Emerging Role of Nanotechnology-Based Devices for Detection of Environmental Contaminants

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Abstract Nanotechnology has opened up new possibilities for detecting and monitoring environmental pollutants. Nanodevices, which are devices at the nanoscale level, have emerged as a promising tool for pollution detection due to their unique physical and chemical properties. Nanodevices can be designed to detect a wide range of pollutants such as heavy metals, organic compounds, and gases. They offer several advantages over conventional detection methods such as high sensitivity, selectivity, and specificity. Additionally, they are small, portable, and cost-effective, making them ideal for field-based monitoring of pollution. One of the most promising applications of nanodevices for pollution detection is in water quality monitoring. For example, researchers have developed nanodevices that can detect heavy metals in water at very low concentrations. These nanodevices work by binding to the heavy metal ions, producing a measurable electrical signal that indicates the presence and concentration of the pollutant. Nanodevices are also being used to monitor air quality by detecting harmful gases such as nitrogen oxides, carbon monoxide, and sulfur dioxide. These nanodevices are designed to be small and lightweight, making them ideal for integration into portable air monitoring devices. In conclusion, nanodevices are emerging as a powerful tool for pollution detection and monitoring. They offer high sensitivity, selectivity, and specificity, and can be designed to detect a wide range of pollutants. As the technology continues to advance, nanodevices are likely to play an increasingly important role in protecting the environment and human health. In this chapter, we discuss the emerging roles of gold, silver, copper, and titanium nanoparticles-based nanodevices that are being used for pollutant detection.

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1 Introduction

Nanoparticles are tiny particles with sizes ranging from 1 to 100 nm. They can be made from a variety of materials, including metals, semiconductors, and polymers, and can have unique properties that differ from their bulk counterparts [12]. Due to their small size, nanoparticles have a high surface area-to-volume ratio, which makes them highly reactive and useful in a range of applications, from medicine to electronics. Nanoparticles can be synthesized using a variety of methods, including physical, chemical, and biological approaches. Physical methods include milling, laser ablation, and lithography, while chemical methods include sol-gel synthesis, precipitation, and hydrothermal synthesis [24]. Biological methods involve the use of living organisms, such as bacteria or fungi, to produce nanoparticles.

Nanodevices are small devices that can detect and analyze environmental pollutants at a very small scale. These devices can be used to monitor and analyze air, water, and soil pollution, among other things [1]. Nanodevices use nanotechnology to detect and analyze pollutants, and they can provide more accurate and precise results than traditional detection methods. One example of a nanodevice for environmental pollutant detection is a carbon nanotube-based sensor. These sensors can detect pollutants such as carbon monoxide, nitrogen oxides, and volatile organic compounds in the air [32]. Carbon nanotubes are extremely small and have a large surface area, which allows them to interact with pollutants and detect them at very low concentrations. Another example is a nanodevice based on gold nanoparticles. These sensors can detect heavy metals such as lead, mercury, and cadmium in water [28]. The gold nanoparticles are functionalized with specific molecules that can bind to the heavy metals, allowing them to be detected at very low concentrations [35]. Nanodevices have the potential to revolutionize environmental monitoring and pollution control. They can provide more accurate and precise data, and can be used to detect pollutants in real-time. They are also more cost-effective than traditional methods of pollutant detection. However, there are still some challenges to be overcome, such as ensuring the reliability and durability of the devices, and addressing potential environmental and health risks associated with their use.

Also, nanodevices have shown great potential for detecting allergens in food and other environments. One example of a nanodevice for allergen detection is the immunosensor, which uses nanoscale materials to detect specific allergens. Immunosensors work by using antibodies that are attached to a nanomaterial surface [19]. When the allergen comes into contact with the antibody, it binds to the surface and produces a measurable signal, such as a change in electrical conductivity. This signal can be detected and used to identify the presence and concentration of the allergen [19]. Other nanodevices for allergen detection include nanomaterial-based optical sensors, which use changes in light absorption or reflection to detect allergens, and nanomaterial-based electrochemical sensors, which measure changes in electrical current to detect allergens.

