

Multidimensional applications and potential health implications of nanocomposites

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ABSTRACT

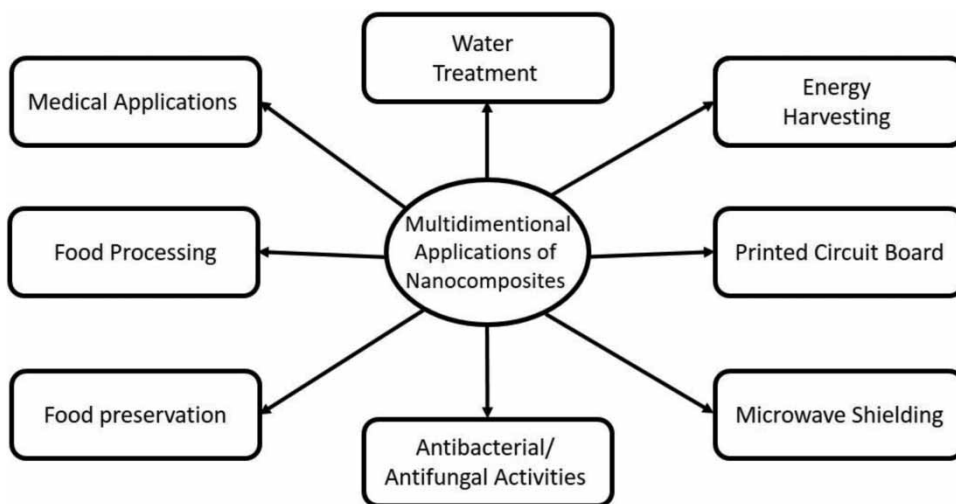
This study reviews the concept, classifications, and techniques involved in the synthesis of nanocomposites. The environmental and health implications of nanoparticles and composite materials were detailed, as well as the applications of nanocomposites in water remediation, antibacterial application, and printed circuit boards. The study gave insights into the challenges of water pollution treatment and provided a broad list of nanocomposites that have been explored for water remediation. Moreover, the emergence of multi-drug resistance to many antibiotics has made current antibiotics inadequate in the treatment of disease. This has engineered the development of alternative strategies in the drug industries for the production of effective therapeutic agents, comprising nanocomposites with antibacterial agents. The new therapeutic agents known as nanoantibiotics are more efficient and have paved the way to handle the challenges of antibiotic resistance. In printed circuit boards, nanocomposites have shown promising applications because of their distinct mechanical, thermal, and electrical characteristics. The uniqueness of the write-up is that it provides a broad explanation of the concept, synthesis, application, toxicity, and harmful effects of nanocomposites. Thus, it will provide all-inclusive awareness to readers to identify research gaps and motivate researchers to synthesize novel nanocomposites for use in various fields.

Key words: nanoantibiotics, nanocomposites, printed circuit board, therapeutic agents, water remediation

HIGHLIGHTS

- The size of nanocomposites makes them ideal for different applications.
- The applications of nanocomposites in water treatment, antibacterial activity, and printed circuit boards are detailed.
- There are concerns about the environmental and health implications of nanomaterials.
- The review gave insights into the challenges, research gaps, future considerations, and health implications of nanocomposites.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Nanostructured materials have found widespread use in a variety of technologies, including energy devices, cars, sensors, medical devices, structural components, water treatment, and others. Metals, polymers, and ceramics, which are frequently used materials in material science, have inherent limits. Consequently, a composite approach – in which two or more materials are combined to achieve increased functionalities – is frequently selected for usage in a variety of applications. When one of the components of the composite is compressed to the nanoscale (1–100 nm), the characteristics are further improved (Hussain *et al.* 2006). A combination of two or more components, comprising a regular and irregular phase with at least one in the nanoscaled dimension, results in nanocomposites (NCs), which are multiphase solid materials. It typically comprises a matrix into which reinforcing fillers are introduced depending on the qualities to be improved. The matrix and the reinforcing fillers may be organic (e.g. plastics, cellulose microfibrils) or inorganic (aluminum oxide, silicon oxide) (Lefatshe *et al.* 2017). The fillers may also be used as sheets, such as graphite, double hydroxides stacked, and layered SiO₂ composed of montmorillonite, hectorite, saponite, etc. (Camargo *et al.* 2009; Kango *et al.* 2013). In other words, the definition of NCs may comprise porous materials, copolymers, gels, and colloids, but are often understood to be the solid mixture of a bulk matrix and nano-dimensional phase(s) with different characteristics as a result of structural and chemical differences. This concept filters in naturally occurring materials such as bone, wood, abalone shell, and so on. Because of the extraordinarily high surface-to-volume ratio of the reinforcing phase, NCs deviate mechanically from traditional composite materials and also show better enhanced mechanical, electrical, thermal, optical, electrochemical, and catalytic properties. There are numerous examples of NCs, ranging from natural to synthetic materials. The creation of strong composites like wood (cellulose/lignin), bone (apatite/collagen), granite (quartz/feldspar), and abalone shell (aragonite/protein) utilizing natural reagents and polymers like carbohydrates, lipids, and proteins is a skill that nature has perfected. Wood is a composite comprised of straight-chain cellulose (a polymer) in a porous matrix called hemicellulose that is kept together by lignin, a far more fragile component. Cellulose (found in cotton) and lignin are both weak substances when bound together to form a much stronger substance. The two primary components of the bone are collagen (a protein), which is soft and flexible, and hydroxyapatite, a strong but brittle substance consisting primarily of calcium phosphate (Kumar & Kumbhat 2016). Examples of various synthesized NCs are graphene oxide (Mittal *et al.* 2015), nZVI@SiO₂@celluloses (Hui *et al.* 2019), ZnO/cellulose NCs (Lefatshe *et al.* 2017), polyethylene/Ag NPs (Zapata *et al.* 2011), and so on. Materials with various structures, compositions, and therefore characteristics can be used to create NCs, allowing for the creation of multifunctional composites (Narendra & Sunita 2016). The characteristics of the component materials, the size, shape, amount, and distribution of reinforcement, as well as the efficacy of the connection between the matrix and reinforcement in transmitting stress across the interface, are significant factors that affect the attributes and performance of composites.

The various applications of NCs range from water treatment, printed circuit boards (PCBs), antibacterial and antifungal activities, energy harvesting, medical applications (blood clots and wound healing), and microwave shielding, to food processing and preservation. In energy-harvesting technologies, various NCs have been developed to convert different energy sources, such as mechanical, thermal, and solar energy, into electrical energy that can be used in power supply systems (Bakhtar *et al.* 2022). NCs attracted attention due to their cutting-edge uses in blood clotting and wound healing, diagnosis, and treatment of cancer, and infectious diseases such as COVID-19, tuberculosis, hepatitis, and HIV infection. Their broad and distinctive application depends on NCs' remarkable physicochemical behavior, outstanding antibacterial capacity, and anticancer and anti-inflammatory actions (Qamar 2021). Furthermore, it is crucial to protect electronic devices from undesirable pollution, and several materials have been investigated for this purpose. Advanced classes of materials with the best electromagnetic absorption qualities include polymer blends and NCs. To create systems with excellent electrical conductivity, dielectric characteristics, and magnetic properties, nanoparticles (NPs) can be customized into polymer-based materials (Deeraj *et al.* 2022). Numerous areas of food science have also undergone radical change as a result of the quick development of nanotechnology, particularly those that deal with food processing, packing, storage, transportation, functioning, and other safety-related issues. The food industries have applied a broad variety of nanostructured materials and their NCs (Bajpai *et al.* 2018).

In this comprehensive review, the recent progress in the application of NCs in water and wastewater remediation, antibacterial applications, and the use of NCs in PCBs will be detailed. The review is organized as follows: the background of the study, classification and synthesis of NCs in Sections 1 and 2. Section 3 detailed the application of NCs in water and wastewater treatment, whereas Sections 4 and 5 described the applications of NCs as antibacterial agents and in PCB, respectively. The environmental and health implications of NPs and composite materials are described in Section 6. Consequently, the current trends and future considerations associated with the different applications of NCs were discussed.

2. CLASSIFICATIONS AND SYNTHESIS OF NCS

Composites either natural or engineered are solid materials produced by combining two or more different materials having significant individual characteristics, to form a new material of better quality with higher properties in a definite structure as a finished product (Shen *et al.* 2012; Liu & Antoniette 2013). NCs or nanostructured materials are solid-structured crystallites of characteristic size measuring a few nanometers of 1–100 nm (Pawar & Lee 2015). They are known to exhibit excellent chemical and physical properties due to their size, chemical composition, and arrangement of atoms. The availability of NCs in one, two, and three dimensions has resulted in their enhanced properties (Chimene *et al.* 2015), hence their application in medical, biological, energy, optics, electric, magnetic, and other fields. Their properties can be evaluated based on their shape, chemical composition, size distribution, and reactivity interface (Siegel 1993). NCs are multiphasic in nature with nanoscale morphology such as lamellar nanostructure, nanoparticle, or nanotubes in one of their phases but of a nanometer range dimension (Sen 2020). As NPs, they are heterogenous materials produced by combining inorganic solids like clay and oxides with polymer, at a range within the nanometric dimension. Their nature and effect depend mainly on the composition, structural components, and interfacial interactions of individual properties but are known to have much more complicated structures than microcomposites (Sen 2020). The dimension of each phase ranges from 10 to 100 nm, however, at an atomic level and due to their nano size, NCs have varying properties which made them useful and applicable in many fields (Pan *et al.* 2009; Yang *et al.* 2015) including the biological sciences and most importantly in the area of antibiotic activity.

2.1. Formation of NCs

The potential of NCs is predicated on the hybrid nanomaterials they include. Clay, mixed inorganic nanoclusters, metals, oxides, biological molecules, enzymes, semiconductors including organic polymers or organic and organometallic compounds, as well as polymers made from sol-gel are all possible materials for their formation (Sen 2020). In particular, their antimicrobial action has made them significant in improving the biological potential of drugs, catalysts, biomaterials, etc. (Xin *et al.* 2012). Because of their unique nano size, wide surface area, and interfacial interaction within the multiphasic NCs, nanomaterials created by mixing two or more different hybrid compounds in a single material result in an NC with a variety of improved advantages (Behrens 2011; Ilyas *et al.* 2022; Sayson & Regulacio 2022).

Based on current research and developments, polymers are the major nanomaterials in many NCs. Several polymer properties which made them suitable nanomaterials in polymer-based NCs include variability in dimension, film-forming ability,

and functionality activation (Al-Johani & Salam 2011). NCs can be classified based on the presence or absence of polymer and polymer-derived materials in the composites. NCs containing polymeric materials are known as polymer-based NCs while those whose composition does not contain any polymeric material are known as non-polymer-based NCs or inorganic NCs which are classified into metal-based, ceramic-based, ceramic–ceramic-based NCs (Khandoker *et al.* 2011). The three major classifications of NCs based on the matrices used (polymer matrix, metal matrix, and ceramic matrix NCs) are discussed in the following.

2.2. Polymer matrix NCs

Polymer NCs are multiphase solids, in which the nanoparticle or nanofiber-based fillers are incorporated into/with polymer. Due to their simplicity in processing, low cost of route synthesis, and several beneficial features including light weight, flexibility, and ductility, polymers have been widely employed in a variety of sectors. However, compared to ceramics and metals, polymers have certain drawbacks, including low strength, weak mechanical characteristics, and limited stability, and hence, a need to incorporate a material that can improve these properties (Kapoor & Kundu 2016; Xue *et al.* 2021). Polymer composites overcome these limitations. As a result, they may find use in the domains of catalysis, electronics, photonics, biotechnology, nanomedicines, sports gears, solar cells, and water treatment (Camargo *et al.* 2009; Chen *et al.* 2014). Cellulose is widely used in the synthesis of polymer NCs owing to the fact that it is the most widely used, most readily available, and most biodegradable natural polymer. Cellulose also has low density, low thermal expansion, good mechanical properties, high modulus, and specific strength, (Lin *et al.* 2012; Habibi *et al.* 2010; Lefatshe *et al.* 2017). Because of its structure's affinity for complexing with metal ions and other cations, inorganic NPs disperse uniformly over the cellulose matrix with improved functioning (Kalia *et al.* 2011). Among the sources of cellulose are the fibers of wood, bananas, oil palm, and rice husks. Bacteria and animals are other sources of cellulose, e.g. tunicate.

2.2.1. Synthesis of polymer NCs

There are various synthetic pathways to synthesize nanocomposites, but the main methods of polymer NCs synthesis are solution blending, melt processing, and *in situ* polymerization.

2.2.1.1. Solution blending. This is an easy and commonly used technique for NC fabrication. This method simply involves combining mixtures of the host polymer and fillers dissolved in appropriate solvents. Water, chloroform, dimethylformamide, and toluene are the solvents that are most frequently utilized (Wang *et al.* 2012a, 2012b). The regular continuous mixing of solutions and further removal of the solvent by precipitation and simple filtration (using filter paper or vacuum pump), as well as drying yields the NCs. This approach has the advantages of being simple to use, generalizable to all NP kinds, and applicable to both thermoset and thermoplastic polymers. The demerits also include aggregation, environmental, and economic constraints (Cong *et al.* 2007; Bhattacharya 2016). The major overemphasized drawback to this method is finding a suitable solvent and removing it in the last stage. The solvents used may be toxic and expensive. Manafi *et al.* (2017) applied solution blending techniques to synthesize a novel polymer NC (polyacrylamide/graphene-based NC) for water purification. The synthesis of biopolymer Fe₃O₄/MWCNT/chitosan NCs by solution mixing was reported by Marroquin *et al.* (2013).

