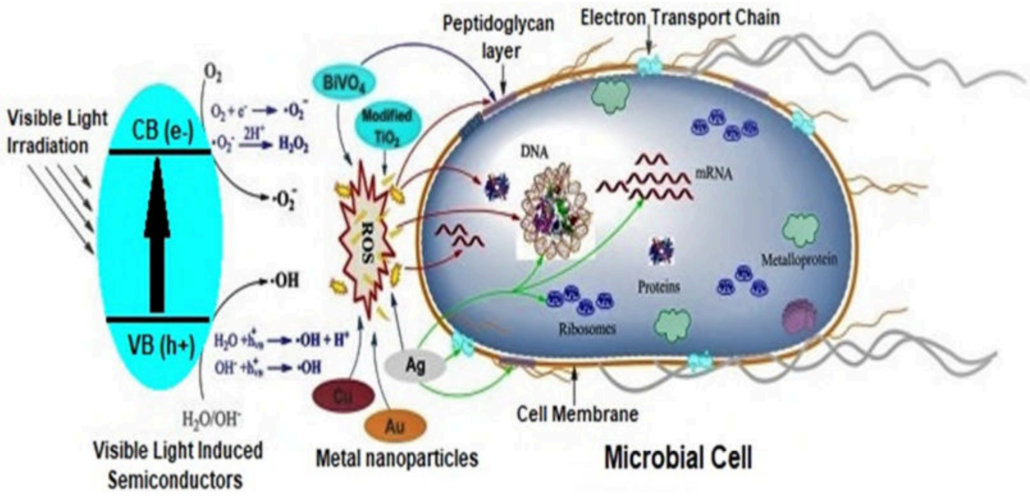

Figure 7. Pictorial mechanism of bacterial inactivation by nanomaterials to remediate wastewater, ROS generation and subsequent degradation of peptidoglycan layer of the microbial cell have been labelled, Reproduced with permission from (Regmi et al., 2018b)

The application of nano zero valent iron (nZVI) and carbon nanotubes in environment clean-up such as decontamination of groundwater, removal of organochlorines, heavy metals such as arsenic and chromium, pesticides (DDT, Lindane) and inorganic anions has shown remarkable and promising future (Lu et al., 2016). The key features favouring nZVI and carbon nanotubes include low standard reduction potential, high mobility, high reactivity and flexibility. In contaminated water, nZVI are supposed to change from Fe^0 to Fe^{2+} and then further oxidative transformation to Fe^{3+}, thereby reduce inorganic and organic pollutants readily (Bonaiti et al., 2017).

Carbon nanotubes are considered as efficient adsorbents because of their potential adsorption properties and ability to attach a variety of functional groups. Several researchers have investigated the adsorption behaviour of SWCNT and MWCNT for transforming organics eluted in wastewater and activated sludge (Gupta et al., 2015). Carbon nanotubes are utilized for the removal of heavy metals, harmful chemical compounds, inorganic wastes and volatile organic compounds. The adsorption activity of the carbon nanotubes can be further modified by surface modification techniques such as metal ions grafting, acid treatment and surface impregnation with reactive moieties (Anjum et al., 2019). The modified carbon nanotubes with metal oxides like MnO_2, Al_2O_3 and Fe_2O_3 shows promising and efficient results for pollutant degradation and heavy metals removal from the wastewater (Khajeh et al., 2013).

The vast structural diversity of carbon-based materials combined with large surface area and hollow layered structure and high adsorption capacity has made them promising materials for wastewater decontamination (Smith and Rodrigues, 2015). Carbon based nanomaterials are efficiently used as nanoadsorbents for removal of different liquid or gaseous pollutants and have been the focus of contemporary research due to their peculiar mechanical and excellent electronic properties. Moreover, Carbon nanotubes can adsorb and simultaneously detoxify both organic as well as inorganic pollutants (Baby et al., 2019). From the recent past chitosan-based nanomaterials have received considerable attention in wastewater treatment because of their efficient functionality in adsorption of heavy metals, dyes and other water born pollutants. Among other carbon based materials, Graphene oxide and activated carbon has been the better candidates for water treatment owing to their high adsorption capability, better compatibility and excellent selectivity for a range of pollutants (Wu et al., 2019).