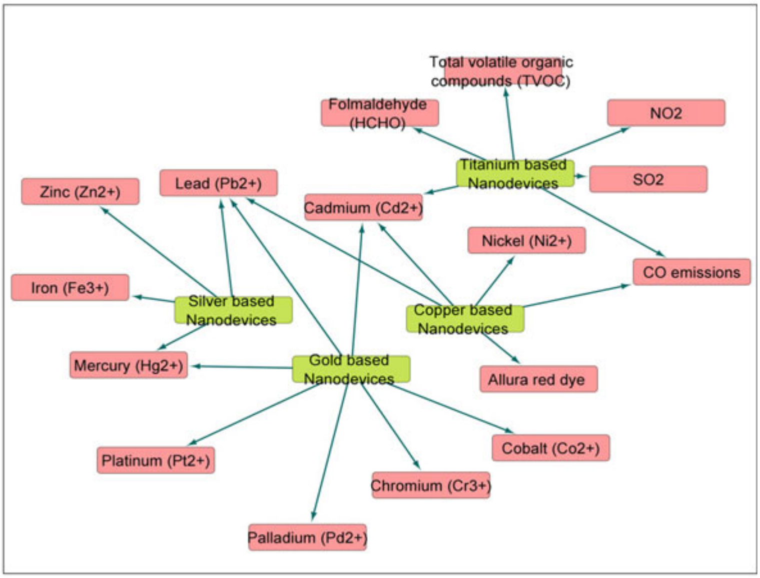

Fig. 1 Pollutant remediation capabilities of Gold, Silver, Copper, and Titanium based nanoparticles. The green nodes represent the nanoparticle-based nanodevices and the pink nodes represent pollutants that they are capable of remediating. Note that three nanoparticle-based nanodevices are capable of remediating lead (Pb^{2+}), two nanoparticle-based nanodevices are capable of remediating cadmium (Cd^{2+}) and two nanoparticle-based nanodevices are capable of reducing CO emissions

Overall, nanoparticles have unique physical and chemical properties that make them attractive for the development of nanodevices for environmental pollutant detection and remediation. Nanoparticles can be designed to selectively bind to specific pollutants and generate a detectable signal in response to their presence. Again, nanodevices have the potential to provide rapid and accurate detection of allergens, which is important for individuals with allergies and for ensuring the safety of food and other products. This chapter discusses various nanodevices based on gold, silver, copper, and titanium that are being used for environmental pollutant detection (Fig. 1).

2 Gold Nanoparticle-Based Nanodevices in Environmental Pollution

The nanoparticles based on gold also called Gold Nanoparticles or GNPs have been heavily used to prepare nanodevices and engrossed in different fields of biology including medical sciences [7]. It has been shown, that these gold-based nanodevices are very useful in detecting environmental pollutants such as heavy metals as they show the typical surface plasmon resonance and absorption property depending on the shape, dimensions, and intermolecular distance [45]. One such device was shown by Wei Ha et al. who developed an eco-friendly heavy metal detection process that uses GNPs orchestrated with *Xanthocerus sorbifolia* tannin as a color imparting probe. Here the Cr^{3+} detection both in river water and tap water was done by colorimetric method after *Xanthocerus* stabilized GNPs were successfully able to chelate with $Cr^{3+.}$ Subsequently the aggregation of GNPs induced the change in color from red to purple quickly [10]. Similar device was developed to detect Hg^{2+} ions in aquatic environment where citrus fruits such as *Citrus limon* and *Citrus limmeta* were used to prepare gold-based nanoparticles and colorimetric detection technique was employed to search Hg^{2+} in micromolar concentration in water [29]. It has been found that the Hg^{2+} ions can also be detected by colorimetric method using gold nanoparticles functionalized by poly gamma glutamic acid (PGA) [9]. Negatively charged PGA was assembled using an electrostatic self-assembly process on top of positively charged cetyltrimethylammonium bromide (CTAB)-capped GNPs. The color of the solution would evolve from light red to purple blue as the quantity of Hg^{2+} increased. With correlation values of 0.998 and 0.991, respectively, the results demonstrated that the absorbance ratio (A750/A580) was linear with the Hg^{2+} concentration in the range of 0.01–10 μM and from 50 to 300 μM. The determination of Hg^{2+} in tap water and mineral water using this method was effective, with recoveries ranging from 90 to 103% and from 103.53% to 113%, respectively. The suggested approach allows for the quick, inexpensive, and equipment-free analysis of Hg^{2+} in a variety of water samples. The polluting agent Pb^{2+} can also be detected by GNPs. In aqueous solution, Au^{3+} is stabilized and transformed into gold nanoparticles by glutathione (GSH) [23]. These GNPs aggregate in the presence of Pb^{2+} ions in NaCl containing aqueous solution and can be monitored by both colorimetrically and UV-vis spectroscopy [23]. Another device for detecting Pb^{2+} was developed by Karuvath et al., where gallic acid was used to produce GNPs at room temperature [42]. To detect the presence of Pt^{2+}, Pd^{2+}, and Co^{2+} at micromolar concentration peptide-functionalized GNPs have been demonstrated as useful nanodevices [33]. An important biomarker for tracking plant damage caused by heavy metal stress is vitronectin-like proteins (VN), which are found on the surface of plant cells. To track hidden damage to plant cells brought on by cadmium (Cd) or lead (Pb), a live plant cell-based biosensor has been developed [39]. L-cysteine was first changed on a glassy carbon electrode, then anti-IgG-Au antibody, in order to create this sensor. The live plant cells were then modified onto the electrode and treated with the anti-VN. By detecting changes in electrochemical impedance, the sensor operated. In the linear dynamic ranges of 45–210 and 120–360 $\mu mol\ L^{-1}$, respectively, Cd and Pb were identified. Additionally, this biosensor's Cd and Pb detection limits were 18.5 $nmol\ L^{-1}$ and 25.6 $nmol\ L^{-1}$, respectively [39]. Pb^{2+} can also be detected rapidly in soil by producing GNPs strip biosensor functionalized by GR-5 DNAzyme. Here the graphene oxide provides assistance to detect Pb^{2+} ions specifically [37]. In the presence of additional divalent metal ions, the strip biosensor displayed high selectivity toward Pb^{2+}. The obtained recoveries for actual soil samples ranged from 91.5 to 113.1%. Thus, gold nanoparticle-based devices are emerging as technological breakthrough in environmental pollution detection.