2.2.1.2. Melt processing or melt blending. In this process, the fillers are directly mixed and dispersed in the melted host polymer using an extrusion or injection molding technique. It is a straightforward method that is relatively inexpensive and eliminates the need for hazardous chemicals. Due to the high viscosity of thermoplastic polymers, regulating the filler dispersion in the matrix is challenging, necessitating mechanical or shear forces to evenly disperse the fillers and high temperatures to melt the polymer. Applying high temperatures may alternatively cause damage to the surface-modified NPs (Tanahashi 2010). Polyethylene terephthalate/montmorillonite clay NC was reported by Davis *et al.* (2002) to be synthesized by melt mixing at 285° in a co-rotating small twin-screw extruder. Different blending conditions on the final NC were investigated. There are also several publications of graphene/polymer, CNT/polymer, and clay polymer NCs that were produced using this technique (Wei *et al.* 2010; Potts *et al.* 2011).

Clay/polymer NCs were synthesized by Dlamini *et al.* (2011) using melt blend and solution blend techniques. According to the scientists, the solution blending methodology generated composites with greater intercalated-exfoliated morphology and

less porosity and thermal stability, whereas the melt blending method produced NCs with high porosity, intercalation, and thermal stability.

2.2.1.3. In situ polymerization. In this procedure, a combination of monomer and filler particles is prepared, and it is then polymerized using common methods, such as mechanical means (ultrasonication, stirring, etc.) or photoinitiation (UV curing). The process results in an even distribution of the fillers throughout the polymer matrix, and it typically does not involve the use of solvents when compared to melting processing and solution blending. This technique can be used to process polymers that cannot be handled by solution mixing and melt blending. This method can also be used to treat polymers that are insoluble or thermally unstable. Nanocellulose extracted from oil palm empty bunches was employed as a host polymer for the *in situ* solution casting process to create zinc oxide nanostructures (Lefatshe *et al.* 2017). The zinc oxide/cellulose NCs were shown to have better antibacterial activity against Gram-positive *Staphylococcus aureus* and Gram-negative *Escherichia coli*, as well as more photocatalytic activity than the pure ZnO nanostructures when they were applied to the degradation of methylene blue. The advantages of this method include high load percentages, better performance of the resultant products, expansion to the solvent-free form, and covalent bonds among the NPs functional groups and polymer. The major drawback is agglomeration (Cong *et al.* 2007; Naz *et al.* 2016). Zapata *et al.* 2002 also synthesized polyethylene NCs containing silver NPs (PE/Ag NPs NCs) with antimicrobial properties via *in situ* polymerization. Poly(ethylene terephthalate) (PET)/LDH NC was synthesized by *in situ* polymerization. Ethylene glycol was combined with terephthalate-intercalated LDH. It was combined with catalysts made of manganese acetate and dimethyl terephthalate. The whole reaction took place between 190 and 280 °C (Cui *et al.* 2012). GO/epoxy NC and clay NCs (N-methyl-polyamide 12)/organo-MMT NCs were also synthesized by *in situ* polymerization by several authors (Dizman *et al.* 2011; Guo *et al.* 2011).

2.2.1.4. Sol-gel methods. This process, which mostly entails hydrolysis and condensation processes, includes the production of sol and its subsequent gelation. The precursors commonly used are metal alkoxides or organic and inorganic salts. Controlling particle size and shape may be accomplished *in situ* using sol-gel (Oliveira & Machado 2013). The advantages of this method include having control over the particle size and good miscibility of the reactants. However, the limitation of using organic solvent is that it is only applicable to those polymers with the capability of hydrogen bonding. The research reported by Shao *et al.* (1995) on the synthesis of SiO₂-TiO₂/Nafion and SiO₂-Al₂O₃/Nafion NCs used the sol-gel reaction between the pairings of tetrabutyltitanate/tetraethoxysilane and aluminum tri-sec butoxide/tetraethoxysilanealkoxide, respectively, in Nafion membranes. A number of other researchers have also used this technique since it works well with polymers (Yeh *et al.* 2008). The governing factors in this technique include temperature, gelatin conditions, solvent, catalyst usage, drying conditions, etc. Zu *et al.* 2014 reported the preparation of the polypropylene (PP)/SiO₂ NCs via a modified sol-gel technique. Polyethylene block poly (ethylene glycol) was employed as the surfactant and the PP was utilized in its melting condition in boiling xylene.

As reported by Xia *et al.* (2019), the incorporation of NPs into the carbon nanotube (CNT)-based polymer modified the frequency-dependent electrical conductivity and dielectric permittivity of CNT polymer NCs. He *et al.* (2017) explored how SiO₂ involvement affected the tribological characteristics of the polymer matrix. They found that the parameter increased by 113% for composites compared to pure polymers, indicating that the interactions between the polymer and nano-SiO₂ are Van der Waals interactions. The interfacial interaction potential energy levels between the SiO₂ and the polymer were believed to be the cause for this improvement in the tribological characteristics. Sadeghi *et al.* 2008 investigated the impact of varying SiO₂ NP concentrations on the separation characteristics of certain gases (N₂, O₂, CO₂, and CH₄) for the NC membranes based on ethylene vinyl acetate copolymer. They found that, when the SiO₂ concentration was increased, the permeability of all gases significantly increased as well as the selectivity of CO₂ over the other permanent gases. The increase in the diffusivity and solubility of gases in hybrid membranes was the reason for this occurrence. In reality, the sorption sites and routes for the polar gases are made more readily available at the interfaces and in the SiO₂ domains by raising the SiO₂ content. In another experiment, Masjedi-Arani *et al.* 2016 showed that the polymer matrix's flame retardancy characteristic is enhanced by the incorporation of SiO₂ NPs. They acknowledged that the active Si-O-Si layer serves as a barrier to the entry of flame and oxygen.

2.3. Metal matrix NCs

Metal matrix NCs put forward a number of recompense over monolithic metals, which contain higher specific strength and modulus, better abrasion resistance and hand down coefficients of thermal expansion (Faith *et al.* 2010; Kori *et al.* 2014). The techniques used to create metal matrix NCs may be divided into the following categories: liquid-phase procedures, solid-phase processes, two-phase (solid-liquid) processes, deposition techniques, and *in situ* processes (Rosso 2006).

2.3.1. Synthesis of metal matrix NCs

2.3.1.1. Solid-phase processes. The solid-phase techniques use blended basic powders to create particulate-reinforced metal matrix NCs. The principal method that belongs to this group is powder metallurgy. The primary steps in using this process are powder preparation, powder mixing, compacting, sintering, sizing, and machining. Metal matrix NCs have been prepared using a number of reliable solid-phase techniques including powder metallurgy, high-energy ball mill, spark plasma sintering, cold spraying, diffusion bonding, and friction stir processing, etc. In this regard, many powder metallurgy processes in particular were effectively used. In a high-energy ball mill, powder particles are repeatedly cold welded, fractured, and re-welded to form the powder metallurgy process known as mechanical alloying. Using a solid-phase process approach is essential for improving the dispersion of nanopowder in the composite by dispersing ceramic clusters (Casati & Vedani 2014). Zhang *et al.* 2000 reported the formation of Al-TiN metal matrix composite via mechanochemical route, Lu *et al.* 2002 carried out the structure and properties of Mg-Al-Ti-B alloys synthesized via mechanical alloying, whereas the consolidation of 1 vol.% CNT-reinforced metal matrix NCs via equal channel angular pressing was investigated by Quang *et al.* 2007.

2.3.1.2. Liquid-phase processes. In this technique, metal matrix composites are created in a liquid state by incorporating a dispersed phase into a molten matrix metal and then solidifying it. It is important to have effective interfacial bonding (wetting) between the dispersed phase and the liquid matrix in order to give the composite with high levels of mechanical characteristics. Coating the fibers that make up the dispersed phase particles can promote wetting. A proper coating minimizes interfacial energy while also preventing chemical reactions between the matrix and the dispersed phase. Stir casting, compocasting, squeeze casting, ultrasonic-assisted casting, infiltration, thermal spray, laser melt-particle injection technique, etc. are all examples of liquid state processing routes (Sharma *et al.* 2020). The following conditions are taken into consideration when selecting a ceramic reinforcement: matrix alloy, melting temperature, tensile strength, thermal stability, elastic modulus, size and shape of the reinforcing particle, and cost. Three new approaches for the transient liquid-phase diffusion bonding of aluminum-based metal matrix composites were developed by Shirzadi & Wallach 1997.

2.3.1.3. Two-phase deposition and *in situ* techniques. The two-phase procedures entail the amalgamation of a filler, often ceramic, and a metal matrix at a region of the phase diagram where the matrix comprises both solid and liquid phases. The main methods that fall under the category of two-phase procedures are spray deposition and compocasting/rheocasting. This process is also known as liquid-solid phase or solid-liquid phase.

In the decomposition technique, the matrix material required to adopt the form of the composite is pulled over individual fibers. After that, a solidified composite plate or structural form is created by diffusion bonding. The other crucial deposition methods include immersion plating, electroplating, and spray deposition. Also, for the *in situ* methods, the reinforced phase is created *in situ*. From a suitable starting alloy, the composite material is created in one process.

2.4. Ceramic NCs

Metal is the second element in a ceramic matrix NC, which is mostly made of clay (an element compound made from oxides, nitrides, silicides, and other materials). Generally, there are several different methods used to create ceramic matrix NCs. The most popular methods for creating ceramic NCs are powder processes. Mechanochemical synthesis, vapor phase synthesis, high temperature synthesis, and solution combustion (SC) procedures are a few of the methods that may be used to create various types of ceramic NCs using the powder process (Palmero 2015).

2.4.1. Synthesis of ceramic matrix NCs

2.4.1.1. Mechanochemical synthesis. By mechanically combining the component phases, any ceramic composite powder may be created. Mechanochemical synthesis is often carried out in controlled environments and typically requires high-

energy milling processes. This method may be used to prime NC powders made of oxide, non-oxide, and mixed oxide/non-oxide materials. The kind of raw materials, purity, particle size, size distribution, and degree of agglomeration are the main variables that define the attributes of the resulting NC materials. The main drawbacks of this synthesis method are the inability to create discrete NPs in the smallest size range and product contamination by milling medium. To prevent the creation of a secondary phase during sintering, the powders must be kept pure. Al₂O₃/SiC composites are frequently created using this traditional method of powder inclusion, which involves ball milling.

2.4.1.2. Vapor phase reaction technique. Chemical reaction, mass transfer, nucleation, coagulation, and condensation are the processes involved in the vapor phase reaction method. A solid is typically evaporated to create a supersaturated vapor, which is then condensed to produce a nanomaterial with a variety of particle sizes, shapes, and compositions (Granqvist & Buhrman 1976). Joule heating, electron beam evaporation, arc discharge, and laser ablation can all produce supersaturated vapor. Commercial production of oxide and non-oxide ceramic NC powders frequently uses vapor phase techniques. The choice of the gas used is an important factor that must be noted because it determines the type of powder produced. Metal oxide powders are often created using oxygen-containing gases, whereas non-oxide particles are created using inert gases.

2.4.1.3. High temperature synthesis. The preparation of the reactant mixture, ignition and self-sustained propagation of high temperature, and post-synthesis treatment are the three main processes of this simple and commercially feasible method for the synthesis of oxide and non-oxide nanomaterials. It is founded on the idea that heating causes an exothermic reaction to start, which then proceeds on a self-sustained propagation; therefore, it is also called combustion synthesis. By using combustion synthesis, it is possible to create ceramic, composite, alloy, and intermetallic nanostructures (Patil *et al.* 1997). Combustion synthesis can be divided into solid state combustion (SSC), SC, and gas state combustion (GSC) depending on the nature of the reactants. A number of refractory materials and NCs has been reported to be synthesized by this method (Zedda 2001; Zaki 2009).

2.4.1.4. Sol-gel. One of the extensively utilized wet chemical methods for the manufacture of ceramics and NCs (mainly oxides) is sol-gel. The sol-gel process involves the chemical conversion of a sol into a gel (three-dimensional polymer) state, followed by a transition into solid oxide material due to the application of the proper post-treatment. This technique relies on inorganic polymerization reactions such as hydrolysis, polycondensation, gelation, ageing, drying, and calcination or sintering.

2.4.1.5. Spray decomposition. This approach of solution procedures is adaptable and may be used to create ceramic materials with a variety of compositions and morphologies. The steps in the synthesis process are the creation of the precursor aerosol, the evaporation of the solvent, and the precipitation of the solute, and finally, the pyrolytic breakdown of the solute. The advantages of this strategy include the production of highly homogeneous, high purity NPs. The drawbacks include the requirements for vast quantities of solvents and variably the high cost of productions.

2.4.1.6. Coprecipitation. During the coprecipitation process, the essential metal cations from a typical channel are coprecipitated, often as hydroxides, carbonates, oxalates, or citrates. After that, these precipitates are calcined at the proper temperatures to produce the desired resulting nanopowder (Cho *et al.* 2006; Zhang *et al.* 2006; Godinho *et al.* 2007). If each reaction step is properly managed, the structure, morphology, and content of a nanomaterial may be controlled more effectively. Just by combining the reactants in a beaker, the chemical reaction begins in a matter of minutes. The concentration of the reactants, time, and amount of reactant addition to the solution, temperature, pH of the solution, and the surfactants utilized are significant factors that affect the properties of the final nanosized products. Spontaneous nucleation occurs when reaction products become supersaturated, which causes them to proceed through the growth process. The major difficulty in coprecipitation method is the occurrence of contamination resulting from the byproducts of the chemical reaction. Operations parameters including stirring rate, vibration, exposure to light, and glassware cleanliness have a substantial impact on the quality of the nanomaterial generated. It is an easy and straightforward process suitable for the synthesis of fine metal NCs of ceramics. The limitation of this method is that it does not work well with the reactants of different solubility values.