Various wastewater treatment methods have been described in literature, among them adsorption and photocatalytic degradation are most facile techniques which are preferred over other methods because of their cost-effectiveness and environmental friendly approach (Grassi et al., 2012; Suri et al., 1999). In adsorption process, kinetic studies are important to deduce the amount of pollutants adsorbed on the surface of nanomaterials. Several kinetic models have been explained for adsorption mechanisms, but the most used are pseudo-first order and second order kinetic models (Babel and Agustiono Kurniawan, 2003).

The amount of pollutant which can be adsorbed on the surface of nanoadsorbent at equilibrium (Q_e) is calculated using Equation 3.

$$Q_e = (C_0 - C_e) V/m \quad (3)$$

Where C_0 and C_e are the starting and equilibrium concentrations of the pollutant respectively, Vis the volume of solution and m is the mass of nanoadsorbent.

Apart from organic pollutants, the persistence of lead, copper and arsenic in the water bodies above their permissible limits poses serious consequences to the human health. Researchers have developed many functionalized nanomaterials which can efficiently adsorb toxic metals through their reactive groups on the surface. It has been reported that ultrafine magnesium ferrite ($Mg_{0.27}Fe_{2.50}O_4$) nanocrystallites can adsorb both As(III) and As(V) with efficient removal capacities (Tang et al., 2013). The nanocrystallites show supermagnetic behaviour and high surface area (482 m^2/g) with the adsorption capacities of 127.4 mg/g and 83.2 mg/g for As(III) and As(V) respectively. Another group of researchers developed core-shell structure of Fe-Ti bimetallic oxide on magnetic Fe_3O_4 and was used as nanoadsorbent for fluoride removal from drinking and wastewater (Zhang et al., 2014). The nanoadsorbent shows high adsorption capacity and super magnetic behaviour. The adsorption studies were investigated by Langmuir adsorption isotherm and adsorption capacity of 57.22 mg/g was found for fluoride removal. The separation of adsorbent in both cases can be done by magnetic methods and the adsorbents can be again used for removing the pollutants. Furthermore, the Cu(II) removal was carried out by cyclodextrin modified Fe_3O_4 via strong adsorption capacities of hydroxyl and carboxyl moieties on the carboxymethyl-β-cyclodextrin (Badruddoza et al., 2011). The adsorption kinetics follows the second-order kinetics and was dependent on pH and temperature. The adsorption data was fitted with Langmuir model and the adsorption capacity of Cu (II) removal was found to be 47.3 mg/g. It has been also reported that nanoadsorbents shows good recyclability with 96.2% desorption efficiency. The pollutant adsorption and simultaneous removal capabilities of several nanomaterials have been reviewed and are depicted in **Table 3.**

Table 3. Pollutant removal capacity of various nanoadsorbents by surface adsorption

Nanoadsorbents	Pollutant Adsorbed	Removal Efficiency (mg g^{-1})	References
Pristine SWCNTs	Basic Red 46	38.35	(Moradi, 2013)
Untreated SWCNTs	Reactive Red 120	426.67	(Cardoso et al., 2012)
Alkali activated MWCNTs	Methylene Blue	399.0	(Ma et al., 2012)
Untreated MWCNTs	Acid Red 18	166.73	(Shirmardi et al., n.d.)
Hydrotalcite-based nanocompounds	Remazol Red 3BS	134.40	(Asouhidou et al., 2012)
Functionalized hexagonal mesoporous silica	Remazol Red 3BS	250.0	(Asouhidou et al., 2009)
Graphite oxide/magnetic chitosan	Reactive Black 5	391.0	(Travlou et al., 2013)
Fe/Mn oxy-hydroxide (δ-$Fe_{0.76}Mn_{0.24}OOH$)	As(III)	0.0067	(Tresintsi et al., 2013)
Magnesium ferrite ($Mg_{0.27}Fe_{2.50}O_4$) nanocrystallites	As(V)	83.20	(Tang et al., 2013)
Anatase nanoadsorbent	As(III)	16.98	(Özlem Kocabaş-Atakli and Yürüm, 2013)
Mercapto-functionalized nano-Fe_3O_4 magnetic polymers	Hg(II)	140.0	(Pan et al., 2012)
Ferrite coated apatite magnetic nanomaterial	Eu(III)	157.14	(Moussa et al., 2013)
Carboxymethyl-β-cyclodextrin Fe_3O_4 nanoparticles	Cu(II)	47.20	(Badruddoza et al., 2011)
Fe_3O_4@COF(TpPa-1)	Cr(VI)	245.45	(Zhong et al., 2020)