3 Silver Nanoparticle-Based Nanodevices in Environmental Pollution

Silver-based nanodevices can be an effective tool for detecting environmental pollution. Nanoparticles of silver have unique optical and electronic properties because they are capable of absorbing and scattering light efficiently [6]. This property can be utilized in a variety of sensing applications. Heavy metal ions are a major source of environmental pollution [5]. Silver nanoparticles can be functionalized with ligands that selectively bind to specific metal ions, allowing for their detection in environmental samples. Based on a linear change in the strength of the surface plasmon resonance absorption, it is shown that polyvinylpyrolidone-modified silver nanoparticles (AgNPs) can detect the concentration of the heavy metal contamination Fe^{3+} ions in water [27]. Another study reported that Hg^{2+} and Cu^{2+} detection in water is possible using various concentrations of AgNPs [22]. In order to identify Hg^{2+} present in water using a colorimetric approach, AgNP was functionalized using 3-mercapto-1, 2-propanediol (MPD). When Hg^{2+} solution was added to MPD-functionalized AgNP (MPD-AgNP), new peak at about 606 nm appeared. The aggregations brought on by MPD-AgNP's detection of the heavy metal ion Hg^{2+} through the dipropionate ion may be the cause of the new peak. Also, neem extract-based AgNPs offer good solution for eradicating heavy metal toxicity. It was reported that at micromolar concentrations, sun-dried neem leaf extract-based AgNPs (ND-AgNPs) selectively sense Hg^{2+} and Pb^{2+} [15]. AgNPs made from neem bark extract demonstrated selective colorimetric sensing of Zn^{2+} and Hg^{2+}. AgNPs made from green tea extract (GT-AgNPs) and mango leaf extract (MF-AgNPs) also demonstrated selective colorimetric detection of Hg^{2+} and Pb^{2+} ions [15]. Hg^{2+}, Pb^{2+}, and Zn^{2+} selective colorimetric sensor characteristics were present in AgNPs made from pepper seed extracts. Importantly, these environmentally friendly synthetic AgNPs were capable of detecting the presence of dangerous metal ions in aqueous solutions throughout a wide pH range (2.0–11), which is a highly desirable property from the standpoint of various water pollution sources.