3. APPLICATION OF NCS IN WATER AND WASTEWATER TREATMENT

When compared to large particles, the surface area-to-volume ratio of nanomaterials is one of the most promising and practical aspects. Due to the greater availability of reactive surface sites and higher surface energies associated with surface atoms compared to bulk atoms, an increase in surface area can help to boost chemical reactivity. In water treatment, NPs are beneficial due to their smaller size (1–100 nm). They are different from large particles in terms of their physiochemical and biological properties. Due to their unique properties, nanomaterials can be employed in a variety of water and wastewater treatment processes. However, toxicity and the fine particle nature of NPs are some of the existing disadvantages in the application of nanoparticle for water remediation. Technology has been developed to mitigate these adverse effects, resulting in an increase in the efficiency and effectiveness of nanomaterials in water remediation. For example, the nitrifying-enriched activated sludge (NAS) technique by [Sepehri & Sarrafzadeh \(2018\)](#) reduces fouling and improves nitrification efficiency in wastewater with low C/N ratio. With the populations of the autotrophic microbial community dominating the activated sludge, it was reported that this strategy was able to reduce fouling and enhance wastewater treatment performance. NCs slow down the pace at which NPs are released in treated water. By changing the supporting components, such as surfactants, mobile materials, or polymers, numerous NCs may be synthesized.

3.1. Inorganic NCs in water remediation

The non-toxic nature of some NPs, e.g. TiO₂, made its application useful in degrading and removing water pollutant ([Okhovat et al. 2015](#)). The use of TiO₂ in water treatment is also linked to properties that include photocatalytic stability and low expenses especially when sun radiation is present. Common properties varied to achieve results in such photocatalytic processes using NPs of TiO₂ are as follows: pH, intensity of UV, exposure time and concentration of TiO₂. Water polluted with organic contaminants including polychlorinated biphenyls, benzenes, and chlorinated alkanes has been successfully treated with TiO₂ NPs ([Kabra et al. 2004](#)). The removal of total organic carbon (TOC) from wastewater was enhanced by the addition of TiO₂ NPs in a study by [Chitose et al. 2003](#). Additionally, TiO₂ NPs has been utilized in a ‘falling film’ reactor to degrade microcystins in water ([Shephard et al. 2002](#)). Despite the tremendous application of TiO₂ NPs, its composites have performed better in many cases largely due to increased surface area as listed in [Table 1](#).

NCs have been reported to be very effective in water refinement and with special features of eco-friendliness, affordability, and reusability ([Allen et al. 2010](#)). So selecting NCs to meet requirement for stringent regulation in water treatment is in the right direction ([Georgakilas et al. 2012](#)). Various metals and their oxides, NCs, nanotube, metal organic frameworks (MOFs) have been extensively used for water treatment.

[Beller et al. \(1992\)](#) added iron oxides to small scale of Fe-limited anoxic river water which significantly helped in organic pollutants degradation through microbial mediated redox reactions by sulfur species and iron. Iron as a major element for plant growth has been demonstrated in a wider study ([Boyd et al. 2000](#)). In the Arctic Southern Ocean’s Fe-limited regions, it was claimed that iron fertilization induced phytoplankton growth. Positive recommendations were made by [Ridgwell](#) in 2002 that the availability of Fe may play a crucial role in biogeochemical processes that may have an impact on CO₂ sequestration in the oceans ([Ridgwell 2002](#)). An NC of goethite/silica adsorbed As(V) from aqueous solutions better when compared

Table 1 | NCs of TiO₂

Composite components	Application	Reference
TiO ₂ and CeO ₂	Degradation of organic pollutants in ozonation processes	Nawrocki & Kasprzyk-Hordern (2010)
Doping Si into TiO ₂	Decomposition of organic compounds	Iwamoto et al. (2000)
TiO ₂ nanocrystals modified with noble metal	Degradation of methylene blue	Wu et al. (2006)
Nitrogen and Fe(III)-doped TiO ₂ nanoparticles	Degrading azo dyes and phenol	Liu et al. (2005)
TiO ₂ nanoparticles deposited onto porous Al ₂ O ₃	Removal of total organic carbon	Sun et al. (2004)
TiO ₂ NCs with mesoporous silica	Treatment of aromatic pollutants	Tuel & Hubert-Pfalzgraf (2003)
Nanosized /TiO ₂	Degradation of 4-nitrophenol	Samantaray et al. (2003)
TiO ₂ nanotubes	Degrade toluene	Chen et al. (2005)

with many other adsorbents (Attinti *et al.* 2015). Kumar *et al.* (2014) reported Pd-Cu/ γ -alumina NCs as being effective in the reduction of nitrate.

Sugarcane bagasse and nano-magnetic adsorbent composites were used to create a new composite (SCB-NMAC) by Wannahari *et al.* (2018). The equilibrium Cu^{2+} adsorption data obtained fitted well to the Langmuir model, an indication of the occurrence of monolayer adsorption process of Cu^{2+} . Kinetically, the adsorption of Cu^{2+} onto the composite aligned with the pseudo-second-order model. The authors reported that the uptake characteristics of Cu^{2+} by SCB-NMAC NCs are significantly better than those of the other adsorbents.

Vinod *et al.* (2015) found that carboxyl-, amine-, and thiol-functionalized Fe_3O_4 NPs may be used to eliminate toxic metal ions from wastewater. These magnetic nano-adsorbents captured the metal ions either by generating chelate complexes via ion exchange process or through electrostatic mechanism of removal and hydrogen bonding between the adsorbate and adsorbent molecule, depending on the surface functionality (COOH, NH_2 , or SH). Vinod *et al.* (2015) further explained that these modified surface-engineered Fe_3O_4 NPs exhibited a significant affinity for simultaneous adsorption of Cr^{3+} , Co^{2+} , Ni^{2+} , Cu^{2+} , Cd^{2+} , Pb^{2+} , and As^{3+} from wastewater.

The relevance of nanosized zinc oxide has also been demonstrated due to its strong photocatalytic properties, lack of secondary pollutants, non-toxicity, cost-effectiveness, ease of synthesis, and stability in hostile environments (Aremu *et al.* 2021). Thus, Nakkeeran *et al.* (2018) and Rupa *et al.* (2019) looked at employing zinc oxide NCs to removing color from textile industrial effluent. Rupa *et al.* 2019 synthesized *n*-sized ZnO sea buckthorn (SBT) composite for the degradation of industrial dyes. Malachite green, methylene blue, Congo red, and eosin Y were the industrial dyes that were used. The application of *n*-sized ZnO SBT composite to each dye solution gave different degradation rates at different time intervals. The result shows that the maximum degradation achieved at 70 min was 99% for methylene blue, 70 min was 100% for malachite green, 80 min was 99% for Congo red, and 90 min was 100% for eosin Y. The higher degradation rate of the industrial wastewater was as a result of the SBT added which improved the quality of the *n*-sized ZnO.

A thin coating of TiO_2 and ZnO composites produced by spray pyrolysis degraded reactive red 152 and terephthalic acid with exceptional success when exposed to UV light. In 120 min, photocatalytic degradation by TiO_2 composite exhibited 70% efficiency, but ZnO composite with a hexagonal structure demonstrated outstanding degradation of up to 91%. Both fit well into pseudo-first order kinetics (Ali *et al.* 2018; Hunge *et al.* 2018). ZnO and ZnO- TiO_2 NCs were also synthesized by Baseri & Alizadeh 2018 and used for the treatment of malachite green dye in wastewater. It was recorded that the ZnO- TiO_2 NCs showed higher percentage degradation of 99% compared to ZnO nanoparticles.

Ayanda *et al.* 2013 examined the kinetics and equilibrium models for the sorption of tributyltin to nano-ZnO, activated carbon, and nano-ZnO/activated carbon composite in synthetic sea water. It was recorded that >99%; a higher removal efficiency of tributyltin from artificial seawater was obtained for the *n*ZnO/activated carbon composite material.

Chemicals used in the synthesis of nanomaterials can also be incorporated to form a composite which improves the performance of such nanoparticle in removing a specified pollutant from water as reported in the sol-gel synthesis of Al_2O_3 with sodium dodecyl sulfate (Al_2O_3 +SDS) (Konne *et al.* 2017). Al_2O_3 was reported as the major phase in the nanoparticle and its composite (Al_2O_3 +SDS) after instrumental characterization. During experimentation the adsorption of Ni^{2+} by the composite (Al_2O_3 +SDS) gave higher adsorption capacity than single Al_2O_3 nanoparticle which makes its application a recommendation for effectively removing nickel ions from crude oil-water mixtures (Konne *et al.* 2017).

Guo *et al.* 2017 observed that the availability of a wide surface area and more active sites boosted the photodegradation effectiveness of Rhodamine B in N-doped molybdenum disulfide (MoS_2 nanosheets). The higher electric conductivity, high surface area, and optical activity of the NCs comprising carbonaceous components supported organic-inorganic materials, making them attractive choices for photocatalytic applications. N-doped graphene/ MoS_2 NCs performed excellently in photodegradation as a result of improved photo-induced charge carriers, which also prevents charge recombination (Park *et al.* 2016). There is toxicity associated with CNT but a CNT- MoS_2 composite has strong photocurrent properties, excellent photo responsiveness, and great recovery capacity (Song *et al.* 2006).

NCs of BiVO_4 have been widely utilized for treating water. Wetchakun *et al.* (2012) reported the degradation of methylene blue and methyl orange in the presence of $\text{BiVO}_4/\text{CeO}_2$ NCs and halogen lamp. Nanosheets of Au/ BiVO_4 in the presence of Xenon lamp of 300 W degraded methyl orange in 50 min (Cao *et al.* 2012). $\text{ZnFe}_2\text{O}_4/\text{BiVO}_4$ NCs in the present of visible light worked effectively in the degradation of methylene blue in 5 h (Zhang *et al.* 2013). $\text{V}_2\text{O}_5/\text{BiVO}_4/\text{TiO}_2$ NCs has been explored to degrade toluene in the presence of Xenon lamp of 500 W in 6 h (Sun *et al.* 2014) and $\text{BiVO}_4/\text{Ag}_3\text{PO}_4$ in the presence of Xenon lamp of 250 W degraded Rhodamine B in 20 min (Patil *et al.* 2017).

Distillation product of crude oil spill is an accidental disaster associated with processing, storage and transportation of these products which produce several environmental degradations and hazards due to toxic organic pollutants released into water bodies. Such disasters have two major economic effects, i.e. loss of money due to the loss of these non-renewable energy resources and the money required to remediate the damaged environment. In their research, [Ayman *et al.* 2017](#) employed an ionic liquid based on 1-allyl-3-methylimidazolium oleate (AMO) to cap and stabilize magnetite at low temperatures. The produced superhydrophobic magnetite NPs showed monodispersity and superparamagnetic characteristics. It has a mesoporous structure and is highly effective at collecting oil at low concentrations. It was reported that the findings provided a low-cost way of producing magnetite capped with AMO on an industrial scale to collect wide areas of oil spills.

3.2. Bio-based NCs in water remediation

Composites could be a combination of plant bio-resource isolates, e.g. nanocellulose and inorganic nanoparticle materials normally referred to as bio-based NCs. These combined nanomaterials have improved surface area for adsorption as seen in starch stabilized magnetic NPs (SSMNPs) for the removal of nickel from crude oil ([Konne & Opara 2014](#)).

Using the electrospinning approach, [Hassan *et al.* 2017](#) synthesized a new composite by hybridizing nano-magnetite zinc oxide and cellulose-acetate (CA). The physicochemical analysis of the novel fabricated hybrid CA nanofiber confirmed the uniform distribution of nano-magnetic ZnO on CA nanofiber. When compared to other examined CA-based nanofiber, the magnetite ZnO-CA hybrid nanofiber with 0.1% magnetic ZnO immobilization was the most effective. The composite nanofibers absorb 64% of phenol in just 2 h. The phenol sorption process onto the novel magnetic ZnO-CA composite nanofiber was adversely affected by increases in both the solution pH and temperature.

CA was synthesized using the cellulose from the rhizomes of *Alpinia nigra* and was then combined with organophilic montmorillonite to form a composite ([Goswami & Das 2019](#)). Physicochemical analyses of cellulose, CA and the composite were done using standard methods. The synthesized composite was effectively used to remove toxic dye Eosin Y. A more promising feature of the adsorbent is that the composite was biodegradable in 6 months confirmed through compost test. The authors reported that the composite is economical and effective for the treatment of wastewater effluents.

In order to effectively degrade the antibiotic tetracycline when exposed to ultrasonic irradiation, [Reza *et al.* 2019](#) coupled ZnO nanostructures with nanocellulose. About 12.8% of tetracycline was removed by only ultrasound (US) but removal efficiency increased up to 70% by the US/ZnO treatment process. The removal efficiency of 87.6% was attained in 45 min because of the integration of ZnO nanostructures with nanocellulose. Tetracycline molecules can be transformed into less harmful chemicals by using the US/ZnO/nanocellulose method. Although full conversion into harmless chemicals requires a longer reaction time.

