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Review article

Naturally occurring nanoparticles (NONPs): A review

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ABSTRACT

Nanotechnology represents a burgeoning scientific field that focuses on materials within the nanometer size range. Nanoparticles, categorized as incidental, engineered and naturally occurring nanoparticles (NONPs), constitute a critical aspect of nanotechnology. Incidental nanoparticles are inadvertently generated as byproducts, engineered nanoparticles are synthesized by humans for diverse applications and NONPs exist naturally in the environment. NONPs are further categorized based on their location in the environment, such as Naturally Occurring Carbon Nanoparticles, Naturally Occurring Metal Nanoparticles, NONPs present in food, NONPs of biological origin and NONPs present in the aquatic environment. NONPs exhibit ubiquity, spanning the atmosphere, hydrosphere, lithosphere and biosphere. They exhibit distinct properties in comparison to their bulk counterparts, such as a substantial surface area-to-volume ratio, immune-boosting capabilities, scavenger activity, nutritional significance and electron-donor attributes. NONPs have been utilized by humans since ancient times. Owing to these properties, they have been used unknowingly in various fields like medicine, cosmetics, decor, textile and the food industry. NONPs are found in artifacts such as Copper Ruby and the Lycurgus Cup, as well as in medicine, cosmetics and the food industry. Even today, NONPs continue to play pivotal roles in diverse fields such as cancer treatment, biosensors and the food industry. Also they contribute to environmental processes, soil fertility, nutrient transport and bioremediation. This review sheds light on multifaceted significance of NONPs in our evolving scientific landscape and comprehensively explores the history, sources, properties, types and uses of NONPs. It also focuses on the fate of NONPs in water, soil and plants and their environmental and human hazards. A special section on the environmental transformation of NONPs is included.

1. Introduction

Nanoparticles are materials characterized by dimensions falling within the range of 1–100 nanometers, rendering them imperceptible to the unaided eye. As per the definition established by the International Organization for Standardization (ISO), nanoparticles encompass materials possessing external nanoscale dimensions or an internal nanoscale surface structure [1]. These entities manifest markedly distinct physical and chemical attributes compared to their macroscopic counterparts in terms of size, shape, chemical composition and stability. Notably, the mechanical properties of nanoparticles, exemplified by the transition of bulk copper from a soft material to the hardness exhibited by copper nanoparticles smaller than 50 nm, illustrate the profound effects of nanoscale dimensions on material behavior. Similarly, gold nanoparticles of 2.5 nm exhibit a significantly lower melting point of 300°C compared to the bulk gold's melting point of 1064 °C [2]. The ISO definition further extends to encompass diverse nanostructures such as nanofibers, nanoplates, nanowires, quantum dots and related terms. This burgeoning scientific domain, leveraging the unique characteristics of nanoparticles at the nanoscale, is denoted as Nanotechnology [3]. It is imperative to distinguish nanoparticles from ultrafine particles, notwithstanding their shared nanometer-scale dimensions. While both categories exhibit nanoscale sizes, their origins differ substantially. Ultrafine particles, stemming from anthropogenic activities like diesel combustion and tobacco smoke, represent air pollutants [4–6]. In contrast, nanoparticles are classified into three categories based on their source: incidental nanoparticles, engineered nanoparticles and naturally occurring nanoparticles (NONPs).

Incidental nanoparticles arise inadvertently as byproducts of industrial processes, encompassing emissions from vehicle engines, welding activities, combustion processes and natural phenomena such as forest fires. Engineered or synthetic nanoparticles result from human-driven

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processes, employing physical, chemical, biological, or hybrid methodologies. The escalating presence of engineered nanoparticles in the environment raises concerns regarding potential impacts on human health [3]. Even the engineered nanoparticles from biological source have cytotoxic effects. One such example is of gold nanoparticles synthesized from a biological source that is by using the medicinal plant *Andrographis paniculata*, showing cytotoxic effects on Zebrafish embryos with LC50 of 116 µg/ml inducing morphological and developmental changes. The mechanism predicted these changes were due to hypoxic condition and metabolic protein interaction which led to higher oxidative stress causing apoptosis inside the embryos [7]. Naturally occurring nanoparticles (NONPs) are those that are neither intentionally synthesized by humans nor artificially created but rather exist naturally in the environment or are formed through natural processes. The term "environmental nanoparticles" is also used to describe NONPs, reflecting their pervasive distribution throughout the environment [8]. This review concentrates on the historical context, sources, properties, types, applications, fate and adverse effects of NONPs.

Humans have unknowingly utilized NONPs since ancient times, dating back to around 4500 B.C., with continued applications for the betterment of humanity and the environment. Nanotechnology has opened a new industry of production of nanomaterials which are biocompatible and specifically made from metal and metal oxides. These nanomaterials are used for catalysis, magnet cooling, optical and recording devices, purification of enzymes and other biological materials, water purification and targeted drug delivery [9]. NONPs are ubiquitously present in the atmosphere, hydrosphere, lithosphere and biosphere. They are further categorized based on their environmental presence, including Naturally Occurring Carbon Nanoparticles (NOCNPs), Naturally Occurring Metal Nanoparticles (NOMNPs), NONPs in food, biologically derived NONPs and those found in aquatic environments. Due to their distinctive properties, such as substantial surface area, adsorption capabilities, electron-donating characteristics, robust electrostatic interactions and unique optical, magnetic, biological and electronic attributes, NONPs find extensive applications in cosmetics, medicine, textiles, agriculture and other fields. However, the journey of NONPs in the environment involves interactions with soil, water and plants, subjecting them to physical, chemical and biological transformations.

2. History

A timeline of the history of NONPs is mentioned in Fig. 1

2.1. Ancient times

Humans have been unknowingly using nanoparticles present in nature since ancient times, which is evident from the use of ceramic matrices made of natural asbestos nanofibers over 4500 years ago [3]. The nanosized clay minerals present in soil were used for industrial and commercial purposes, such as bleaching clothes, manufacturing thin ceramics, cosmetics, medicine and the food industry in China, Cyprus and Greece [10]. Nanoparticles are also present in food, such as milk and milk products, consumed by humans since ancient times [11].

2.2. Organic dye

Two thousand years ago in the Greco-Roman period, organic dye from plants, such as Heena was used which consisted of lead sulfide. The lead was observed to be deposited on the hair shafts, whereas the sulfur reacted with the keratin protein in the hair. In recent studies, it was discovered to be a 5 nm PbS nanoparticle [12].