Silver nanoparticles can be functionalized with biomolecules or polymers that selectively bind to organic pollutants, such as pesticides or hydrocarbons. This can allow for the detection of these pollutants in environmental samples. A sizable portion of water contaminants are organic pollutants. They damage aquatic life and terrestrial life through drinking water when present in water. Pesticides, organic dyes, pharmaceuticals, nitro-aromatics, and mycotoxins are just a few of the several forms of organic pollutants that can be found in the environment. In agricultural production, pesticides are used to lessen crop damage from weeds and pests [44]. Organic dyes, which are utilized in textiles, leather, paints, papers, and plastics, are made up of a generous number of intricate aromatic compounds [43]. Due to their severe toxicity, nonbiodegradability, and potential to change into agents that are carcinogenic, teratogenic, and even mutagenic, pesticides and organic dyes have garnered a lot of attention as environmental pollutants from a worldwide perspective [13]. For the detection of pharmaceuticals, nitro-aromatics [30], pesticides [11], organic dyes

[8], and mycotoxins [17], AgNP-based optical sensors have been described. When compared to optical sensors, electrochemical sensors, such as those based on AgNP, are thought to be more capable of detecting organic contaminants with enough sensitivity and selectivity [40]. They also take less time to set up and take less effort. While different targeted analytes need to be transformed into detectable species for optical sensors, targeted analytes can be detected immediately by electrochemical sensors. Electrochemical sensors can be used for in situ studies since they can directly detect the desired analytes. Electrochemical sensors can also track the evolution of analyte concentration over time.

Silver nanoparticles have been shown to have antimicrobial properties, which can be utilized in the detection of bacteria and viruses in environmental samples. It has been proposed that the lipid-enveloped virus's exterior membrane can be bound by silver nanoparticles (AgNPs) to stop infection [18]. Nevertheless, little is known about how AgNPs interact with viruses. AgNPs have been examined specifically in relation to HIV, where it was shown how the nanoparticles work against viruses as well as how they prevent the spread of HIV-1 infection in human cervix organ culture [18]. Silver nanoparticles can be incorporated into gas sensors to detect air pollutants, such as carbon monoxide [16]. Overall, silver-based nanodevices have the potential to be an effective tool for detecting environmental pollution. However, more research is needed to optimize their performance and develop practical applications for their use.

4 Copper Nanoparticle-Based Nanodevices in Environmental Pollution Detection

Copper-based nanodevices can potentially be used for environmental pollutant remediation. Copper nanoparticles have been shown to have antibacterial properties. The chitosan-copper nanoparticles' exceptional high surface-to-volume ratio allows them to make contact with the *P. aeruginosa* cell membrane through its surface, ultimately killing *P. aeruginosa* [36]. Thus, it can be used to remove pollutants from contaminated water. They can also be used to detect pesticides and dyes. Like, Thiram is essential in preventing many crop diseases from harming fruits and vegetables, but its leftovers have a negative impact on the environment and pose a substantial risk to human health. According to a study, Tween 80-capped copper nanoparticles (Tween 80-CuNPs) are a practical and affordable colorimetric probe for the targeted detection of the pesticides thiram. The CuNPs-based colorimetric probe with a Tween 80 cap demonstrated good selectivity and high sensitivity (LOD around 0.17 M). The maximum residue limit (MRL) set by the governments of the Europe and Vietnam was found to be higher than the thiram limit of detection (LOD) of the proposed sensor [3]. Copper nanoparticles can also be used to remove heavy metals from water by adsorbing them onto their surfaces. The adsorption application of CuO NPs on the removal of Pb^{2+}, Ni^{2+}, and Cd^{2+} is shown to be dependent on the nanosorbent dosage, the metal ions concentration, pH, and the contact duration, as demonstrated by the green CuO NPs synthesized using mint leaf and orange peel extracts as reducing agents. These metal ions had an affinity for CuO NPs in the order $Pb^{2+} > Ni^{2+} > Cd^{2+}$. For demonstrating wastewater remediation under typical environmental circumstances, the removal efficiency of Pb^{2+}, Ni^{2+}, and Cd^{2+} was determined to be 84.000, 52.50%, and 18,000%, respectively, and attained at pH 6. With CuO NPs-1, the highest adsorption uptakes for Pb^{2+}, Ni^{2+}, and Cd^{2+} were 88.80, 54.90, and 15.60 mg g^{-1} [20]. According to these results, CuO NPs can effectively remove heavy metals from polluted water, and more research into their regeneration and reuse is necessary.