Cellulose nanofiber produced from sugarcane bagasse and synthesized hierarchical nano-Fe(0)@FeS-doped cellulose nanofibres were used for the treatment of organic dyes ([Nalini *et al.* 2020](#)). The nano-Fe(0)@FeS-doped cellulose nanofibres are an attractive sorbent for the textile or paper industries due to their high adsorption capacity, potential for degradation, and simplicity of manufacture using agricultural waste.

[Neha & Manu 2020](#) developed a composite (cellulose/MoS₂) with photocatalyst properties by *in situ* hydrothermal approach. In the experiment, the composite recorded 96% degradation efficiency during the degradation of Rhodamine B dye which can be adopted for the decontamination of industrial wastewater. Although MoS₂ has photodegradation capacity but the large increase in photodegradation efficiency is due to the incorporated cellulose used as support with MoS₂ which causes a delay in recombination of photo-generated charge carriers. The GC-MS spectroscopy of treated water sample revealed significant disappearance of parent ion peaks associated with pollutant present in the sample.

[Kadam *et al.* 2018](#) demonstrated the adsorptive-remediation of cobalt oxide (CoO) NPs from water by M-WP- α CFs composite. The α -cellulose fibers (α CFs) used in the study was extracted from waste-paper biomass (WP- α CFs) and then magnetized with Fe₃O₄ NPs (M-WP- α CFs). The characterization of developed bioadsorbent (M-WP- α CFs) was done using XRD, FT-IR, and TGA and applied for adsorptive-remediation of CoO from water. A pseudo-second-order phenomenon was observed in the kinetics investigation. The successful adsorption of CoO NPs onto M-WP- α CFs surfaces was confirmed by XPS, VSM, TEM, and EDS mapping. The Langmuir adsorption isotherm model was shown to be the best match to the experimental data. The study revealed that the developed composite is effective for the remediation of CoO NPs and becomes quickly separable, preventing the production of harmful secondary waste and sludge.

[Komal *et al.* 2020](#) developed an assembly of CdS and silanized cellulose nanofibers (SCNFs) via solvothermal methodological route. Uniform and efficient distribution of the CdS NPs in the channels provided by SCNF was established. The

adsorption efficiency was compared for CdS and the NCs using harmful pollutants; methylene blue, safranin and chloropyrifos at varied experimental conditions to achieving optimized adsorption. The adsorption mechanism best fits into the Langmuir isotherm model and pseudo-second-order kinetics to confirm monomolecular adsorption. The authors reported that the synthetic route of the NCs is simple and also the bio-based route allows for a profitable modification for fast adsorption features to develop a commercially exploitable material for wastewater treatment.

Waste fruit peels are potential source of cellulose. [Neha et al. 2020](#) successfully synthesized cellulose/BiVO₄ composite via a solvothermal approach by isolating cellulose from this source. With only a 200-W tungsten lamp present, photocatalytic activity results in an 87% efficiency of methyl orange photodegradation over the course of an hour.

4. ANTIBACTERIAL APPLICATION OF NCS

The importance and use of antibiotics came on board with the discovery of penicillin by a Scottish physician, Alexander Fleming, in 1928 at St. Mary's Hospital, London. However, antibiotic commercial production which started in the late 1940s with penicillin was a huge success especially in reducing the number of deaths from infections, before the development of newer but stronger antibiotics in the 1970s–1980s ([Huh & Kwon 2011](#)). The human quest for infection control has led to wrong use of antibiotics either through self-medication or indiscriminate antibiotic use, as well as over or under dosages of antibiotic when prescribed by a physician. This has caused many global health problems due to the presence of resistance genes and the emergence of antibiotic resistance in many disease pathogens. Hence, the need for alternatives such as nanoantibiotics in clinical medicine for effective disease control. Many metallic materials have been reported to be good antimicrobial composites ([Pereira et al. 2022](#)) as their metallic ions have denaturation capability and can inactivate microorganisms, proteins as well as enzymes, due to the changes in their oxidation state ([Modi et al. 2022](#)). Silver NPs as NCs are proven to have good antibacterial properties due to their surface-to-volume ratio leading to the resultant good microbial contact ([Sweet & Singleton 2011](#)). They are active against Gram-positive and Gram-negative bacteria together with their antibiotic resistant strains.

4.1. Antibiotic resistance and nanoantibiotics

A lot of nanomaterials have been applied as composites in the formation of NCs with antibacterial activity. One such development is the use of polypyrrole-based NCs as antibacterial agents (nanoantibiotics) to subvert or circumvent the multi-drug resistance of bacteria to many antibiotics due to the newly acquired resistance mechanisms by most microorganisms ([Huh & Kwon 2011](#); [Silva Júnior et al. 2021](#)). Therefore, the application of polypyrrole in the development of antibacterial agents according to [Zhou et al. 2018](#) cannot be overemphasized. [Figure 1](#) presents the interaction of polypyrrole with chemical compounds (composites) to form antibacterial NCs.

NCs are referred to as nanoantibiotics because they either exhibit antibacterial activity or they enhance the safety of antibiotic administration and its effectiveness ([Roselli et al. 2003](#)). Most antibacterial NCs are known to target most of the bacterial virulence factors as a way of halting the progression of the disease by disarming the disease pathogen, with resultant enhancement of microbial sensitization to immune clearance ([Munguia & Nizet 2017](#)). Novel antimicrobial NCs have been produced by incorporating carbon-based materials of nano sizes into polymer matrices of various characteristics. This has led to the synergistic effect of antimicrobial NCs on microbial pathogens ([Díez-Pascual & Luceno-Sanchez 2021](#)) including the pathogenic bacteria.

Microbial drug resistance has prompted administration of high dosages of antibiotics which resulted in intolerable toxicity and the quest for new antibiotics ([Huh & Kwon 2011](#)). There has been lots of global public health impact of infections caused by bacterial pathogens which are resistant to antibiotics during treatment, resulting from gene mutations. *Pseudomonas aeruginosa* for instance has always been one of the most common causes of nosocomial infections which has been found resistant to many antibiotics, while *Staphylococcus aureus* colonizing human skin becomes pathogenic once it gains entry into the body causing infections such as endocarditis, pneumonia, wound infection, etc. ([Lode 2009](#)). The presence of pathogenic microorganisms especially bacteria in hospital environments has led to an increase in the occurrence of nosocomial infections. Despite the sterilization of thermoplastic materials as well as antisepsis by dry or wet heating and ionic radiation to avoid contamination of hospital materials/equipment and healthcare products, environmental exposure of these materials still results in their microbial contamination due to the ubiquitous nature of microorganisms. Hence, the need for polymer-based material NCs with antibacterial activity ([Díez-Pascual 2018](#)) for an effective treatment of nosocomial infections.

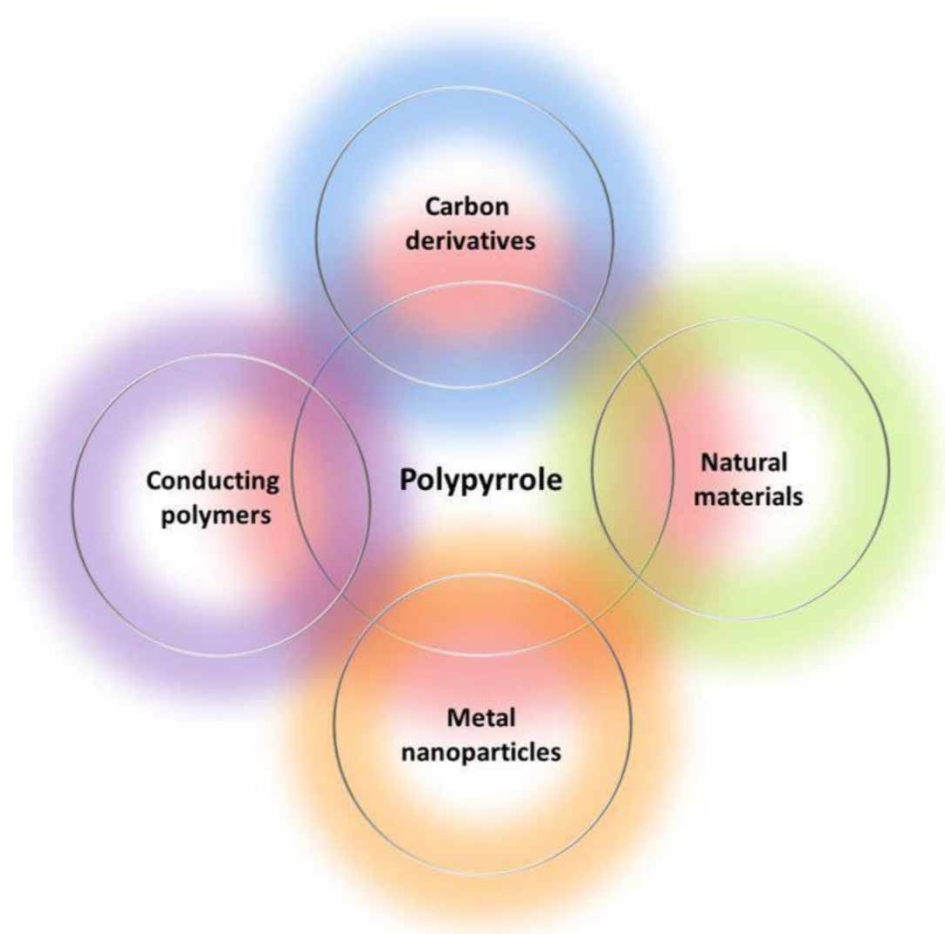


Figure 1 | Interaction of polypyrrole with chemical compounds (composites) to form antibacterial NCs (Silva Júnior *et al.* 2021).

4.2. Mechanism of action of nanoantibiotics

The use of NCs or NPs as a new strategy to deliver antimicrobial agents is highly promising in the development of therapeutic agents with advanced effects on the disease pathogen (Klasen 2000). One of the advantages of antibacterial NCs is their ability to be activated by stimuli such as magnetic field, chemical, heat and pH, once they are engineered for clinical purposes like biological sensors and targeted deliveries (Silva Júnior *et al.* 2021). Their application in antibiotic delivery has been shown *in vivo* and *in vitro* to be effective in the treatment of diseases caused by antibiotic resistant bacterial strains (Huh & Kwon 2011). Nanoantibiotics mechanism of action on microbial and mammalian cells is shown in Figure 2.

The effectiveness of polypyrrole can be explained based on the cationic property which conferred on it an intrinsic antibacterial activity due to the oxidative polymerization of pyrrole monomers, whereas, at fixed intervals of three to five, positive charges are created along the main polypyrrole chain (Seshadri & Bhat 2005; Varesano *et al.* 2013). Thus, the resultant polypyrrole chain net-positive charge interacts electrostatically (Figure 3) with the negatively charged bacterial cell wall (Varesano *et al.* 2013). The physical contact between the polypyrrole (conducting polymer) and the bacterium due to the electrostatic interaction results in the diffusion of the antibacterial NCs into the bacterial cell through the semi-permeable membrane (Varesano *et al.* 2013).

To overcome resistance, there is disruption of the bacterial cell wall which causes leakage of the deoxy-ribonucleic acid (DNA) and other important cell components, resulting in bacterial cell death. Above all, the NCs also cause damage to the mitochondria which is the cell powerhouse. In targeted delivery and with improved pharmacokinetics, the antibiotic targets pathogens with intracellular lifestyle once they are released from the endocytosed nanoantibiotics (Figure 2).

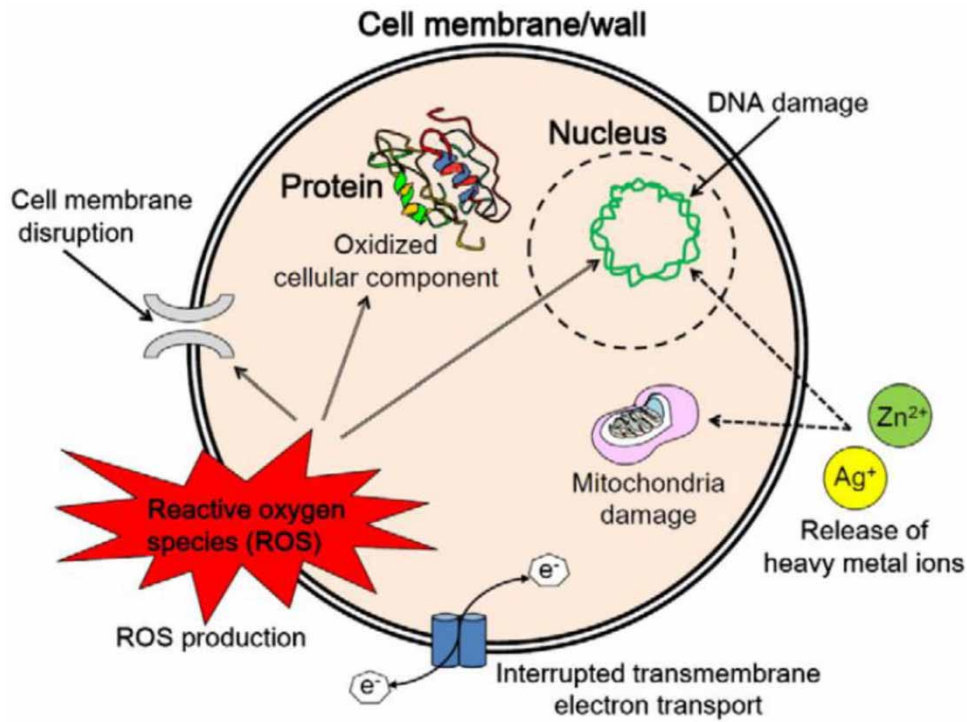


Figure 2 | Nanoantibiotic mechanism of action on microbial and mammalian cells (Huh & Kwon 2011).