4.2. Contaminated soil management: *In-situ* remediation and risk benefit assessment

Soil pollution is a major global concern; the quality of the soil has degraded since the onset of industrialisation and advancement in agricultural techniques. Organic pollutants like pesticides, herbicides and polycyclic aromatic hydrocarbons (PAC) and inorganic contaminants like metals (Cadmium, Cd; Copper, Cu; Lead, Pb; Zinc, Zn; Mercury, Hg) and metalloid (Arsenic, As; Antimony, Sb) are the most common forms of soil pollutants added from various sources like military action, mining, road transport and other agricultural, industrial and domestic sources (Pan and Xing, 2012; Pulimi and Subramanian, 2016). These organic contaminants together with inorganic ions do not get chemically or biologically degraded and accumulate in the soil over years inducing adverse effects (Baragano et al., 2020). The deleterious effects of these contaminants can be studied by evaluating their mobility and bioavailability. Bioavailability stands for the fraction of the total chemical load that is available to be transferred to the living organisms. Thus, to reduce their toxicity it is necessary to reduce their availability to the plants and other life forms. Immobilization is one such technique that can effectively reduce the metalloid toxicity in the soil by reducing the amount of mobile and bioavailable fraction of these contaminants by addition of a potential agent to the soil through adsorption, ion exchange or precipitation (Zhong et al., 2021; X. Gong et al., 2018; Y. Gong et al., 2018; Medina-Pérez et al., 2019). Nanoremediation has the potential to reduce the toxicity of soil contaminants by: immobilisation of soil pollutants (Pb, Cr, As, Cd), conversion of more toxic heavy metals, Cr (IV) to less toxic forms, Cr (II) and degradation of organic pollutants like chlorinated organics, DDT, pesticides and herbicides, as illustrated in **Figure 8**.

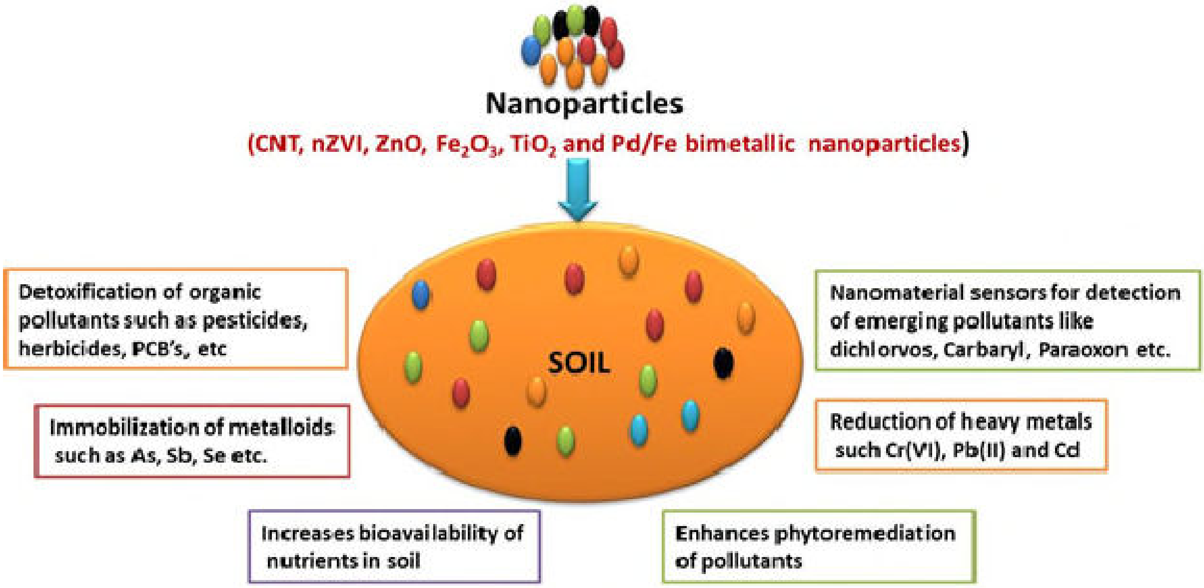

Figure 8. Illustration of pollutant remediation, nutrient biavalaibilty, matallic immoblization in soil using nanomaterials

In the past few decades, the role of nanoparticles as potential soil remediating agents has gained intensive attention across globe owing to their characteristic properties like high surface area, high reactivity and economic viability (Shafi et al., 2020b, Gomez-Sagasti et al., 2019). A wide variety of nanomaterials have been explored over the years for soil remediation such as metal oxides, organic compounds, metal organic frameworks and the recently added and most extensively recognised nanoscale zero-valent iron (nZVI). nZVI has been widely explored to treat organic as well as metalloid soil pollutants. nZVI is composed of a core of Fe^0 surrounded by a shell of oxides and hydroxides. It is a good electron donor with high reactivity, excellent adsorption capacity and high surface area. nZVI can be employed for the treatment of organic as well as single and multi-metalloid contaminants (Karn et al., 2009; Xue et al., 2018).