2.3. Egyptian blue

During the third millennium BC (3000 BC), Egyptian blue, a durable pigment, was used extensively for decorative purposes in ancient Egypt, Mesopotamia, Greece and Roman Empire. It is a mixture of monolayer nanosheets of calcium copper tetrasilicate, $CaCuSi_4O_{10}$ and SiO_2. The characterization of Egyptian blue started in the 19th century and it was discovered to be acid resistant. A colloidal suspension of Egyptian blue in water at 80°C formed nanosheets and nanoplatelets which were later visualized using a Transmission electron microscope [13].

2.4. Copper ruby

Gallo-Roman opaque red glass, also known as copper ruby, was found by Pettenkofer in an archaeological excavation that aged between the 4th to 1st BC. The colour of the glass was due to the naturally occurring copper nanoparticles of size around 50 nm which was discovered later using TEM and XRD [14].

2.5. Lycurgus cup

The exquisite Lycurgus Cup also known as cage cups was made by Romans in the 4th AD using gold droplets made by nanofabrication where nanosized gold metal wires were used which is now placed in the British Museum by Lord Rothschild in 1958. It is dichroic, that is, it appears to be opaque greenish yellow in colour whereas when light

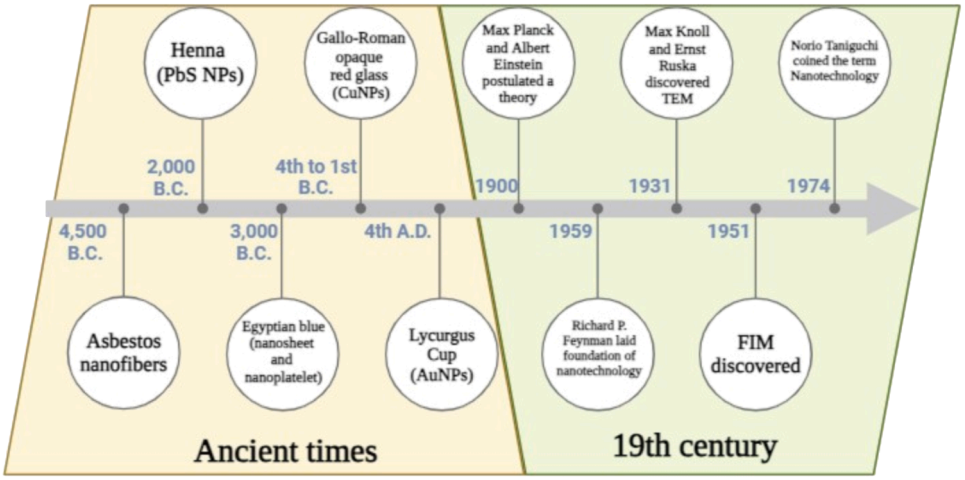

Fig. 1. History of NONPs (Naturally occurring nanoparticles).

passes through it turns translucent ruby red colour. Later it was found to be a mixture of gold and silver nanoparticles [15,16].

2.6. 19th century

In 1900, Max Planck and Albert Einstein postulated a theory that there must be a range of tiny particles which obeyed their own laws. Also, the foundation of nanotechnology was laid by Nobel prize winner Richard P. Feynman in 1959 who mentioned in his paper that "There's Plenty of Room at the Bottom. An invitation to enter a new field of physics". Around fifteen years later, in 1974 the term "nanotechnology" was coined in by Norio Taniguchi and was defined as, "nanotechnology mainly consists of the processing of separation, consolidation and deformation of materials by one atom or one molecule" [17]. Although the term nanotechnology was explained in 1974, the exploration of this field remains ongoing. Even though nanoparticles were used for centuries, their study started only after the discovery of the transmission electron microscope (TEM) developed by Max Knoll and Ernst Ruska in 1931. For example, viruses are one of the NONPs which existed in nature for millions of years but only after the discovery of the first electron microscope it was discovered that the Tobacco mosaic virus is nanosized [18]. In the 19th century, nanoporous ceramic filters were used to separate viruses [17]. Further characterization of NONPs was possible after the discovery of the field ion microscope (FIM) by Erwin Wilhelm Müller in 1951, scanning tunneling microscope (STM) by Gerd Binnig and Heinrich Rohrer in 1981 and atomic force microscope (AFM) by Gerd Binning, Calvin Quate and Christoph Gerber in 1986.

3. Source

NONPs are present in nature in stable form almost everywhere i.e atmosphere, hydrosphere, lithosphere and biosphere and most importantly the area which extends from the topmost forest canopy down to the deepest groundwater aquifer is the critical zone of the earth. This zone is very important because it has strong effects on living organisms in the soil, water and air [8]. The sources of NONPs are explained diagrammatically in Fig. 2.

3.1. Atmosphere

The atmosphere consists of different layers starting from the innermost layer troposphere (from ground level to 25 km), stratosphere (35 km to 70 km), mesosphere (70 km- 90 km), thermosphere (90 km - 500 km) and outermost is ionosphere (500 km and above). The UV-protective ozone layer is present between the troposphere and stratosphere (25 km - 35 km) [19]. NONPs are present majorly in the troposphere where there are more human and geographical activities. The geographical activities include weathering, earthquakes, volcanic eruptions, forest fires, microbial reaction activity, chemical reactions processes taking place in nature, etc. which give rise to particulate matter. This particulate matter released from the ground gets trapped in the troposphere, condenses with acids, bases and volatile organic compounds (VOCs) and forms clusters having weak intermolecular forces. These clusters formed are in the 50–100 nm size range which further nucleates and forms nanoparticles that grow further by agglomeration and condensation with other particles [19]. Other mechanisms, such as classic crystal growth, aggregation, redox-triggered crystallization, etc, have been reported to be involved in the inorganic growth mechanisms of these NONPs [8]. The nanoparticles move from the troposphere to the stratosphere and finally to the lower mesosphere by the process of vortex motions in the atmosphere [20]. Further movement of nanoparticles to the upper mesosphere takes place rarely due to climatic uncertain conditions like meteor attacks. In 1964, a 3-D chemistry-climate model (CCM) was constructed to prove this theory in which $^{238}PuO_2$ nanoparticles were observed to be deposited in the upper mesosphere [21].