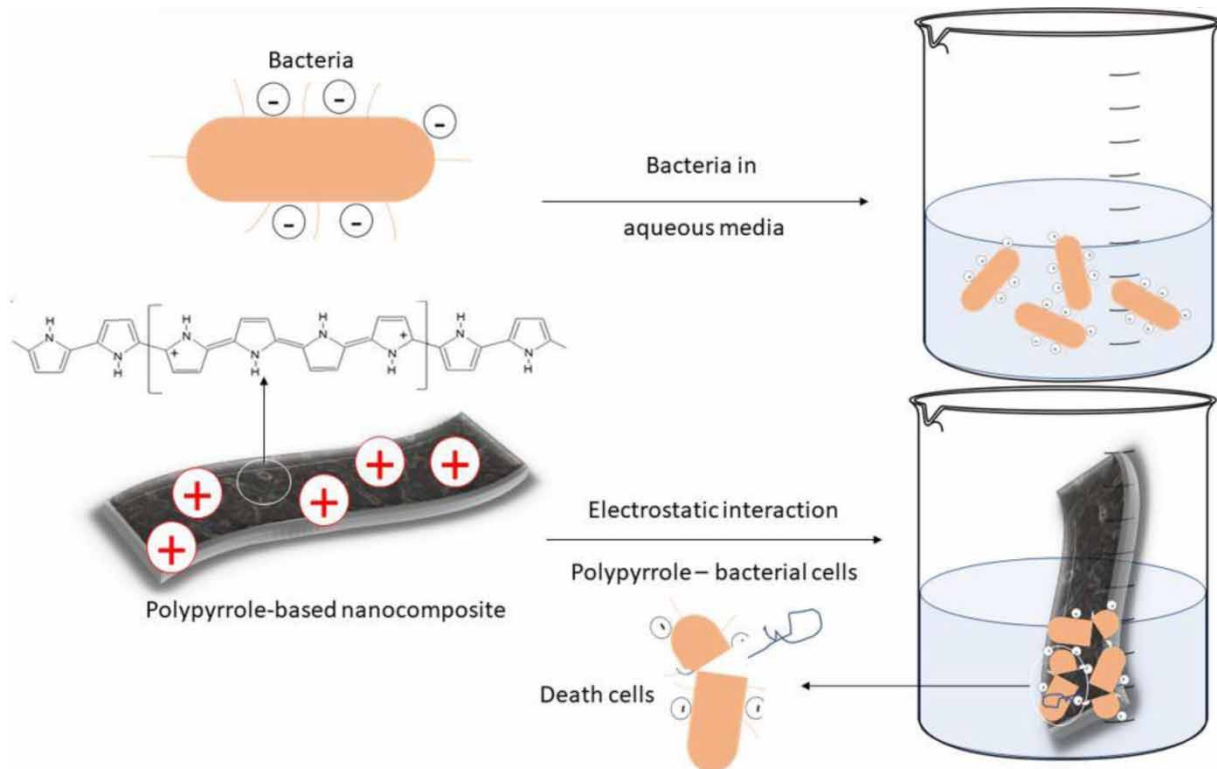


Figure 3 | Electrostatic processes in the antibacterial activity of polypyrrole on a bacterial cell leading to cell death (Silva Júnior *et al.* 2021).

4.3. Emerging applications and current trends of nanoantibiotics

The global public health problem of multi-resistance to many antibiotics by bacterial strains has necessitated the development of alternative antibacterial materials with bactericidal properties. There are variations in bacterial structures which contribute to their antibacterial resistance. Among the Gram-negative bacteria for example, the porin proteins are known to aid water soluble drugs to effectively cross the lipopolysaccharide-rich outer membrane (Silhavy *et al.* 2010) while providing an intrinsic resistance to hydrophobic therapeutic agents which are unable to cross the membrane (Delcour 2009).

As a current paradigm in proffering solutions to the public health problem resulting from antibiotic resistance, the importance of nanoantibiotics as therapeutic agents cannot be underestimated globally. According to Jampilek & Kralova 2022, NPs can on their own serve as antibacterial agents or be used as supplements for regular antibiotics, but either way, they are always referred to as nanoantibiotics. It has been reported that the presence of multiple sites of activity on nanoantibiotics make the development of resistance genes by microorganisms to such therapeutic agents impossible (Ovais *et al.* 2018). Much attention has been given to antibiotic resistance from the nanotechnology perspective currently through the NCs specifically using nanoantibiotics. As a recent feat in biology, specifically in health and medicine, nanoantibiotics represent NCs that possess either antimicrobial potential or have the capability of enhancing the efficacy of therapeutic agents on different disease pathogens (Jamil & Imran 2008; Edson & Kwon 2016). With the progression of antibiotic resistance and as an emerging threat, it has been currently reported that there will be an estimate of 10 million annual deaths from human casualties by 2050 which will result in a predictable 100 trillion US dollars financial burden (O'Neill 2014; Simpkin *et al.* 2017; Jampilek & Kralova 2022). However, nanoantibiotics emerged as an alternative solution to therapeutic agents (antimicrobial drug) resistance and with long-term microbial effects (Ovais *et al.* 2018). Compared to the available conventional antibiotics, nanoantibiotics are known to offer lots of advantages including adsorption, durability, circulation, controlled release, targeted delivery, cost effective, and economical in usage. They are also adaptable to the antimicrobial resistance world (Huh & Kwon 2011; Saúde *et al.* 2013; Jamil *et al.* 2016; Zazo *et al.* 2016). Nanoantibiotics have been reported as superior medicines relevant in the treatment of diseases through the reduction of drug resistance in bacterial pathogens (Sánchez-López *et al.* 2020). They evade the antibiotic resistance processes in disease pathogens by adopting a Trojan horse technique (Mamun *et al.* 2021).

Metal-based nanoantibiotics are recently reported to be nonspecific in their bacterial cell receptor binding, resulting in an extension of antibacterial field and making the development of bacterial resistance difficult (Jampilek & Kralova 2022). Furthermore, carbon NCs which are organic-based contain organic materials (NPs) like liposomes, polymeric NPs, dendrimers and micelles, with non-covalent bonds transforming them into desired forms. However, inorganic antibacterial agents have been reported to be more stable than organic materials at specific temperatures. It has been reported by Modi *et al.* 2022 that liposomes play an important role in targeted drug administration as they are essential in the encapsulation of many antibacterial and other medicinal drugs. As nanoantibiotics, liposomes are administered intravenously and are found to have secured biological delivery mechanisms for hydrophobic and hydrophilic drugs (Maja *et al.* 2020) which makes it possible for liposomes to evade the bacterial structural variation contributing to multi-drug resistance. (Mitchell *et al.* 2021) also stated that the toxicity of immunomodulators activating macrophages can be reduced through immunomodulators liposomal encapsulation while directing them to phagocytic cells for activation of nonspecific resistance to diseases. The different types of organic and inorganic nanomaterial for antimicrobial action are provided in Figure 4.

4.4. Future prospects in overcoming multi-drug resistance

A wide range of nanostructures, including Au, Ag, CuO, TiO₂, MgO, and ZnO, have been projected to become antibacterial nanosystem alternatives. This is due to the increase in antibiotic resistance and the behavior of some bacterial strains as superbugs. Hence, the need for the development of nanoantibiotics as an alternative paradigm. The slow growth of persistent and intracellular microorganisms has made them tolerant to antibacterial agents, with tolerance resulting from mutation rather than genetics (Bald & Koul 2013). This makes the elimination of such persisters at the site of infection impossible, making them a major cause of re-infection (Maurin & Raoult 2001). Pathogenic intracellular microorganisms which try to evade the action of antibiotics are thus a major threat in the healthcare system during infection management (Briones *et al.* 2008). However, liposomes have been found to be effective nanoantibiotics in the eradication of intracellular pathogens (Sachetelli *et al.* 2000). A lot of research works have proven that nanoantibiotics are effective in the treatment of diseases caused by intracellular pathogens and with recorded promising results (Lutwyche *et al.* 1998). Therefore, there is a need

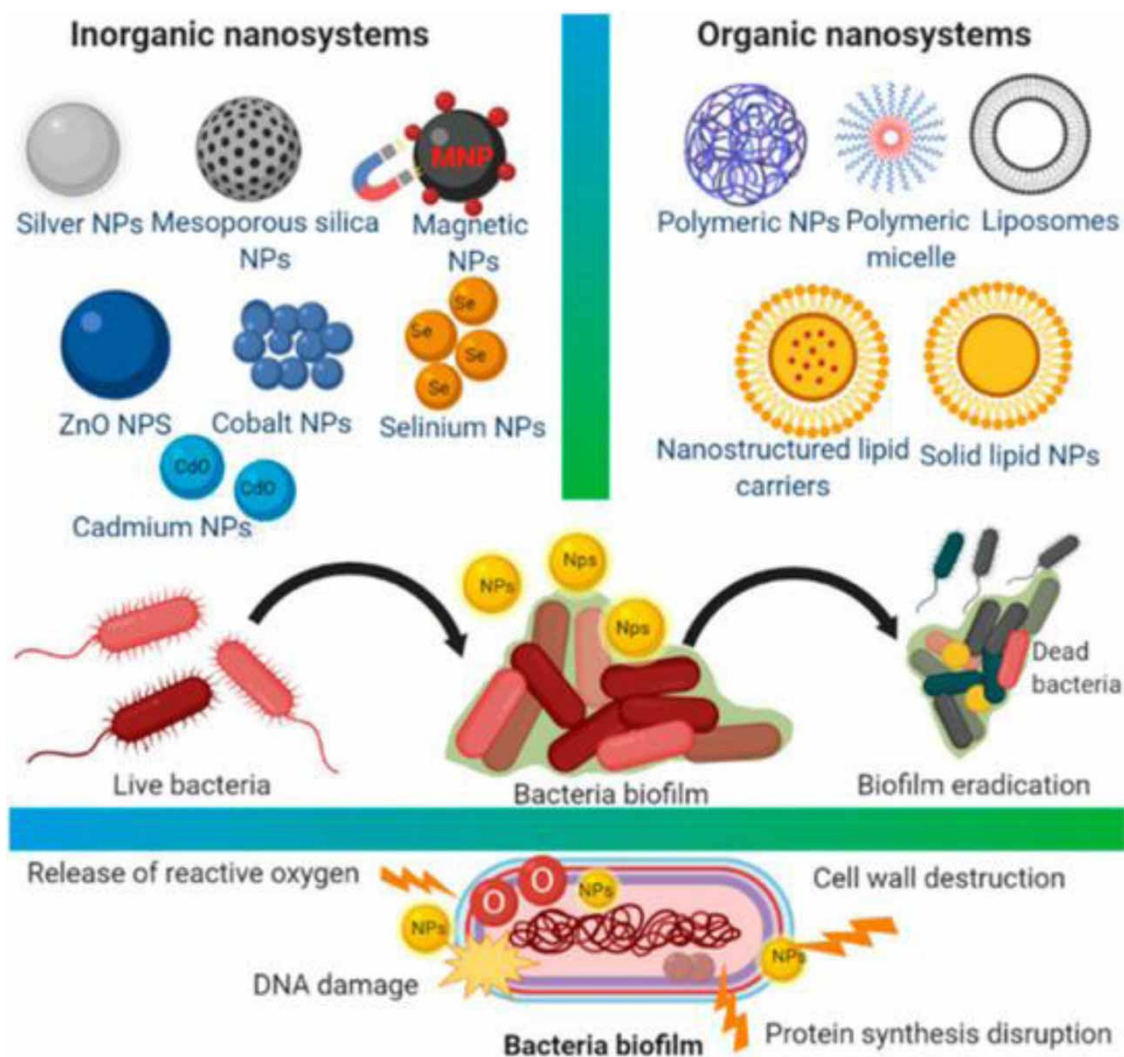


Figure 4 | Different types of organic and inorganic nanomaterials for antimicrobial action (Jampilek & Kralova 2022).

for the development of many nanoantibiotics in this regard since intracellular lifestyle by pathogens has been a threat not only in disease management but also to the immune cells at large.

Although antibacterial NCs have been stated to have no direct and acute effect unlike other antimicrobials, their long-term usage may lead to a questionable potential toxicity (Huh & Kwon 2011). This report poses a potential null hypothesis which needs to be accepted or rejected through an *in vitro* study using animal models exposed to long-term treatment with NCs. However, since long-term use of nanoantibiotics has been reported to have a potential toxic effect, efforts should be made to monitor patients during usage to ensure that prescription guidelines are strictly adhered to.

5. APPLICATION OF NCS IN PCB

NCs have shown promising applications in PCBs due to their unique electrical, thermal, and mechanical properties. One application of NCs in PCBs is as a replacement for traditional metal-based conductive inks. NC inks made of conductive NPs dispersed in a polymer matrix have been shown to have better electrical conductivity, adhesion, and flexibility compared to traditional metal-based inks. This allows for more precise printing of circuitry on the board, reducing the size of the board and the overall cost of the device. NCs are also being explored as materials for PCB substrate. Traditional substrates such as fiberglass or plastic have limitations in terms of their mechanical properties, such as brittleness and poor dimensional stability. By incorporating NPs such as CNTs or graphene into the substrate, NC PCBs can be made with enhanced mechanical

strength, stiffness, and durability, making them more resistant to damage and able to withstand harsh environments. Another application of NCs in PCBs is for thermal management. High-density electronic devices generate a lot of heat, which can damage components and reduce their lifespan. By incorporating NPs with high thermal conductivity, such as boron nitride or diamond, into the PCB substrate or as a coating on the surface, heat can be dissipated more efficiently, improving the overall performance and reliability of the device.