4.2.1. Immobilization of single metalloid contaminants

Single metalloid contamination can be effectively treated with the help of immobilising agents. Soil contaminated with elements like As, Cd, Se are severely affecting human health if exposed beyond acceptable limit. Selenium, an essential trace element has been widely detected in soil both naturally and through anthropogenic activities. Excessive intake of Se can be hazardous to humans and animals with its bioaccumulation being lethal to fishes and birds. It exists in more toxic Se (IV) and less toxic Se (VI) form with its mobility and transport being redox dependent. Its comparative in-situ immobilization with the help of nanosized Fe-Mn binary oxide stabilised with starch or carboxymethyl cellulose (CMC) was studied and starch stabilised Fe-Mn nanoparticles showed greater Se (IV) adsorption capacity. It was further observed that >90% of the leachable Se (IV) treated with nanoparticles was immobilised and retained in the soil matrix (Gong et al., 2018). In another study performed by Xu et al., (2016), Cd contaminated soil was comparatively treated with three types of iron phosphate nanoparticles: $Fe_3(PO_4)_2$, $FeHPO_4$ and $Fe(H_2PO_4)_2$. The study revealed that all the three nanoparticles treat Cd effectively, however Cd immobilization was best observed for $Fe_3(PO_4)_2$. The study further suggested the formation of cadmium phosphate to be the main reason for diminished bioavailability of Cd in soil. In another study, Cd contamination was further treated with the help of biochar supported $Fe_3(PO_4)_2$ nanoparticles. After 28 days of experiment the Cd immobilization efficiency was found to be 81% while the bioavailability decreased by 80% (Qiao et al., 2017). Nanoremediation of Cr-contaminated soil has been performed with the help of biochar supported nZVI with the immobilization efficiency of 100% for Cr (VI). Further, a significant decrease in phytotoxicity of Cr (VI) has been observed with enhanced growth of cabbage mustard after the treatment (Su et al., 2016). In another study performed by M. Gil-Díaz et al., (2016), Arsenic, a highly toxic, carcinogenic priority pollutant metalloid was immobilized and the barley plant was cultivated on the treated soil. It was reported that the dose of 10% of nZVI as compared to 1% dose effectively immobilized the As. Further, the treatment did not affect the available iron concentration and physico-chemical and biological properties of the soil.

4.2.2. Decontamination of multi metalloid contaminants

The remediation of soil contaminated with multi metalloids is even more complex as the presence of different ions has a retarding or synergetic effect on the immobilization of mixed contaminants. Shipley et al., (2011) demonstrated the application of hematite (an iron oxide) to potentially remove a variety of metal contaminants from soil like As, Cd, V, Tl, Pb, Mn, Th, Se and U. Phosphate compounds also present a potential option for immobilising the heavy metal pollutants in the soil. The possibility of hydroxyapatite in immobilizing the Cu and Zn was investigated by Sun et al. in the presence of ryegrass plant. The results depicted a significantly retarded bioavailability of Cu and Zn to ryegrass plant after the treatment emphasising the effectiveness of hydroxyapatite as an immobilisation material (Sun et al., 2016). The metalloids bioavailability in the soil depends on various factors like pH, type of soil, type of ions and environmental factors. The presence of multiple ions in the soil can also affect their immobilization. M Gil-Díaz et al., (2016) compared the immobilisation of single and multi-metalloid (As, Pb, Cu, Cd, Zn) contaminated soil with nZVI and reported effective immobilisation of all metals for single contaminated soil except Cd. Alternatively, for multi metalloid polluted soil, the immobilization was affected by the co-presence of different ions with best immobilization results for As and Cr in acidic soil while for Pb, Zn and Cd the immobilization was significant in calcareous soil depicting that the immobilisation was soil, ions dependent. In a recent study, metal oxide nanoparticles (Al_2O_3, TiO_2 and SiO_2) were explored and employed for the remediation of multi-metal (Cd, Ni, Zn) contaminated calcareous and non-calcareous soils. The study revealed SiO_2 as a potential immobilizing agent for the three metal tested contaminants in calcareous soil while in non-calcareous soil, Zn and Cd immobilization was highest for Al_2O_3 nanoparticles (Peikam and Jalali, 2018). Moharem et al., (2019) further studies the treatment of calcareous soil polluted with Cr and Hg using water treatment residual (drinking water industries by-product) nanoparticles and observed a strong sorption capacity of the nanoparticle for Cr and Hg with their residual fraction reaching up to 90 and 94%. Mining sites are one of the most heavily metalloid contaminated sites where the soil displays severe physico-chemical and biological limitations like limited organic matter and nutrient content with high concentration of toxic elements making the soil unfit for plant and microbial growth. One such mine site, Iberian Pyrite Belt, was explored for the potential remediation and immobilization of As, Pb and Sb elements with the help of three different nanoparticles- hydroxyapatite, maghemite and hematite. The results depicted a significant decrease in the ion concentration irrespective of the nanoparticle used. However, hydroxyapatite was found to be most effective in limiting the bioavailability of Pb in the soil as compared to maghemite and hematite while maghemite and hematite were more effective in decreasing Arsenic bioavailability. The Sb bioavailability was observed to be considerably well lowered for all the tested nanoparticles (Arenas-lago et al., 2019).