Copper oxide nanowires can be used for the photocatalytic degradation of pollutants. When exposed to light, copper oxide nanowires can break down pollutants, such as organic dyes, into harmless substances. For example, The Allura Red AC (AR) dye, an organic pollutant/food dye, was degraded effectively by porous CuO nanosheets, as demonstrated by a color change from red to colorless and monitored by UV-vis spectrophotometric analysis [25]. Copper-based sensors can also be used to detect pollutants in the environment. For example, copper oxide nanowires can be used to detect nitrogen dioxide, a common air pollutant [38]. Copper-based electrochemical sensors can also be used to detect heavy metals like lead (Pb) in surface water [14]. Lastly, copper-based catalytic converters can be used to reduce the emissions of pollutants from cars and other vehicles. Copper-based catalysts can convert harmful pollutants, such as carbon monoxide and nitrogen oxides, into harmless substances. It has been reported that a copper-based catalytic converter reduces the hydrocarbon and CO emissions from a four-stroke single-cylinder Compression Ignition (CI) engine by 38% and 33%, respectively, at full load [2]. Overall, copper-based nanodevices hold great potential for environmental pollutant remediation, and research in this field is ongoing.

5 Titanium Nanoparticle-Based Nanodevices in Environmental Pollution Detection

Titanium nanodevices have the potential to be used in a variety of environmental applications, including pollution control and remediation. The formation of titanium metal and titanium oxide nanoparticles is just a couple of the many useful features and uses of titanium oxide (TiO_2). Rutile titanium dioxide and anatase titanium dioxide are its two main forms. Their outward appearances are what distinguishes them the most. Rutile titanium dioxide often has a dark red hue while anatase titanium dioxide is colorless. Anatase titanium dioxide has an optically negative spectrum, whereas rutile titanium dioxide has a positive spectrum [41]. Titanium dioxide (TiO_2) is a common material used in water purification due to its ability to break down organic pollutants and harmful microorganisms. When exposed to ultraviolet light, TiO_2 nanoparticles can produce reactive oxygen species that can oxidize and destroy pollutants. This process is known as photocatalysis and has been shown to be effective in removing a wide range of contaminants from water, including pesticides, dyes, and pharmaceuticals. According to [26], Degussa P-25, a commercially available TiO_2 photocatalyst, contains roughly 25% rutile and 75% anatase form [26]. Numerous researches have applied it as a benchmark for photocatalytic degradation [34]. Furthermore, TiO_2 anatase form, which is more effective than rutile form due to its increased surface area and open structure, was the most extensively employed photocatalyst [4].

Titanium nanodevices can also be used to purify the air. TiO_2 nanoparticles can be coated onto air filters or used as a thin film on surfaces to break down pollutants when exposed to light. This technology can be particularly useful in indoor environments where air quality is a concern, such as hospitals or schools. Accordingly, it was found that Saudi myrtle plants treated with TiO_2, reduced the concentrations of formaldehyde, TVOCs, NO_2, SO_2, and carbon monoxide (CO) from 0.251, 401, 0.032, 0.009, and 0.99 to 0.014, 54,0.0003, 0.003, and 0.01 in air in the fourth day after intervention [31]. Titanium nanodevices can also be used to remediate contaminated soil. Cu and Cd were observed to be eliminated by 88.01% and 70.67%, respectively from soil, upon application of $NTiO_2$-NCh [21]. Overall, the use of titanium nanodevices in environmental pollution control and remediation shows promise and warrants further investigation and development.

6 Conclusion

While nanodevices have shown great potential for detecting pollutants, there are several limitations and shortcomings that need to be addressed before they can be widely used for environmental monitoring. For example, nanodevices can detect very low levels of pollutants, but their sensitivity can be affected by various environmental factors, such as temperature, humidity, and interference from other chemicals. Also, nanodevices can also be prone to false positives or false negatives, as they may not be able to distinguish between similar chemicals or may react to other substances in the environment. Some nanomaterials used in nanodevices might also be sensitive to oxidation, moisture, or temperature, which can affect their stability and accuracy over time. Lastly, developing and producing nanodevices can be expensive, which can limit their accessibility and affordability for widespread use. Overall, while nanodevices hold great promise for detecting pollutants, their limitations and challenges need to be carefully considered and addressed to ensure their successful implementation for environmental monitoring.

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