The problem is compounded by the worldwide market-oriented mindset that promotes the disposal of obsolete hardware. Although most electronic equipment and modules are essentially non-biodegradable, ensuring proper recycling is also a critical issue. In recent times, regulations have been enforced to prohibit the production of devices containing hazardous components, such as the 'RoHS Directive,' which was a significant measure taken over a decade ago to address this matter. The field of printed electronics has a rich history in the research and development of electronic devices. Hanson was the first to file a patent for printed wires, which utilized paraffin paper as the dielectric material (Hanson 1903). Eisler's technology was the basis for the mass production of PCBs, and in 1948, commercial PCB technology was first introduced (Coombs & Holden 2016). Only in recent advanced research has the use of bio-based and modern biodegradable materials surfaced in the field of printed electronics. It is important to distinguish printed electronics on plastics and flexibles from conventional PCB technologies that utilize rigid, multilayered PCBs. These substrates hold promise as an alternative in the electronics industry's pursuit of circular economy-based approaches, which seek to address the challenges posed by ever-increasing e-waste management requirements. Traditional electronics substrates pose significant environmental concerns, as they are considered the fastest-growing category of hazardous solid waste worldwide. According to estimates, the quantity of e-waste reported in 2020 was roughly 50 million tons, and it is expected to increase to 120 million tons per year by 2050 (World Economic Forum Report 2019). To reduce the use of plastics in electronic products, it is possible to explore the use of materials that can be recycled and recaptured at the end of their life cycle. Biodegradable materials hold potential as a future application in this regard, which depicts the use of a biodegradable layer for traditional surface-mount technology (SMT)-based PCB assembly. However, modifying the mechanical, electrical, or thermal properties of biodegradable electronic circuit substrates is often necessary for advanced applications. This can be achieved by incorporating nanomaterials as fillers, which can be used to control and enhance their physical properties to meet specific application-driven requirements. In addition, new functionalities can also be enabled (Staat *et al.* 2016).

5.1. Biopolymer NCs in PCB

Biopolymer NCs are nanoscale fillers modified biopolymer matrices. In bulk NCs, these nanofillers are evenly dispersed throughout the polymer matrix. However, in surface NCs, the nanomaterials are typically placed on top of the surface of a polymer or isolated in a subsurface layer. Nanomaterials serve a dual purpose in NCs; they can enhance the physical characteristics of the matrix material or allow new characteristics and practicalities. The addition of different nanomaterials such as metallic NPs and wires, metal-oxides, carbon allotropes, and others typically does not affect the biodegradable or biocompatible properties of the substrates. However, it can significantly affect the mechanical, electrical, optical, thermal, and other properties. This review focuses on the key properties of NCs that are relevant to printed circuit substrates. For those who wish to explore the broader use of NCs in electronics, we recommend reading more comprehensive reviews (Liu *et al.* 2019).

5.1.1. Electrical characteristics

The main goal of using biodegradable substrates is for e-waste management. Advanced applications necessitate some changes in the electrical properties of the matrix materials, particularly for flexible substrates where matching conducting layers and the mechanical properties of the substrate is crucial (Choi *et al.* 2019). As a general principle, anisotropic metallic NCs (such as nano-wires and nano-flakes) give a good conductivity value at the lower filler contents, which is very important for maintaining the favorable mechanical properties of the substrate. Hetero-structures, structure that combines nanomaterials with different measurements (Hu *et al.* 2018), or surface nanomaterial (Huang *et al.* 2015) are also effective for addressing this issue. Moreover, nanomaterials can also improve the dielectric properties of substrate materials for electrical energy storage applications, as demonstrated by the use of boron nitride nanosheets in producing dielectric polymer films with high-energy storage density and breakdown voltage (Cho *et al.* 2018, 2019; Hu *et al.* 2018).

5.1.2. Mechanical characteristics

The materials are often flexible, which is a desirable property during both processing/manufacture and application, especially in electronics that require bending, stretching, or wearability. While the flexibility is primarily determined by the matrix, the nanofillers can also affect it, so it is important to maintain the flexibility when creating a conducting NC. This balance between mechanical properties and electrical properties is also critical for rigid printed circuit substrates. By adding carbon nanomaterial fillers such as 5 wt% CNTs to a PLA matrix, significant improvements were achieved in yield elongation, toughness properties, strength in the yield and Young's modulus.

5.1.3. Thermal characteristics

Flexible electronic applications that require high power output need substrates that can dissipate heat effectively without sacrificing their mechanical stability. Doping can increase and improve the thermal conductivity of the substrate and still maintain its flexibility. Carbon-based nanofillers show potential in achieving this goal due to their low density and high thermal conductivity ranging from approximately 100 W/m/K for bulk graphite to 2000 W/m/K for graphene. Graphite nanoplatelets were used by [Burzynski 2021](#) to achieving a 9-fold increase in the thermal conductivity of PDMS to 1.8 W/m/K with only 11 vol% filler content.

5.2. Current trends in the use of NCs in PCB

[Nägele et al. 2005](#) stated that in addition to the ecological impact of renewable bio resources, the depletion of fossil resources may lead to increased costs, emphasizing the need for the development of novel materials and technologies in electronic substrate production. While PCBs and substrates are essential components of electronic assemblies, the replacement of traditional compositions (such as flame-retarded epoxies with glass fiber reinforcement) with more environmentally friendly alternatives remains a challenge in the field. Although the use of environmentally friendly materials in electronics is a subject of advanced research, such layers are still rarely used in consumer devices due to the current low level of technological readiness for mass production. It should be noted that the use of biodegradable materials as printed electronics substrates does not necessarily mean that they will decompose during their lifespan, but rather in specific composting processes or dissolution ([Zhai et al. 2022](#)). The key benefit is that as the item reaches the end of its useful life and becomes e-waste, the disposal process becomes simpler and more environmentally friendly. However, the use of bio-based and biodegradable materials may not always be desirable for every application.

According to [Adnan et al. \(2016\)](#), the issue is made worse by the global market-driven attitude that pushes customers to discard out-of-date hardware. Additionally, because the majority of electronic components are not biodegradable, effective recycling is a very important issue. Regulations have only recently been put in place to stop the production of gadgets with dangerous components. For example, the 'RoHS Directive' was a key action taken more than a decade ago to address this issue. In [Yedrissov et al. \(2022\)](#), a novel method for producing PCBs made of polylactic acid (PLA) was unveiled in an effort to switch out ecologically harmful polymer binders with biodegradable ones. The production and recycling processes were outlined, with the proposed material and recycling method designed to preserve and reuse the most valuable components of the PCBs. Other researchers have also employed PLA for the composition of such devices. [Géczy and coworkers](#) showed that PLA and CA boards have been suggested for surface mounting by researchers. The same research group has published many papers on using PLA and CA as PCB substrates ([Geczy et al. 2011](#)). Just recently, they presented a promising advancement by reinforcing flame-retardant PLA with flame-retardant flax fibers, resulting in a biodegradable substrate ([Géczy et al. 2022](#)).

[Lincoln et al. 2008](#) also examined flax-reinforced bio-epoxies for prototype circuit boards, evaluating their flammability, thermal resistance, mechanical performance, and electrical properties. When compared to petroleum-based epoxy-fiberglass composites, the bioepoxy-flax composites showed favorable results in terms of toxicity, biodegradability, energy consumption, GHG emissions, and economic expenses. [Henning et al. 2019](#) conducted a comparison between ternary and binary PLA composites for use as printed wiring substance. As a result, they were able to successfully create double-sided wiring boards utilizing PLA. [Guna et al. 2016](#) utilized biocomposites that incorporated natural cellulose fibers extracted from banana stems and wheat gluten to create biodegradable PCBs. They achieved flame retardancy, appropriate dielectric properties, and performance stability, demonstrating that the use of agricultural waste and coproducts is a viable option for producing biodegradable PCBs. [Bharath and colleagues](#) in the year 2020 also developed PCBs using rice-husk fiber that was mixed with epoxy resin, resulting in a composition that is only partially degradable ([Bharath et al. 2020](#)).

Kumar & Gupta 2021 performed various tests, including tensile testing, three-point bending testing, thermal analysis, and dielectric analysis, to evaluate the potential use of jute, hemp, and sisal in PCBs as a replacement for glass fiber epoxy composites. They concluded that these natural biocomposites are suitable for producing PCBs. A life cycle assessment study was conducted by Immonen *et al.* 2022 to analyze the environmental impact of multilayer PCBs made from paper. The research assessed a number of variables, including the possibility for acidification, global warming, hazardous substances, and ozone layer depletion. Their findings show that the environmental impact index of paper-based PCBs is about two orders of magnitude lower than that of organic PCBs. However, it should be noted that paper-based PCBs are not suitable for high-density or high-performance integrated circuit applications.

A study was conducted to explore the feasibility of using cardboard and veneer as substrate materials for biodegradable PCB. The study investigated various factors such as print quality, electrical conductivity, fire performance, and biodegradability. The findings indicated that wood-based substrates could be useful for environmental or medical analytics, but a suitable fire-retardant coating is crucial to prevent ignition due to electrical shortcuts. In a study conducted by Liu *et al.* 2014, paper-based substrates were utilized in PCB manufacturing. The conductive pattern was created using screen-printed polyurethane (PU)-based electrically conductive adhesive (ECA), while SMDs were assembled using polyacrylate-based ECA. Compared to other organic PCBs, the paper-based ones exhibited excellent reliability performance in thermal cycling tests. However, they were found to be susceptible to moisture and mechanical stress and not suitable for high-frequency signal transmission. In another study by Schramm *et al.* 2012, biopolymer substrates made from PLA and thermoplastic polyester elastomer (TPC) were prepared. The SMDs were mounted using an ECA composed of an epoxy-based binder and silver filler. In the study, the use of a hot embossing procedure to organize the conductive pattern was evaluated, and the impact of humidity was also assessed. The finding showed that delamination was a concern rather than conductive joints. In contrast, Guna *et al.* 2016 and Abdulrhman *et al.* 2022 utilized a different method of PCB fabrication. They deposited silver on the biodegradable substrate and then covered it with Cu. In Abdulrahman's work, a substrate made of polycaprolactone (PCL) was prepared, while Guna *et al.* 2016 established a composite consisting of banana fibers and wheat gluten. In both cases, the circuit components were mounted using ECA. Even after several days of use, the tests did not find any defects in the circuit. Staat *et al.* 2016 conducted a comparison between adhesive and soldering methods for mounting components on the biodegradable substrate. Additionally, their paper explores different finishing processes for pattern formation on the PLA substrate.

Bozó *et al.* 2021 have suggested the possibility of using bioplastics in the production of microelectronic components and devices, however, their study indicated that these materials exhibit inferior thermal and mechanical properties compared to conventional polymers. Many researchers have identified this as a general issue with biodegradables in electronic packaging. Additionally, the presence of silver in conductive adhesives can cause electrochemical migration, which may be influenced by the type of substrate used. Compared to conventional FR4 substrates, biodegradable substrates have a distinct surface structure, which affects how well liquids adhere to them. Increased sensitivity to electrochemical migration can result from this paired with less accurate conductive pattern structure (Medgyes *et al.* 2014). Biopolymers have high crystallinity and hydrophobicity, which makes them suitable for use as packaging materials (Liu *et al.* 2019). Cao & Uhrich 2019 have shown that the mechanical flexibility of synthetic polymers can be adjusted for stretchable biodegradable electronics.

6. ENVIRONMENTAL AND HEALTH IMPLICATIONS OF NPS AND COMPOSITE MATERIALS

In the last two decades nanotechnology has been contributing to the advancement of many areas that include health, environment, energy, and manufacturing. Some concerns have been raised on the potential environmental, health, and safety risks associated with nanomaterials. An increasing amount of research has indicated the adverse effects on humans, animals, and plants due exposure to NPs. These effects include cellular and DNA damage, carcinogenic and oxidative stresses, brain damage of animals, and bioaccumulation (Karunaratne 2015). It is clear that the widespread introduction of NPs into our lives, as well as their growth and accumulation in natural environments, provide justification for classifying them as a specific sort of pollution. Experts have determined that there are substantial differences in the behavior of smaller particles and the processes of nanoparticle transfer with air and water movements and their accumulation in soil, water, and bottom sediment (Terekhova *et al.* 2017). Unexpected concerns associated with nanomaterials exist for both people and the environment. In an effort to strike a balance between consumer safety and industrial interests, regulatory agencies in the European Union, the United States, and Asia closely monitor advancements in nanotechnology (Chen *et al.* 2020).

6.1. Release of nanomaterials into the environment

Anthropogenic and natural sources can both introduce NPs into the environment. For millions of years, biological items as well as forest fires, sandstorms, dust, confused waterways, aerosol creation, gas clustering, volcanic eruptions, and salt evaporation have been sources of nanomaterial entrance into the environment. The so-called inadvertent nanoparticle introduction into the environment is caused by several human objects and activities. They consist of home waste, mining activities, open pits and mines, industrial production and emissions, construction, welding, soldering, food preparation, and the burning of waste and fuel with combustion catalysts in transportation vehicle engines and at power plants. Various home and hygiene products, motor tire resin, typographic colors, textile products, and other items are polluted throughout their manufacturing, transit, and usage (Terekhova *et al.* 2017). NPs may enter the environment through bioplastic or recycled plastics. The End-of-Life choices for plastic items have historically received little attention, and as a result, plastics have accumulated significantly in the aquatic and terrestrial ecosystems due to their exceptionally high resistance to disintegration in natural environments. It is anticipated that hundreds of millions of metric tons of plastic garbage will build in the environment over the next few decades, despite quick and coordinated action. Coordinated worldwide efforts are required to reduce plastic usage, enhance recycling and reuse rates, and speed up innovation in the development of sustainable replacement materials in order to reverse this trend (Carroccio *et al.* 2022). Examples of nanomaterials and their possible environmental exposure are included in Table 2.