4.3.3. Remediation of Organic Contaminants

Organic chemicals like PAH, pesticides and other persisting and recalcitrant compounds affect the quality of soil making it toxic and unfit for living organism's survival. These pollutants are added to the soil through various sources like organic wastes, disposal, spillage and leakage of chemicals. As these contaminants pose difficulties in biotreatment and are persistent in nature and tend to enter the food chain via food crops and accumulate, threatening the lives of animals and humans alike, they need to be treated and removed from the soil. Various physical (thermal treatment, air sparging) and chemical (photochemical degradation, electrokinetics), biological and phytoremediation techniques have been employed to treat soil contamination. Recently, nanoparticles because of their impressive capabilities like stability, reactivity, mobility and sorption capacity have attained focus as a soil remediation technique (Kuppusamy et al., 2016; Q. Li et al., 2016). In a study performed by He et al., (2007), Fe-Pd nanoparticles stabilised with sodium carboxymethyl cellulose

(CMC) are applied for the treatment of trichloroehtene contaminated soil and observed 17 times faster treatment efficiency as compared to the unstabilized nanoparticles. The treatment of soil contaminated with of 2, 4-dichlorophenoxyacetic acid (2,4-D) with the combined effect of Fe_3O_4 nanoparticle and indigenous microbial community of soil is investigated by Fang et al., (2012). The results depicted the successful degradation of 2,4-D with a significant decrease in the half-life of 2,4-D as compared to the individual treatment with microbes and nFe_3O_4. In another study performed by Machado et al., (2013) the treatment of ibuprofen contaminated sandy soil was performed with the help of nZVI and observed that he nZVI produced from vine extracts could successfully degrade ibuprofen with the highest degradation efficiency of 62%. Wang et al., (2015) successfully demonstrated the viability of silica nanoparticle supported zwitterionic lipid bilayer in treating benzo-a-pyrene, a hydrophobic polycyclic aromatic hydrocarbon. Decabromodiphenyl ether, a type of polybrominated diphenyl ethers present in soil were treated using biochar supported Fe/Ni bimetallic nanoparticles with the removal efficiency reaching to nearly 88% within 72 h of the treatment. The activity of Fe/Ni bimetallic nanoparticles was found to be an integrated effect of reductive degradation and adsorption. The nanoparticles were also effective in adsorbing and immobilising the bye-product of degradation and Ni released during the treatment (Wu et al., 2016). DDT although banned worldwide persists in the soil and biomagnifies in food chain affecting the living beings and making it crucial to be treated. However, the treatment of DDT has been observed to be lower in soil (El-Temsah et al., 2016). Polybrominated diphenyl ether (PBDE) are a class of e-wastes that heavily contaminate the soil and can be successfully treated by silica immobilised nZVI up to 78% within 120 h of treatment (Xie et al., 2016). Oil transporting pipelines are the major source of oil contamination of fertile soil that greatly affects the soil quality and demands effective treatment. The role of surfactants in solubilising and immobilizing the hydrophobic oil contaminants is an attractive approach. A silica nanoparticle stabilised ethanol-sodium lauryl sulphate surfactant was put to test for the remediation of oil contaminated soil and observed the removal efficiency to be nearly 95% for hydrophobic silica stabilised surfactant as compared to only 75% for hydrophilic silica stabilised surfactant which was suggested to be the result of higher stabilisation of surfactant foam with hydrophobic silica nanoparticles (Chattopadhyay and Karthick, 2017). One of the critical issues with nZVI is its limited mobility which hampers its efficiency in soil remediation. Techniques like electrokinetic remediation (EK) assist in soil decontamination by application of direct current, which can enhance the mobility and thus performance of nZVI in treating organic contaminants like polychlorinated biphenyls and molinate pesticide (Gomes et al., 2016, 2014). Some of the remediative approaches for the treatment of metal contaminants in soil are shown in **Table 4.**