3.2. Hydrosphere

In hydrosphere, NONPs are present in oceans, seas, rivers, lakes, ponds, groundwater and hydrothermal vents [3]. Water sources in the critical zone such as groundwater, lakes and rivers contribute to 1 % of the drinking water and agricultural use thus NONPs present over here directly affect the living organisms [8]. NONPs present in the hydrosphere includes iron oxides/sulfides such as FeS_2, Fe_2O_3, SiO_2, Al_2O_3, MnO_2 and silver and gold nanoparticles [22].

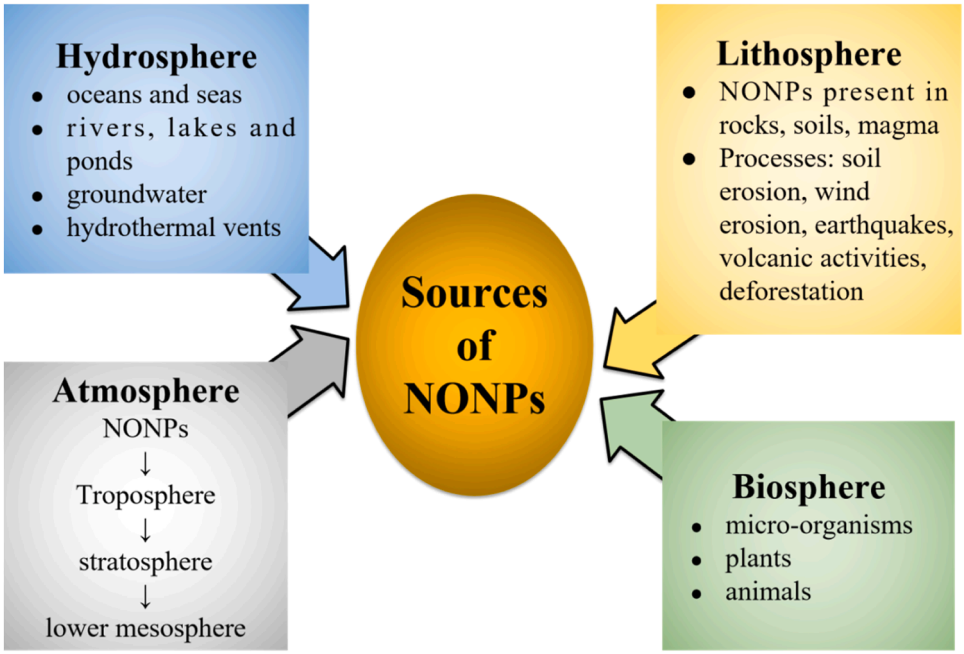

Fig. 2. Sources of NONPs (Naturally occurring nanoparticles).

3.3. Lithosphere

NONPs in this zone are formed by mechanical processes such as soil erosion, wind erosion, earthquakes, volcanic activities, deforestation, etc. First, nanoparticle growth and nucleation occur and then through hydrothermal vents, they are deposited on land and so are found in rocks, soils, magma, etc. NONPs present in the lithosphere includes ferrihydrite nanoparticles, Mn, Cr, Cu, Ba and Pb nanoparticles. [22].

3.4. Biosphere

NONPs are synthesized by microorganisms and plants and are present in lower as well as higher animals including humans [3]. NONPs are produced by microorganisms through various mechanisms, such as redox reactions, methylation, demethylation, etc. In redox reactions, the metal precipitates that is the metal nanoparticles, formed as by-products, are excreted out of the microbial cell. Mn-oxidizing bacteria produce Mn-NONPs by this method. The microbial mineralization process also produces NONPs [8]. Eukaryotes like insects, possess NONPs and nano-wax for survival and protection from predators. Other examples include marine mussels which have nanopolymer coating which helps them to adhere to any substrate. Similarly, lotus leaves are also covered with nanolayers which makes the leaves superhydrophobic [23].

NONPs are also present in plants due to the uptake of minerals from the soil which accumulates in nanoform. NONPs are present in animals in form of DNA, enzymes, hormones, antibodies, other proteins and secretions, etc which carry out important biological processes [3].

4. Properties

NONPs have unique properties such as large surface area, adsorption property, electron donor, strong electrostatic interactions and unique optical, magnetic, biological and electronic characteristics which resulted in their wide applications [10,24]. The properties of NONPs are affected by their source, for example, the iron oxide NONPs synthesized by abiotic source and by biotic source shows different optical and catalytic properties [8]. Some major properties are diagrammatically represented in Fig. 3 and are explained below:

4.1. Surface area to volume ratio

NONPs have the unique property of large surface area which means in small volumes, a larger surface area of NONPs is exposed. Due to this property NONPs become an efficient candidate for biological activities such as antimicrobial activity observed in metallic nanoparticles such as copper, aluminum, gold, silver, magnesium, zinc and titanium [25,26].

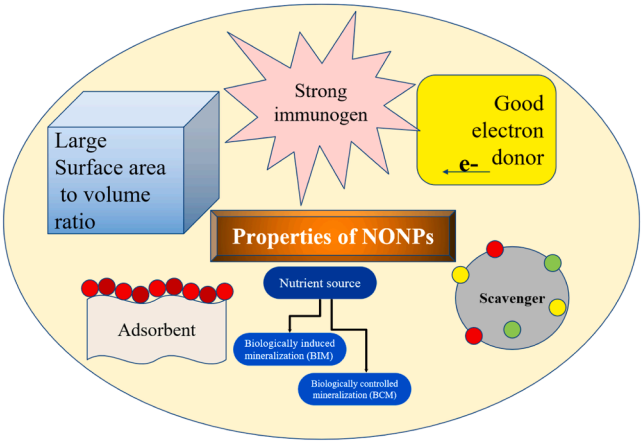

Fig. 3. Properties of NONPs (Naturally occurring nanoparticles).

4.2. Immunogen

According to "Dorland's Medical Dictionary" and the book "Basic Immunology", the immunogen is defined as "a substance capable of inducing an immune response; in most contexts immunogen is synonymous with the term antigen; in some contexts, however, the immunogen is used to draw a distinction between substances capable of inducing and reacting only with antibody (antigen or haptens) or to denote a form of antigen that induces an immune response as opposed to a tolerogen, a form that induces tolerance" [27]. NONPs have highly active surface molecules which increase the efficiency of MHC class II molecules by 5 fold as well as increase the proliferative efficiency of immune cells due to MHC class I molecules. This increased activity of immune cells increases the chances of the capture of luminal and surface antigens [4]. Viruses such as HIV, influenza, etc are also one of the NONPs as their size range in nanometres and act as a strong immunogen [28].