6.2. Exposure of nanomaterials to the ecosystem

The capacity of the NPs to enter and spread across the various environmental compartments (soil, water, and air) is a crucial determinant of their potential toxicity. The quantity of NPs released into the biosphere directly influences this effect. Therefore, the processes that regulate their release into the environment, the transportation between installations and zones or between organisms due to the food chain, and the potential transformations that can take place once they are released all determine the risks associated with the use of nanomaterials (Martinez *et al.* 2020). With regard to NPs exposure to the environment, three emission situations are often taken into account; they are release during the creation of the product and the synthesis of the NPs raw materials, release during usage, and release following disposal or waste processing (Surendranath & Surendranath 2020). The widespread use of nanomaterials may result in considerable releases into the environment, particularly the aquatic environment. Given that the release, spill, and disposal of nanomaterials may cause extensive contamination in a variety of water bodies through several direct and indirect pathways into the aquatic environment (Wang *et al.* 2008). In 2008, Ziccardi *et al.* discovered that C60 NPs may cross the blood–brain barrier and enter the juvenile largemouth bass (*Micropterus salmoides*) through the gills. Fish exposed to aqueous solutions containing 0.5 ppm C60 for 48 h revealed a little decline in glutathione levels in the gills and a considerable rise in lipid peroxidation in the brain, both of which might be signs of oxidative stress. Yamago *et al.* (1995) investigated the biological activity of a water-miscible C60 fullerene that was ¹⁴C-labeled in rats. Oral fullerene administration resulted in simple fecal elimination,

Table 2 | Production for engineered nanomaterials (The Royal Society 2004)

Product	Examples of nanomaterials	Potential release and exposure
Fuel additives	Cerium oxide	Exhaust emission
Cosmetics	TiO ₂ or ZnO	Directly applied to skin, washing off to the environment and the disposal of containers
Paints and coatings	Silver nanoparticles coatings and hydrophobic nanocoatings	Wear and washing
Soil regeneration	Calcium and phosphorus-based Nanoparticles	High local emission and exposure
Clothing	Silver nanoparticles coatings and hydrophobic nanocoatings	Absorption by the skin
Electronics, toys, and utensils	Carbon nanotubes	Electronic waste will lead to emission of CNT
Combustion processes	Ultrafine particles	Emission with the exhaust

whereas intravenous injections caused the body to store fullerenes for a week. The liver received 91.7% of the dosage of the fullerenes administered intravenously, although some of them were also able to marginally cross the blood–brain barrier. Nevertheless, nothing is known about how NPs are distributed in mammals. Nanomaterials cause cell surface inflammation, pierce cell membranes, and eventually exhibit cytotoxicity. Although it is thought that exposure to nanomaterials might cause atherosclerosis, heart stress, and the development of blood clots through inflammation, these effects have not been shown in both people and wildlife (Kashiwada 2006).

6.2.1. Pathways of nanomaterials in soil and water

Their entrance, accumulation, and movement are all characterized by the paths that NPs use to enter soil and water. NPs may contaminate soil by atmospheric precipitation, dust and aerosol deposition, direct gaseous chemical absorption by soil, leaf abscission, or human activity. After entering the water system via sewage or industrial emissions, NPs can build up in plant organisms (such as algae), invertebrate organisms (such as plankton, benthos, and crustaceans), which are the main components of a food chain, and aquatic vertebrate organisms that are a part of the human food chain (Terekhova *et al.* 2017). Most of the inorganic nanomaterials are not biodegradable and thus remain in the environment for a long time. This may lead to changes in the physicochemical and biological properties of water or soil, such as pH, toxicity, salinity, organic matter, and natural abundance and diversity (Perez-Hernandez *et al.* 2020). The effects of nanomaterials discharged into the environment include sedimentation, agglomeration, microbial adsorption, surface adherence, dissolution, and transformation. During their persistence in the environment, certain nanomaterials also undergo transformation via oxidation or reduction (Samanta & Manda 2017). According to Fang *et al.* (2009), when used in large amounts, NPs may potentially pose concerns to the environment and human health. To evaluate potential exposure pathways for people and the ecosystem, it is crucial to comprehend the fate and transit of NPs in the environment.

6.2.2. Toxicity of nanomaterials in plants

Nanooxides and carbonaceous particulates are a significant source of pollution for plants. They enter the ecosystem through artificial soil, which is increasingly popular for promoting plant growth quickly, pesticides made of inorganic and organic compounds as well as colloidal sulfur and lime, and recycled water (Bakshi 2020). Several NP varieties that affect plants have been thoroughly investigated under several circumstances. In a test using *Lycopersicon esculentum* Mill and *Lactuca sativa* L., the development of both cotyledonous plant species was observed to be affected by EC20 (236–414 mg/kg dry soil) of TiSO₄ (Perez-Hernandez *et al.* 2020). According to Deng *et al.* (2016), after 72 h of exposure, the CuO NPs (80 mg/L) completely suppressed the development of onion root tip. The same outcomes were discovered by evaluating the phytotoxicity of Ag NPs on *Capsicum annum* L. at increasing concentrations of 0.01–1.0 mg/L. This was done by measuring the reduction in plant growth. Le Van *et al.* (2016) conducted comparable research on transgenic cotton. After being exposed to 1,000 mg/L CuO NPs for 10 days, they discovered that the height and root length both fell by 26.91 and 42.80%, respectively, but that growth was unaffected by 10 mg/L. Due to their persistence, inability to degrade, and impacts on the entire trophic chain, pollution by inorganic compounds and heavy metals is one of the most serious environmental problems and has a negative impact on plant biodiversity (Matei *et al.* 2022).

Diffusion, bulk flow, and phloem loading are three ways by which NPs might travel through the plant systems. The size, shape, and surface features of the NPs, as well as the pH of the solution and the presence of other ions or chemicals, can all have an impact on how well they are transported. The ability of plants to control the flow of water and gases is greatly influenced by the stomata on their leaf surfaces. Various plant species have various stomata sizes and densities (Wang *et al.* 2023), and often range from 10 to 100 μm in size. Only a small number of plant species have stomata on both sides of their leaves; the majority only have them on the abaxial (lower) side. Eudicots often have more stomata on the abaxial leaf surface than the adaxial (upper) surface when both sides are present, whereas monocots have roughly equal numbers of stomata on both sides. The structure of mesophyll, which can either be loose or compact, resulting in small or large intercellular spaces (as in xerophytes) or both (as in some mesophytes and most hydrophytes), can affect the short-distance transport of NPs after they have penetrated the epidermis but before they have entered the vascular system in the leaf. Another organ that may absorb NPs is the root system of plants. It is important to note that eudicots have a long-lasting main root whereas monocots have fibrous root systems. Monocots may be more vulnerable to NPs exposure because of their larger root surface area (per fresh or dried weight) (Su *et al.* 2019).

6.2.3. Toxicity of nanomaterials to soil organisms

Engineered NPs are included under the functional category ‘engineers of the ecosystem’. McKee & Filser (2016) demonstrated that soil organisms at different trophic levels had negative impacts from Ag NPs at ecologically relevant values below 1 mg Ag/kg. When applying Ag NPs coated with citrate to soils with scouler cultures, Topuz & van Gestel (2017) found that after 21 days, the NPs had an impact on the soil’s pH, which resulted in a high mortality of *Enchytraeus crypticus* at higher concentrations of 60–100 mg/kg of dry soil. These soils had varying contents of organic carbon (0.67–1.61%) and pH-CaCl₂ (5.5–7.3). Comparable findings were made by Sillapawattana *et al.* (2016) who discovered that Ag NPs had the same impact on yeast and *F. candida* strains. The scientists came to the conclusion that the combination of the release of silver ions from Ag NPs and the creation of reactive species was what caused Ag NPs to be toxic to *F. candida*. Romero-Freire *et al.* 2017 discovered that the NPs of ZnO and ZnCl₂ had an impact on the survival, weight change, and reproduction of the *Eisenia andrei* earthworm. However, the characteristics and ageing processes affect how the NPs of ZnO and ZnCl₂ behave. The earthworm *Allolobophora chlorotica* had a behavioral shift in the Brami *et al.* (2017) experiment after being exposed to NPs for 14 days. In contrast to soils containing Ag NPs, a larger mortality was observed in silver nitrate NPs (66.7%), and the increase in silver ions was thought to be the cause of this (Perez-Hernandez *et al.* 2020).

6.2.4. Biotransformation of NPs in plants and soil organisms

NPs penetrate into plants tissues in two ways: the apoplast and the symplast. The way it transports plants is really important, because it can give indications about what parts of the plant they can reach, and where they might end and accumulate. For example, if NPs are transported mainly through the xylem and not the phloem, they will likely move mainly from root to shoot and leaves, and not downwards (Pérez-de-Luque 2017). When NPs with a size of up to 50 nm enter the cell wall of plants and microorganisms, they instantly permeate it. They pierce the cell wall and alter the cell’s cytoplasm’s conductivity. Therefore, the size of the NPs also plays an important part in the processes of surface interaction; when the size decreases, a greater number of atoms are exposed to the surface, and as a result, a greater number of atoms can interact with the bacterial cells (Samanta & Manda 2017). According to Rajput *et al.* (2019), once NPs are released into the environment, they are prone to translocation and undergo a number of alterations, including bio/geo-transformation, which is crucial in determining their final destiny in the environment. Review studies have demonstrated harmful effects on both plants and soil organisms. Plant species and NP physicochemical properties affect NPs uptake and toxicity. In hydroponic cucumber plants, Zhang *et al.* (2017) examined the translocation and transformation of octahedral, cubic, rod, and irregularly shaped CeO₂ NPs. The findings demonstrate that rod CeO₂ NPs converted more quickly and at a quicker rate than other CeO₂ NPs, with approximately 40% of Ce in roots (CePO₄) and shoots (Ce carboxylates) as Ce(III) species.

6.2.5. Transportation of NPs through the xylem and phloem

The type of NPs, the kind of plant, and the environment all affect how well plants absorb NPs. The absorption behavior of NPs in plant leaves can be influenced by variables such as particle size, chemical composition, surface charge, and surface modification. It has been discovered that stomatal pathways can allow metal-based NPs with a diameter of less than 50 nm to penetrate plant leaves. The capacity of leaves to absorb NPs reduced as particle size increased (Wang *et al.* 2023). Zhu *et al.* (2022) investigated the impact of stomatal opening and closing on the absorption of ZnO NPs and found that ZnO NPs mainly passed through the epidermis of wheat leaves by the stomatal pathway, and then accumulated in chloroplasts, decreasing by 33.2 and 8.3%, respectively, with the reduction in stomatal diameter.

There are three ways that plant–NPs interactions can occur: (a) on the plant’s surface (such as a leaf, root, or stem); (b) via the cuticle and epidermis; and (c) movement and modification taking place inside the plant (Su *et al.* 2019). NPs enter the cuticle and epidermis of leaves (just by stomata), where they have very simple access to the vascular system that runs downward, such as the phloem. The root’s excreted mucilage and exudates have the ability to trap NPs, preventing them from entering the root tissue. Short residence times for NPs on leaf surfaces due to high water/nano-suspension repellency imposed by the epicuticular waxes on the surface of leaves can affect their uptake (Wang *et al.* 2012a, 2012b). Tracheids and vessel components are the two different kinds of conductive cells found in the xylem. Pits, which are tiny openings surrounded by a porous pit membrane, are used to connect both cell types to their nearby neighbors. These pit membranes can act as a barrier to solute movement; perforation plates allow their relatively unimpeded transit (Su *et al.* 2019). For the majority of plants, the average sieve plate pores range between 200 nm and 1.5 µm, which should allow the passage of most NPs, unless they are in aggregated form (Jensen *et al.* 2012). The pit membranes of the conductive cells of the xylem

are porous, but they are designed to rest on the phloem's sieve cells, which are connected via porous sieve plates. Their pore diameters are in the range of 43–340 nm and have the potential to restrict the transport of NPs, which explains why NPs accumulated in some tracheids and vessel elements after plants were exposed to NPs because their transport was constrained by the pit membranes (Zhao *et al.* 2012).