Table 4. Application of nanomaterials for contaminated soil remediation

Group of contaminants	Contaminant	Nanoparticles used	Treatment remark	Reference
Inorganic	As	Calcareous soil treated with nZVI	Increasing nZVI concentration (2.5-25 g/kg) and constant time treats As effectively. However, treatment affected by organic content in soil.	(Azari and Bostani, 2017)
Inorganic	Cl, Co, Cd, Cd, Mg	Soil leachate treated with DTPA functionalised maghemite NPs	Efficient recovery of toxic metals and remediation of soil-derived contaminants	(Hughes et al., 2018)
Inorganic	Pb	Comparative treatment with phosphate, compost, nZVI	nZVI was observed to be least effective in immobilising Pb	(Gil-Díaz et al., 2018)
Inorganic	As, Cr, Cu, Pb, Zn	Micro and nano ZVI compared	nZVI more effective than ZVI with highest immobilisation for As. Long term retention of metal(loid)s more efficient in ZVI as compared to nZVI as Fe crystallisation is lesser in ZVI than nZVI	(Danila et al., 2020)
Inorganic	As	α-MnO_2 nanorods	Effective treatment of As with	(B. Li et al.,

		treated As in paddy soil	restricted As influx in rice plants aerial parts controlling As toxicity	2019)
Inorganic	As, Cd, Pb, Zn	nZVI treatment in rhizosphere	Soil retention of As, Zn enhanced with nZVI treatment and significant decrease in metals uptake by plants. Sorption suggested to be associated with Fe/Mn (hydro)oxides and formation of secondary Fe-As phase	(Vítková et al., 2018)
Inorganic	Cd, Cu, Ni, Pb	nZVI	Increased nZVI dose reduced the leaching of treated metals as a result of higher immobilisation	(Vasarevičius et al., 2019)
Inorganic	Cd	Iron oxide NPs effect on Cd contaminated soil and wheat crop growth	Reduction in Cd toxicity and increased Fe concentration in wheat crop observed	(Hussain et al., 2019)
Organic	PCB (tri and tetrachlorobiphenyls)	nZVI combined thermal desorption (300-600 ºC)	nZVI enhances the treatment of PCB by thermal desorption with maximum treatment efficiency of 98.35%	(Liu et al., 2014)
Organic	Polychlorinated biphenyls (PCBs)	Combined nZVI and anaerobic composting treatment	PCB dechlorination improved on addition of nZVI to composting.	(Long et al., 2013)
Organic	Phenanthrene/Pentachlorophenol	Natural soil NPs (Inceptisol-NP, Oxisol-NP, Ultisol-NP)	Phenanthrene mobility influenced by organic content in soil NPs while pentachlorophenol mobility mainly depended on the pH	(F. Liu et al., 2019)

Although, nZVI is considered a widely recognised option for soil remediation, its effect on the physiological properties and microbial communities of soil is crucial to be studied for potential toxicity and negative effect. Fajardo et al., (2015) investigated the residual toxicity and potential impact of aged nZVI on the Pb and Zn polluted soils. Although no effect on the physiological properties of soil was observed, and the Fe concentration was noticed to be significantly increased after the treatment. The toxicological study performed on *C. elegans* (a soil dwelling nematode) revealed a retarded growth in the Pb polluted nZVI treated soil while for Zn contaminated soil a reduced toxicity of Zn on *C. elegans* after treatment with aged nZVI. The study thus suggested the pollutant-nZVI interaction as one of the significant factor in remediation of heavy metal contaminated soil. In another study, the effects of nZVI concentration on soil biota in the clay loam and sandy loam soil revealed that the biota of sandy loam was more vulnerable to nZVI than clay loam soil and suggested the negligible impact on biota of clay loam soil rendering nZVI inactive thereby diminishing its interaction with soil biota (Gomez-Sagasti et al., 2019). In a recent study performed by Baragano et al., (2020) a new graphene oxide nanoparticle (nGOx) was tested as an alternative to nZVI. The remediation of Arsenic contaminated soil revealed a reduction in bioavailability on treatment with nZVI, while an increase was observed on application of nGOx deeming them fit for immobilisation and phytoextraction techniques respectively. The performance of nGOx was compatible with nZVI for the remediation of Cd, Pb and Zn while for Cu it performed significantly better than nZVI. Further the physico-chemical properties of soil were also observed to improve on application of nGOx making it a potential strategy for soil remediation.