4.3. Electron donor

Electron donors are ions or molecules that donate electrons and are reducing agents. Iron-containing NONPs such as iron oxides and oxyhydroxides act as electron-donor in various biogeochemical processes. Iron oxides through redox reactions transfer electrons from primary rocks to sedimentary environments depositing around 10^5 Teragram of naturally occurring iron oxide is present in the soil [29,30].

4.4. Adsorbents

An adsorbent is a substance that adsorbs other substances. Iron oxide NONPs have a large surface area and chemical activity which contributes to their adsorbing property. These nanoparticles can be used for the immobilization of heavy metals [29].

4.5. Nutrient

NONPs are a source of nutrients for plants and animals [29]. NONPs are synthesized naturally by microorganisms by two methods biologically induced mineralization (BIM) and biologically controlled mineralization (BCM). In BIM microorganisms do not play a major role in NONPs synthesis but only form a support media for the process that is NONPs are formed due to microorganism's metabolic processes, whereas in BCM, nucleation and growth of NONPs take place inside the microorganism under optimum conditions. These NONPs are called nanominerals and the process is called biomineralization. Examples of nanominerals are Fe-based nanominerals, Si-based nanominerals, calcium carbonate-based nanominerals and calcium phosphate-based nanominerals. [22,31].

4.6. Scavenger

Heavy metals are present deep inside the earth's crust and thus are not exposed to the environment. But due to anthropogenic activities like mining these heavy metals are brought to the earth's surface, causing adverse effects on the environment. Iron NONPs act as scavengers for these heavy metals such as As (Arsenic) and U (Uranium), hence protecting the environment from its toxic effects [29].

5. Types

Different types of nanoparticles based on their origin are diagrammatically represented in Fig. 4 and explained in detail below:

5.1. Naturally occurring carbon nanoparticles (NOCNPs)

Carbon Nanoparticles are spherical black powder that enters nature through various natural sources like fossil fuel combustion, forest fires,

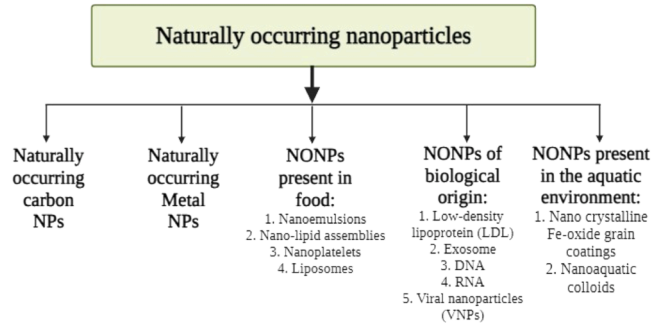

Fig. 4. Types of NONPs (Naturally occurring nanoparticles).

combustion of oils and automobile exhaust. About 15 % of the total natural NOCNPs are derived from wildfire charcoal. NOCNPs are also formed from fossil coal combustion but in negligible amounts. NOCNPs have high stability, good conductivity and low toxicity to humans and animals. NOCNPs are used as good adsorbents, sensors, catalysts, drug delivery, medical imaging, cancer treatment and electronic devices [32].

5.2. Naturally occurring metal nanoparticles (NOMNPs)

NOMNPs encompass non-organic nanoparticles (NONPs) composed of materials such as titanium dioxide (TiO_2), cerium oxide, iron oxides, iron oxyhydroxides, zinc oxide (ZnO), gold, silver, palladium, cobalt, mercury, beryllium, chromium and nickel. Among these, gold, silver and platinum NONPs have been extensively investigated. These metallic NONPs find applications across diverse domains while concurrently exhibiting deleterious impacts on human health and the environment.

For instance, silver nanoparticles find utility in inks, catalysts, cosmetics, electronics, textiles and optics due to their exceptional electrical and thermal conductivity properties, as well as their antibacterial activity. However, these silver nanoparticles also elicit adverse effects, such as the modification of microbial community structure and microorganism function, sublethal effects on plants and animals and bioaccumulation in both plant and animal tissues [33]. Metal oxide nanoparticles are extensively used in the field of medicine such as antibacterial, antifungal, drug delivery, tissue engineering, wound healing, etc. Their toxic effects can be ignored upon high usage and accumulation as they are biocompatible thus a perfect candidate for medical technologies [34].

5.3. NONPs present in food

5.3.1. Nanoemulsions

It arises through the nanoscale amalgamation of two immiscible liquids, exemplified notably in the case of milk. Nanoemulsions, distinct from raw emulsions, pose challenges in their formulation due to the influence of Laplace pressure. Characterized by transparency, stability, sub-visible wavelength sizes and manifestation of Brownian motion, nanoemulsions represent a unique and intricate liquid state at the nanoscale [11,35].

Nanoemulsions, infused with fluorescent dyes and molecules, serve as versatile probes for cell exploration and drug delivery. Their liquid nature offers potential for discovering novel cellular uptake pathways. Capable of incorporating both oil and water-soluble drugs, nanoemulsions find applications in pharmaceuticals, personal care and food industries, delivering moisturizers efficiently and blocking UV light without residue. In medical patches, nanoemulsions show promise.

In printing and data storage, the idea of using zeptolitre droplets for higher resolution is considered. While technological challenges exist, nanoemulsion inks could enable piezo-driven and thermally-driven printers for improved precision [35].

5.3.2. Nano-lipid assemblies

These lipid molecules are found in food products, such as milk, exhibiting nanoscale dimensions with favorable physical attributes derived from their crystalline structure. The macroscopic properties of bulk lipid molecules result from the cumulative effects of crystalline material content, crystal size and shape, spatial arrangement of crystals and the extent of intercrystalline interactions. These identical structural attributes also underpin their physical characteristics at the nanoscale [11].

Nano-lipid assemblies have been engineered for diverse applications in soft matter physics and synthetic biology, employing lipids to create bio-mimetic systems. Beyond conventional bilayer films, liposomes and micelles, lipids exhibit the capability to form lipid nanotubes (LNTs). These LNTs play a role in modulating the nucleation, growth and deposition of inorganic substances on both their external surface and within their hollow core. Consequently, LNTs can serve as scaffolds for the construction of one-dimensional (1-D) nanostructures, including arrays of quantum dots and hybrid nanotubes comprising functional inorganic nanoparticles embedded in the lipid membrane wall [36].