6.3. Toxicity and uptake of nanomaterials in organisms and humans

Nanomaterials can harm the lungs and cause airway inflammation, bronchitis, asthma, emphysema, lung cancer, neurological illnesses, and cardiovascular consequences. This is mostly due to inhalation of dispersed nanoscale particles. NPs may enter the body through the digestive tract, lungs, and skin. This might contribute to the production of 'free radicals,' which can harm DNA and cause cell damage. Additionally, there is the worry that NPs may be able to pass through the blood–brain barrier if they are ingested and enter the bloodstream. The human body is more likely to find NPs hazardous since it lacks a natural immunity to novel chemicals. Sunscreen is an example of an everyday product that contains TiO₂. This may be of concern since TiO₂ may generate free radicals when activated by UV light, and if these radicals are absorbed by the body, they can result in cancer (Koo 2017). Because of their reactive surfaces, ultra-small particles have the potential to directly produce dangerous oxyradicals that can injure cells by destroying their DNA, proteins, and membranes. Additionally, the capacity of these particles to enter cells and the body (via caveolae and fluid-phase endocytosis) offers prospective avenues for the distribution of NPs (Liu *et al.* 2013). Recent research offers compelling evidence that NPs can actively engage in and influence molecular processes that are crucial for controlling how cells behave in addition to passively interacting with cells. The fate of inorganic NPs in the environment and potential toxicity in living things are thought to be influenced by their interfacial features, which include the speeds of reactions mediated on the surface, adsorption capacity, and change in redox status (Auffan *et al.* 2009). The toxicity, persistence in the environment, and bioaccumulation of NPs all affect the dangers they pose to human health. In general, people can absorb NPs through food, inhalation, or, under rare circumstances, through skin absorption. When NPs are inhaled, they can have a significant negative impact on a person's health in one of these two ways: they can cause tissue damage and systemic effects by inducing inflammation of the respiratory tract, or they can travel through the bloodstream to other important organs or tissues in the body, where they may result in extrapulmonary and cardiovascular complications (Roes *et al.* 2012). Aquatic creatures were used in research, which proved that the presence of NPs in a medium causes lower fertility, physiological alterations, aberrant behavior, and an increased death rate. Both the concentration of nanomaterials and the techniques utilized to create their aqueous suspensions have an impact on these effects (Krysanov *et al.* 2010). According to Paquin *et al.* (2002), almost all theories of toxicity presuppose that a toxicant must enter a cell (often via a receptor) before a toxic response can be seen. The most common and plausible method for eukaryotic cells to take up NPs is receptor-mediated endocytosis, which results in their accumulation in the cytoplasm and interaction with intracellular organelles. Inhaled ultrafine TiO₂ particles were observed by Geiser *et al.* (2005) to be disseminated across several lung compartments and to be mostly located in the cytoplasm of cells, but they were not membrane-bound, indicating that endocytosis was not the mechanism of absorption. Additional research utilizing red blood cells as a model for non-phagocytic cells shows that fluorescent spheres, TiO₂, and gold NPs with a diameter of 200 nm may enter the cells by adhesive contact or diffusion (Apte *et al.* 2009).

6.4. Health and safety aspects of nanomaterials

The exposure to NPs may damage the lungs by causing inflammation, tissue changes, and an increased susceptibility to infection. Skin cancer can be brought on by NPs penetrating the skin. Unintended hand-to-mouth material transfer can result in ingestion of NPs, which can cause digestive issues. Particularly hand-to-mouth contact between engineers, scientists, and industrial employees who are working on cutting-edge items in laboratories. As an alternative, these NPs can be consumed directly through food, water, medications, or medication delivery systems. Finally, NPs can produce genetic changes in cells directly or by inducing inflammation, and they can migrate from the respiratory system into the gastrointestinal tract after being cleared by the mucociliary escalator. Nanomaterials are also considerably more easily absorbed by the human body than equivalently sized bigger particles due to their incredibly tiny size. One of the problems that has to be overcome is how these NPs act inside the body. The buildup of non-degradable or slowly degradable NPs in organs is a significant worry. These substances will adsorb onto their surfaces and some of the macromolecules they come into contact with when exposed to tissue and fluids, which might alter the regulatory processes of enzymes and other proteins (Thomas *et al.* 2014). Most research has shown that exposure to nanomaterials will be through goods that incorporate nanomaterials

in their product. Personal care items, sunscreen, household paints, and even sporting goods are some of products that may contain nanomaterials, a greater safety concern would be at the factories where these products are produced, where the concentration and exposure levels are much higher than those from handling consumer products (Koo 2017). According to Eastlake *et al.* (2012) the majority of the material safety data sheets (MSDSs) for full disclosure of the properties and safety of a substance supplied by the manufacturer provide insufficient information for communicating the potential hazards of nanomaterials. The majority (67%) of MSDSs acquired in 2010–2011 still lacked the information necessary to communicate the possible risks of manmade nanomaterials. Assessments of the potential risks posed by nanotechnology have begun to emerge, but there are still many obstacles to overcome because it is impossible to quickly and thoroughly assess the safety and environmental consequences of every form of NP (Chen *et al.* 2020).

Major barriers to assessing the safety and environmental consequences of NPs include the lack of adequate detection and characterization techniques, the lack of reproducible and validated methods for toxicological studies, and the slow development of practical and reliable tools to ensure the safe and sustainable use of NPs (Johnston *et al.* 2020). Therefore, it is necessary to create techniques for identifying and characterizing NPs in complex matrices as well as figuring out how NPs transform in such environmental media. Additionally, more validated techniques and reference materials must be made available to enhance both material characterization and nanosafety research. Current gaps in nanotoxicology can be filled by emphasizing precise dosimetry, adequate control trials, and more realistic *in vitro* models. Lastly, there is a need for trustworthy data and enhanced NP data reporting procedures.

6.5. Nanoagriculture

The term ‘nanoagriculture’ is used to describe a wide range of novel technologies that involve nanoencapsulating traditional fertilizers, insecticides, and herbicides to provide exact dose to plants through a delayed and sustained release of nutrients and agrochemicals (Perez-Hernandez *et al.* 2020). With NPs of Ag, ZnO, CuO, TiO₂, Au, Fe, Zn, and Mn, Duhan *et al.* (2017) highlighted the prospective applications and advantages of nanotechnology in precision agriculture (nanofertilizers, nanofungicides, nanoherbicides, nanobiosensors, and nanobarcodes). The composition of the nanoparticle itself, as well as the physiology of the plant and how the nanomaterials interact with the environment, all have an impact on how well NPs are absorbed by plants. Figure 5 highlights the factors that affect how well NPs are absorbed and taken up by plants.

The characteristics of NPs will have a big impact on how they behave and if the plant can take them in. There have been studies on the largest dimensions that plants permit NPs to travel and aggregate inside the cells, often with a size exclusion limit of 40–50 nm. Size appears to be one of the primary barriers to penetration into plant tissues (Pérez-de-Luque 2017). According to Larue *et al.* (2012), and Zhu *et al.* (2012), various plant species from various botanical families that were subjected to magnetic carbon-coated, TiO₂, or gold NPs showed varied patterns of absorption and accumulation inside the plants. However, the methods of application are equally important in determining how well a plant would internalize the nanomaterials. For instance, the presence of humic acids and other organic matter in the soil might increase the stability and subsequently the bioavailability of nanomaterials, whereas salt ions may cause precipitation and have the opposite effect (Navarro *et al.* 2008).

Nanotechnology is widely used for food and agricultural benefits. But there are still a lot of unanswered problems regarding the toxicity, environmental and human safety of NPs (Neme *et al.* 2021). Because of their possible danger of entering cells and probable presence in the system, nanomaterials are linked to a number of safety concerns. The use of NPs in nanoagriculture might be deleterious owing to the several antagonistic effects of different NPs. In food packaging, the degradation of NPs can occur owing to environmental conditions with the release of inserted nanomaterials from polymeric texture into the environment. In nano-agrochemicals, such as nanopesticides, nanofertilizers, and nanosensors, the accumulation of NPs in the soil is expected to impair plant growth and accumulate into edible plant tissues. Finally, once the NPs are released into the agro-environment, they immediately begin to undergo a number of transformations. The exposure of farmers to NPs and NPs transformation products is one of the major concerns.

6.6. Future prospects and recommendations in environmental health

The increasing usage of engineered NPs in a variety of commercial goods and the quick development of nanotechnology call for more focus on risk analysis and waste management. Because of their distinctive features, engineered NPs are likely to be of concern, according to the weight of the literature. Two key issues must be resolved in order to advance in the assessment of the risk posed by engineered nanomaterials: (1) comprehensive and standardized tests (data) are needed for NPs toxicity and

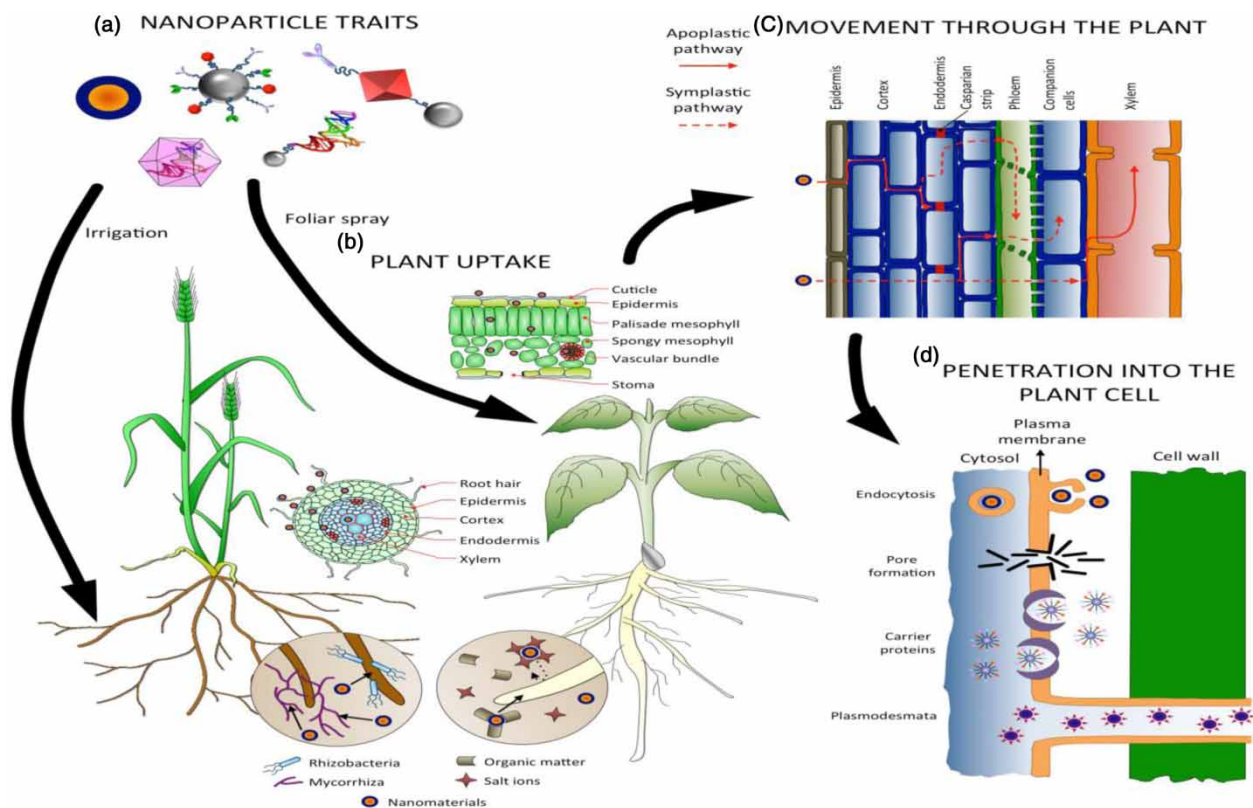


Figure 5 | Factors influencing absorption and uptake of NPs in plants (Pérez-de-Luque 2017).

dose response assessment, as there may be significant variation among laboratories and (2) better data on the potential exposure of NPs in the environment is required, such as their levels, forms, environmental pathways, transformation, and fate. Finally, it is critical to emphasize that the actual legislation regarding these contaminants is out-of-date. Even so, striking a balance between scientific advancement and sustainable development would need the creation of new, exact regulations that rigorously control NPs' emissions.

7. CONCLUSION

NPs' reduced size range of 1–100 nm makes them ideal for different applications. Compared to larger particles, they have different physiochemical and biological characteristics. Nanomaterials may be used in a variety of water and wastewater treatment processes thanks to their unique properties. The non-toxic nature of some NPs make their application useful in degrading and removing water pollutants. Agglomeration and difficulty of separation from the treated media are the major drawbacks associated with NPs application for wastewater, however, these challenges can be overcome by adding an appropriate material as composite. Bio-based NCs are cheap and alternative nanomaterials to treat industrial wastewater and very effective in water refinement and with special features of eco-friendliness, affordability and reusability.

Several composites have been employed in the formation of NCs with antibacterial activity. Some such antibacterial NCs can be polymeric or non-polymeric in nature depending on whether a polymeric material is incorporated into the composites or not during the formation of such nanoantibiotics. Bacterial pathogens possess lots of virulent factors which are genetically encoded and play an important role in disease pathogenesis. However, the development of nanoantibiotics has proffered solutions in the treatment of nosocomial infections and other diseases resulting from the presence or acquisition of resistant genes which have posed a global public health problem with lots of economic challenges. As an emerging area in the technological revolution for the 21st century, nanoantibiotics is still in its infant stage and needs to be focused on as an alternative paradigm for the development of therapeutic agents against multi-drug resistant pathogens. The review also discussed the use of biodegradable materials in printed electronics, focusing on flexible substrates and the importance of maintaining reliability

and quality. It was demonstrated that the addition of nanomaterial fillers could improve the physical properties of biodegradable matrices, allowing for novel functionalities and meeting the demands of advanced applications. While current examples are mostly laboratory prototypes, the technology readiness level is expected to increase in the future, leading to more promising applications of biodegradable substrates.

The extensive use of nanomaterials in various fields requires attention to the risk assessment and waste management associated with them. The increasing amount of research has indicated the adverse effects on humans, animals, and plants from exposure to NPs. Thus, the development of new and precise laws that strictly regulate NPs' discharge, use and application is highly necessary and essential. The exceptionality of this review is that it provided a broad explanation into the scope, concept, synthesis, application, and harmful effects of NCs. It also gave insights into challenges, research gaps and future consideration of the application of NCs and provided a broad list of NCs that could be explored.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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