4.4.4. Management of nutrients in soil

Nanotechnology has a budding capability to bring sustainability in the prospects of agriculture and its allied fields which include food science, fisheries, aquaculture, horticulture, vegetable sciences, veterinary sciences and animal husbandry (Prasad et al., 2017; Salata, 2004). In agriculture, the main goal is to decline the utilization of fertilizers and pesticides besides the improvement in crop yields by proper nutrient management (Mukhopadhyay, 2014). Nanotechnology is offering promising sustainable tools like nanoemulsions, nano-agrochemical coatings, microencapsulation, and other active constituents to boost the nutrient availability for soil and plants.

Nanotechnology has potentially developed the new methods of food packaging which may include nanocomposite active packaging, nanocomposite smart packaging and nanoreinforcement packaging (Kuswandi, 2016). Nanocomposite food packaging has potential to work against microbes by liberation of some useful compounds which are antimicrobial or antioxidant and improves the food stability, enhances the shelf life and oxygen scavenging property (Sharma et al., 2017). Moreover, nanotechnology can play an important role in improving the germination ability of agricultural seeds, which are otherwise less germinative. Various techniques were implemented for increasing germination percentage like the use of nano-polymer, nano-sensors, nano-barcodes, etc. It is reported that carbon nanotubes were utilized for increasing the germination of tomato seeds by raising the effective penetration of moisture content (Mondal et al., 2011).

5. Practical implications of nanoparticles and consensus recommendation for future research needs

Although, nanoparticles (NP) can deliver cost effective and facile on-site remediation of vast number of contaminated sites, but the technology lacks the certification of complete sustainable approach because of the uncertainties associated with the use of nanoparticles. Currently, the fate and transport of nanoparticles in the contaminated sites, whether it may soil, drinking water or air is still unclear and doubtful and has become a major hindrance in evaluating risk assessment of the nanomaterials. The potential risks to the human or ecological health are associated with the dispersal, ecotoxicity, persistency, bioaccumulation and reversibility of the nanoparticles. The understanding of these principles lacks background literature and underlying topics are still evolving. Moreover, the application of nanoparticles lacks proper regulatory or legislative guidelines at national and international levels (Corsi et al., 2018; Patil et al., 2016).

Keeping in view the ecological and health risks associated with the use of nanotechnology, further research needs to be conducted in this field with special focus on the ecological concerns. The consensus recommendations for the effective application of nanotechnology and sustainable remediation of environment are as follows **(see figure 9)**:

1). Greener and sustainable approaches for synthesis of nanomaterials. (i.e. bionanocomposites, emulsified nZVI, EAB mediated nanoparticle synthesis, etc.)

2). Assessment of remediation plan for sustainability considerations as per SuRF-UK indicator checklist

3). Development of advanced tools for ecotoxicological assessment and safety measures (i.e. biomarkers, permeable iron barriers, PIBs, nanoparticles with new coatings and surface functionalised groups),

4). Establishment of regulatory bodies at national and international level to monitor the distribution of nanoparticles in environmental medias and deploy nano-enabled techniques for better outcomes, limiting the negative impacts to possible minimum,

5). Strong collaboration between researchers and industrial sector.