5.3.3. Nanoplatelets

Edible commodities like milk, chocolate, margarine, lard, etc., consists of solid fats characterized by dimensions of approximately 200 nm in length, 80 nm in width and 20 nm in thickness. These nanoscale platelets, constituting colloidal fat crystal networks, are denoted as nanoplatelets and fall within the category of naturally occurring nanoparticles (NONPs). The aggregation and size modulation of these nanoplatelets can be achieved through processes involving heat and mass transfer [11,37].

5.3.4. Liposomes

Ingredients like monoglycerides and phospholipids undergo spontaneous reactions, resulting in the formation of nanoscale structures known as liposomes. These structures, also referred to as mixed micelles, are prevalent in food. When polar lipids are combined in liquid environments, they give rise to single or multiple-lamellar liposomes. These liposomes, with dimensions as small as 10 nm, exhibit biocompatibility, thermodynamic stability and colloidal stability [11]. The different types of liposomes based on their dimensions and bilayer volume are tiny single lamella (10–50 nm), sizeable single lamella (50–1000 nm) and several lamellar (20–100 nm). Multiple bilayers when entrap in aqueous fluid it give rise to multilamellar vesicles (>0.5 m, >5 bilayers) that are resolvable due to interactions of non-covalent such as London dispersion forces and electrostatic dipole-dipole interaction between molecules [38].

Their application in targeted drug delivery is noteworthy, encompassing formulations of drugs such as amphotericin B, doxorubicin, verteporfin, cytarabine, morphine sulfate and daunorubicin for the treatment of diverse cancers, including ovarian, breast, lung, head, neck, pancreatic and gastric cancers and Alzheimer's disease [38–40].

5.4. NONPs of biological origin

5.4.1. Low-density lipoprotein (LDL)

It represents a lipid molecule indigenous to mammals, featuring a singular layer of phospholipid enveloping a hydrophobic core. Serving as a carrier protein for cholesterol, it exhibits a size of approximately 22 nm, categorizing it as naturally occurring nanoparticles (NONPs). Renowned for its organized delivery system, researchers employ it for precise drug targeting applications. The low-density lipoprotein (LDL) interfaces with the surface receptor, LDLR (LDL receptor), on the target cell, leading to fusion with the target cell's membrane and subsequent endocytosis. Within the cell, fusion with lysosomes ensues, facilitating the breakdown of LDL particles into amino acids, fatty acids and free cholesterol. Furthermore, NONPs LDL aids in the transportation of small interfering RNA (siRNA), a gene silencing tool, to the target cell

[41–43].

5.4.2. Exosomes

These are naturally occurring nanoparticles (NONPs) ranging in size from 30 to 100 nm, released via exocytosis by various cellular entities, including tumor cells, red blood cells, platelets, lymphocytes and dendritic cells. They are also discernible in biological fluids such as blood, urine and plasma. Comprising a phospholipid bilayer bearing surface proteins that facilitate interaction with specific cells, exosomes exhibit the potential to evoke an immunogenic response. Extracted from samples through ultracentrifugation, exosomes stand as a promising platform for targeted drug delivery systems [39].

5.4.3. DNA

It constitutes the cellular genetic material, following the central dogma wherein DNA undergoes transcription to form mRNA and subsequently, mRNA is translated into proteins. Thus, DNA, as a naturally occurring nanoparticle (NONP), assumes a pivotal role in the 'bottom-up' approach of nanotechnology. Researchers construct a nanogrid structure utilizing DNA, characterized by substantial cavities and specific binding sites. Notably, Yan et al. designed a DNA nanogrid in a plus shape, with each DNA tile comprising nine DNA strands. DNA functions as both an electron donor and acceptor, serving as a conductive nanowire. Its versatile properties enable it to act as an insulator, conductor and semiconductor due to its helical structure formation [44]. Electron transfer occurs through the formation of a triple bond between guanine and cytosine and a double bond between adenine and thymine, resulting in the generation of an electron-hole pair. This electrical conductivity peaks in the initial stages and diminishes as the DNA strand lengthens [45]. Based on this principle, DNA exhibits utility as an insulator, conductor, semiconductor and can function as a nanodevice or nanomachine, leveraging specific gene fragments to synthesize desired proteins for targeted cellular functions [44].

5.4.4. RNA

These NONPs serves as a foundation for diverse nanostructures, thereby contributing to the emergent field known as RNA nanotechnology. This field finds extensive applications in medicine, particularly in therapeutic interventions, notably in cancer therapy, involving small interfering RNA (siRNA) and microRNA (miRNA). RNA constructs, such as RNA aptamers, have demonstrated utility as polymeric vehicles for drug delivery in cancer treatment. Polyvalent RNA nanostructures function as carriers for siRNA, ribozymes and anticancer agents targeting various cancers such as breast cancer, lung cancer and liver cancer [46].

5.4.5. Viral nanoparticles (VNPs)

Viruses have undergone evolutionary adaptations to efficiently infect host organisms. Owing to the precision of their infection mechanisms, viruses emerge as promising candidates for targeted drug delivery. Notably, Virus-Like Particles (VNPs) derived from plants, such as Brome mosaic virus, Cowpea chlorotic mottle virus, Cowpea mosaic virus, Potato virus X and Tobacco mosaic virus, as well as those from animals, exhibit characteristics of biocompatibility, biodegradability, non-infectiousness and non-hazardous nature. This establishes VNPs as suitable carriers for drug encapsulation, where the outer membrane proteins can be tailored for precision in targeted drug delivery [47].

5.5. NONPs present in the aquatic environment

As mentioned earlier, NONPs are also found in the aquatic environment and there are different types of NONPs based on their location in the water bodies. Some of these are as follows:

5.5.1. Nanocrystalline Fe-oxide grain coatings

These naturally occurring nanoparticles (NONPs) are prevalent in subsurface aquifers and sediments, harboring trace metals and contaminants such as uranium and arsenic. They exert an influence on the soil's zinc concentration. Nanocrystalline iron-oxide grain coatings, falling within the size range of 5–50 nm, have been identified as contributors to the groundwater transport of radioactive elements, including plutonium and uranium [8].

5.5.2. Nanoaquatic colloids

It predominantly exists in a colloidal state on the surfaces of water bodies and can be isolated from the colloidal mixture through fractional distillation. Researchers have identified elevated concentrations of nanoparticles, measuring below 5 nm in diameter, in lake and river samples proximate to Birmingham, UK. These nanoparticles exhibit extensive transport over long distances through river systems, ultimately reaching seas and oceans. Comparative assessments suggest greater stability of nanoparticles in river water as opposed to seawater. The stability of these nanoparticles is purportedly influenced by heightened levels of dissolved organic matter. Furthermore, nanoparticles entering saltwater manifest altered characteristics, including modifications in structure and charge. For instance, salt-induced aggregation leads to the removal of inorganic nanoparticles. Consequently, during the transition of NONPs from low to high salt concentrations due to osmotic imbalances, only a limited quantity of inorganic NONPs progress further [8].

6. Uses

Since ancient times NONPs are used in various fields due to their unique properties. Nowadays, it is used in various industries such as the food industry, genetic engineering, cosmetics, applied physics, device physics, health and textile. Other fields such as materials science, interface and colloid science, as well as chemical, mechanical, biological and electrical engineering. Nanotechnology has also given rise to new fields such as nanomedicine, nanolithography, DNA nanotechnology, molecular nanotechnology, molecular electronics and nanorobotics [4]. Especially silver nanoparticles that have applications in cosmetics, textile, agriculture, food industry and various applications in medical fields such as implications in catheters, detection of Alzheimer's disease, dental applications, orthopedic applications, role in wound healing, anti-inflammatory substance, anti-bacterial, anti-fungal, anti-plasmodial, anti-cancer, anti-viral and anti-diabetic properties [48]. In chromatography, NONPs are used to remove organic pollutants from water due to their selective adsorption characteristic. It is also used to design improved pesticides, molecular sieves, chemical sensors, etc. Some of its uses in various fields are diagrammatically represented in Fig. 5 and explained in detail as follows:

6.1. Uses of NONPs for human activities

6.1.1. Laundry

NONPs present in clay minerals were used as a bleaching agent since ancient times. In Rome, clay was mixed with decaying urine to enhance the process which was evidence of the interaction of nanoparticles with organic interactions [10]. Even today NONPs are used for the improvisation of laundry. BSA is a natural protein of size 116 nm and thus is considered a NONP which is biocompatible, biodegradable, nontoxic and nonimmunogenic [49]. BSA is used as a nano-drug delivery vehicle that possesses unique characteristics of extreme stability over a wide pH range of 4–9, thermally stable and solubilizes hydrophobic fatty acid molecules [50]. Due to these characteristics, BSA NONPs are used in washing clothes. They are emulsified with various oils, such as almond oil, jasmine oil, mustard oil and olive oil along with commercial washing powder and were used to wash clothes stained with mehndi, aalta, dry sindoor and wet sindoor. It was found that these NONPs have shown good washing efficiency with rapid action as compared to only the use of commercial washing powders. Also, its production requires less labor, is

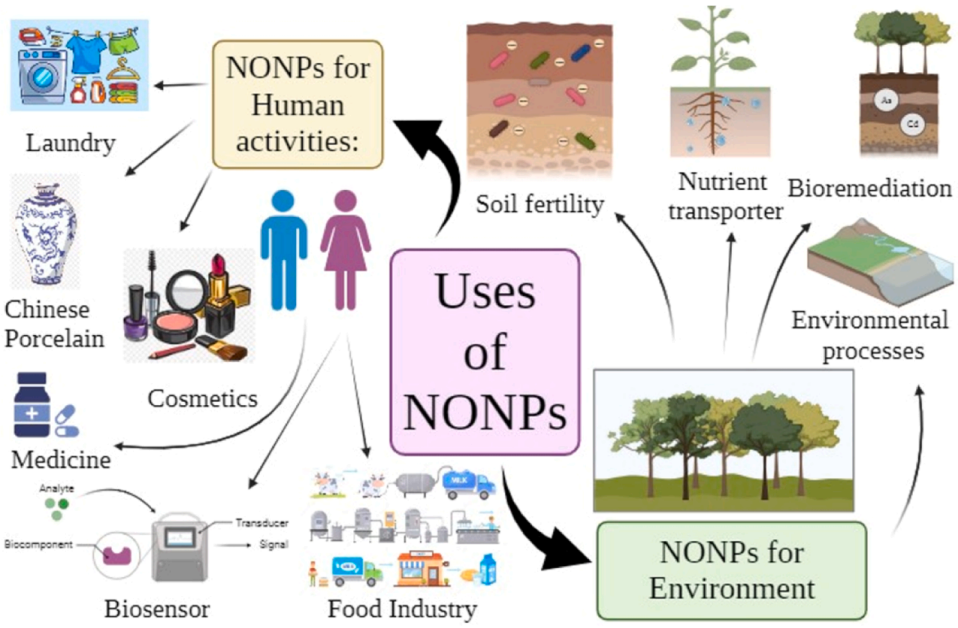

Fig. 5. Uses of NONPs (Naturally occurring nanoparticles).

cost-effective and time-saving [51].

6.1.2. Chinese porcelain

NONPs present in clay minerals were used to make lightweight but strong crockeries. The materials include quartz, feldspar and kaolin [10]. Roman Cup or Lycurgus Cup were made from nanosized gold clusters to create different colors. Nowadays naturally occurring metal nanoparticles like titanium, zinc, aluminum, iron, silicon, etc are used to produce clay nanoflakes applied in metal oxide ceramics [52].

6.1.3. Cosmetic

In Mesopotamia, a mixture of different clays was used as soap and facial ointment. In Egypt, red ochre, synthesized from naturally tinted clay minerals, was used as a balm for lips and cheeks The clay used for this purpose is French Green clay, Rhassoul clay, etc. NONPs are present in these clays along with minerals which have enhanced the use of clay as cosmetics [9]. UV light which escapes through the ozone layer and enters the earth's atmosphere causes various skin problems such as blistering sunburns and long-term problems like skin cancer, melanoma, cataracts and immune suppression. UV - A results in oxidative damage and protein denaturation whereas UV - B causes a mutation in DNA by forming pyrimidine dimers and photo-products. To protect skin from these UV radiations several cosmetics are made such as face creams & sunscreens. These cosmetics consists of metal NONPs of size more than 20 nm which cannot easily penetrate through the stratum corneum layer of the skin. Thus NONPs do not enter the body as well as form a protective layer on the skin [53].