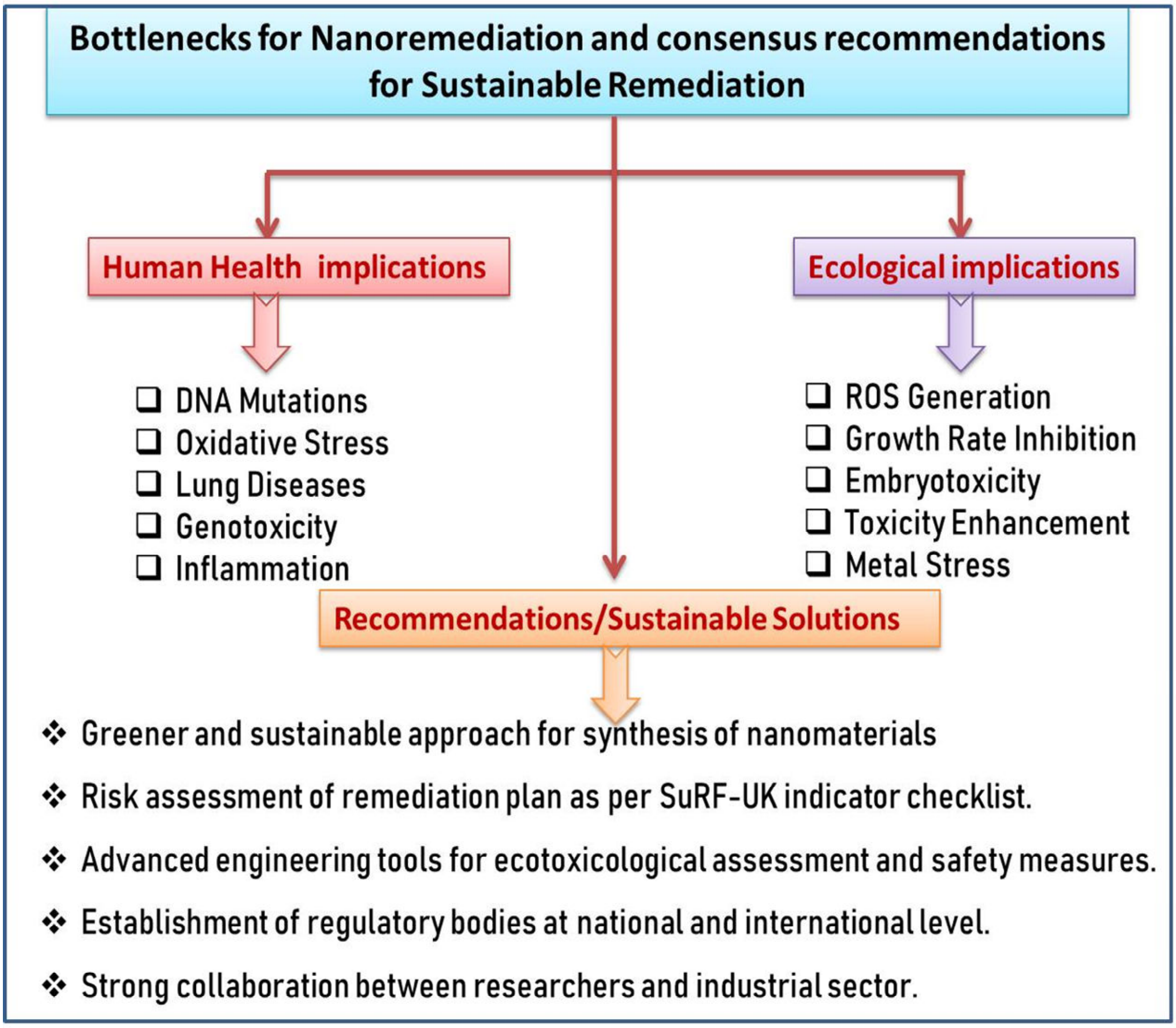

Figure 9. Practical implications of nanotechnology with consensus recommendation for sustainable remediation of environment

6. Conclusion

In summary, nano-based remediation technologies are emerging tools to mitigate the pollution crisis all over globe, whether it may be air, water or soil pollution. Nanoengineered materials (NEMs) like nanoadsorbents, nanomembranes, nanosensors, modified photocatalysts, metallic nanoparticles have shown promising potential for the environmental remediation due to their structural robustness and improved surface properties.

The manipulation of materials at nano-dimensions offers several potential properties to the matter which has been utilized for multitude of applications. The characteristic properties like high surface to volume ratio, functional surface structures, tunable absorption properties, high adsorption capability, chemical stability and above all cost effectiveness have made these materials efficient and effective for monitoring and safeguarding the status of environment.

Apart from this, nanoremediation techniques can treat persistent pollutants by both chemical reduction and catalytic processes and can be beneficial in reducing the clean-up time and avoiding degradation intermediates. Although nanoremediation techniques have shown plethora of applications but they are yet to penetrate mass markets due to ecological concerns. Most of the nanoremediation techniques are limited to the laboratory premises with much less commercialization. Therefore, the commercialization of nanoremediation techniques is highly needed to ensure their proper sustainable use for maintaining ecological and public health.

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