6.1.4. Medicine

During the 2nd century A.D., in countries like America, Africa and Australia, NONPs present in clay were used as a dietary supplement or hearing aid [10]. Fungal NONPs are synthesized from the growing mycelia of the *Arthrobotrys oligospora* of size 360–370 nm. These are composed of 28 μg of glycosaminoglycan and 550 μg of protein. These fungal NONPs are immunostable, have antitumor activity, induces TNF-α secretion and increases cytotoxicity activity thus are a suitable candidate for immunotherapy and cancer treatment [54]. Various NONPs present in the animal body, as described earlier, have a well-organized transport mechanism that can be exploited for targeted drug delivery [39,41,42,55]. Nacre also known as mother of pearls which consists of 95 % calcium carbonate and 5 % of polymeric organic matter having size 5 μm in length and is about 0.5 μm in thickness. It has 3000 times the fracture strength of pure calcium carbonate and thus this naturally occurring nanograin can be used as medicinal and pharmaceutical industries like dental bone implants, contact lenses, drug delivery, tissue regeneration, and stem cell engineering [56].

6.1.5. Food industry

NONPs present in food have significantly developed the food industry. Milk contains 100–200 nm casein micelles coated with calcium and phosphate and helps in providing these two major micronutrients. This has given rise to a new concept of nanoemulsion which has increased stability compared to a raw or coarse emulsion. This increases the shelf life of dairy products [11]. During the fermentation process, many proteins break down and form positively charged molecules causing turbidity in the solution. In addition to negatively charged clay NONPs, the positively charged molecules form a complex that sediment thereby clearing the solution. This process does not hamper the taste of the liquid like wine, juices and other drinks [10].

6.1.6. Biosensors

Biosensors are the molecules that convert the biological mechanism into a desired product formation signal. The signal can be electrochemical, optical, thermal, or piezoelectric. The biosensor consists of two components: a target analyte and a transducer. The target analyte is the bio-origin NONPs like DNA or RNA whereas the transducer is the metal NONPs such as gold NONPs. The detection limit of such biosensors in oncology studies is found to be around 100 cancer cells/ml of blood [46].

6.2. Uses of NONPs for the environment

6.2.1. Environmental processes

Iron NONPs are produced on earth for several millions of years. These iron NONPs act as an elemental carriers through water bodies at long distances. It is also part of the primary component of the critical zone thus maintaining various environmental processes such as soil genesis, element cycling and water quality [8].

6.2.2. Bioremediation

NONPs play an important role in the removal of contaminants, such as heavy metals, from the environment. For example, iron oxide NONPs are used for the removal of cadmium and arsenic from water bodies. Arsenic bioremediation at the nanoscale also includes activated carbon and oxides of Mn, Fe and Zr. This application of NONPs is possible due to their adsorption property [8]. Other NONPs involved are Fe_2O_3, Fe_3O_4, SiO_2 and Al_2O_3 [57]. Zero-valent iron nanoparticles (nZVI) are used for groundwater remediation. Immersion of nZVI in water activates the reactivity and breakdown the protective film. This process is called auto-reduction [58].

6.2.3. Nutrient transporter

NONPs help in nutrient transport, retention and availability in soil and water. NONPs act as transport vectors carrying nutrient molecules strongly absorbed on mobile nanoparticles. For example, Fe-oxyhydroxide nanoparticles act as carriers for soluble phosphorus in soil. The major factor for nutrient transport and retention is that the nutrient molecules should be absorbed strongly on NONPs and should be desorbed very slowly. Due to their large surface area and high reactivity, NONPs generally contain a higher concentration of nutrients than bulk soil or sediments [57].

6.2.4. Soil fertility

The activity between NONPs and microorganisms present in the soil makes the soil more fertile. They interact with each other and can control biogeochemical reactions, catalytic formation of humic substances, mineral transformation, aggregate turnover and transformation of organic and inorganic pollutants. Mineral colloidal NONPs in the soil provides a suitable environment for soil microorganisms if the soil is enriched in ions, water and organic matter. On the other hand, these microorganisms promote mineral weathering due to their activity of NONPs which enhances soil fertility [57].

7. Environmental transformation of NONPs: release and fate

NONPs are synthesized by nature and thus are assimilated easily in nature either by dissolution or ionization process. For example, silver NONPs easily dissolve in the environment to yield ionic form [22]. Similar events are explained further in detail.

7.1. Release & fate

The fate of NONPs in the environment depends on their reactivity, mobility and bioavailability. The processes through which NONPs end up in the environment include aggregation, disaggregation, dispersion, diffusion, adsorption, desorption, flocculation, dispersion, biotic and abiotic degradation, transformation, charge enhancement and steric stabilization by natural organic matter and charge neutralization by oppositely charged ions [59,60]. The fate of NONPs are diagrammatically represented in Fig. 6 and explained in detail below:

7.1.1. The fate of NONPs in water

When NONPs enter natural water, they undergo aggregation and sedimentation to attain stability. During weathering of rocks rich in sulfide, ferrihydrite, goethite and amorphous iron oxide, the NONPs enter water bodies changing the aquatic temperature, pH and oxygen concentration [57].

7.1.2. The fate of NONPs in soil

In soil, NONPs are more stable in colloidal form compared to large-size particles. These colloidal organic matter aggregate in the soil to form microstructures essential for microbial activity and nutrient bioavailability. The fate of NONPs majorly depends on the extent of mineral solubility in soil [57].

7.1.3. The fate of NONPs in plants

NONPs also enter the plants by an active or passive pathway. Their uptake, translocation and transformation depend upon the plant species along with the chemical composition, size, type and stability of the NONPs. Transport of NONPs in plants occurs mainly through the semi-permeable root cell wall, which transmits the particles of 5–20 nm, enabling them to reach the plasma membrane. Embedded transport carrier proteins such as aquaporins and ion channels provide the alternate route for the same. Other pathways include endocytosis, creating new pores, or binding to organic molecules present in the environment. Studies also revealed the movement of NONPs through plasmodesmata leading to accumulation in intracellular space and apoplast and adsorption onto the membranes. NONPs present in the air can also enter the cells through leaf stomata [57].

7.2. Environmental Hazards

NONPs accumulate in the environment through air, water, soil and sediments including wastewater sludge. These accumulated NONPs have adverse effects on the environment which mentioned in Table 1 and explained in detail are as follows:

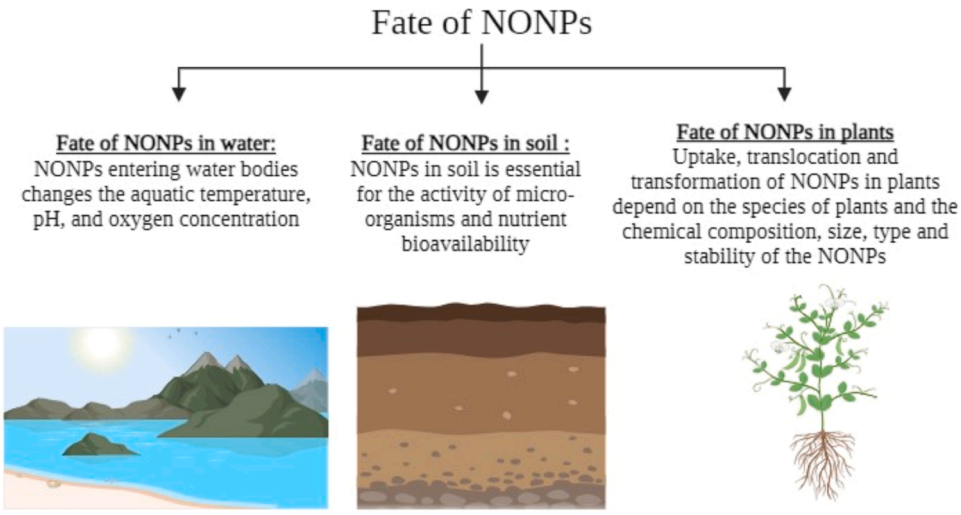

Fig. 6. Fate of NONPs (Naturally occurring nanoparticles).

Table 1
Environmental Hazards of NONPs.

Sr. No.	Environmental hazards	Description	Reference
1.	Dust cloud formation	NONPs forms dust clouds which causes glacial melting, blocking sunlight, extreme weather conditions and reduced rainfall	[61]
2.	Environmental hydroxyl radical reduction	NONPs reduces environmental hydroxyl radical thus increasing greenhouse gases	
3.	Ozone layer depletion	NONPs causes ozone layer depletion causing severe diseases like skin cancer	
4.	Stratospheric temperature change	NONPs decreases stratospheric temperature	

7.2.1. Dust cloud formation

Soot from burning activities results in the coagulation of NONPs leading to the formation of dark-colored dust clouds also known as atmospheric brown clouds. As these NONPs are formed marjorly due to soot, these NONPs are a type of NOCNPs. The harmful effects of these clouds include glacial melting, blocking sunlight, extreme weather conditions and reduced rainfall affecting agriculture. The brown clouds also reduce the monsoon season in India. The weather extremes may also contribute to the reduced production of key crops such as rice, wheat and soybeans. These clouds have been reported to affect human health and cause cardiovascular diseases, pulmonary illnesses, fungal or bacterial diseases and chronic respiratory problems. Brown dust clouds formed due to NONPs have a major effect on Himalayan glaciers, agriculture and human health, which are as follows:

a. Effect on Himalayan glaciers: Dust clouds containing NOCNPs settle on the Himalayan glaciers, enhancing sunlight absorption and consequently contributing to glacier melting.
b. Effect on agriculture: The presence of dust clouds containing NOCNPs has been observed to alter rainfall patterns, resulting in heavy rainfall in typically dry regions and drought conditions in traditionally rainy areas. This phenomenon significantly affects food production [61].

The impact on human health will be detailed in the subsequent section titled "Human Health Hazard from NONPs."

7.3. Environmental hydroxyl radical reduction

The highly reactive hydroxyl radical, crucial for the photochemical degradation of organic matter and pollutants, interacts promptly with NONPs, leading to an overall reduction in hydroxyl radicals. This reduction, responsible for elevated greenhouse gases, contributes to ozone layer depletion (Fig. 4) and environmental harm. Additionally, it heightens UV radiation exposure, resulting in an increased incidence of various types of skin cancer in humans [61].

7.4. Stratospheric temperature change

NONPs in the troposphere inadvertently interact with molecular hydrogen released from sources like hydrogen fuel cells. This hydrogen, combined with NONPs, ascends to the stratosphere, leading to an increase in water vapor. This, in turn, causes stratospheric cooling, boosts ozone-depleting heterogeneous chemistry, elevates noctilucent clouds and alters tropospheric chemistry and atmosphere-biosphere interactions. Noctilucent clouds, composed of tiny water ice crystals, exist at high altitudes and are formed on nanosized dust particles. The sources of both dust and water vapor in the upper atmosphere remain uncertain, potentially originating from micro meteors, volcanoes, or tropospheric dust. Moisture may be lifted through tropopause gaps or formed by methane reacting with hydroxyl radicals in the stratosphere. Evidence suggests that the recent appearance and gradual increase of noctilucent clouds may be linked to climate change [61].

7.5. Environmental transformation

Environmental transformation of NONPs is diagrammatically represented in Fig. 7 and explained below in three ways: chemical, physical and biological transformation

7.6. Chemical transformation

NONPs undergo various chemical transformations such as oxidation dissolution, sulfidation, complexation, chlorination and reduction.

i. Naturally occurring silver nanoparticles (NOAgNPs): The chemical transformation of NOAgNPs takes place by its dissolution with the help of oxygen molecules and protons. The reaction is as followed:

$$4\,Ag + O_2 + 4\,H^+ \rightarrow 4Ag^+ + 2\,H_2O$$

This process depends on the physicochemical properties of sediments, such as oxygen concentration, redox potential, natural organic matter (NOM) and pH. Low oxygen concentration can inhibit or slow down the oxidation causing fewer ions to release from naturally occurring silver nanoparticles. This process is inversely proportional to the pH and NOM in the environment. Under aerobic and anaerobic conditions, sulfidation of NONPs takes place and forms a core-shell structure. In aerobic conditions, the following sulfidation process takes place:

$$4Ag + O_2 + 2\,H_2S \rightarrow 2Ag_2S + 2\,H_2O$$

$$4Ag + O_2 + 2HS^- \rightarrow 2Ag_2S + 2OH^-$$

Whereas in anaerobic conditions, the following sulfidation process takes place:

$$2Ag + H_2S \rightarrow Ag_2S + H_2$$

The anaerobic process takes place at pH 9.6 as H_2S exists only at this pH. During the complexation reaction, the NOM forms a coating on NONPs. A similar reaction of NONPs takes place with chlorine which forms a stronger bond. This chlorination process depends on dissolved oxygen, pH and redox conditions in the environment and takes place in acidic conditions at pH 5.7 [33].

i. Naturally occurring carbon nanoparticles (NOCNPs): A similar chemical transformation takes place for NOCNPs which are produced from wildfire charcoal and biochar. It contains a complex network of micropores and mesopores which are bound to minerals including organo-mineral complexes. The accessibility of these pores can be increased by chemical processes such as the formation of precipitates and the binding of large NOM molecules onto the biochar surface [62].

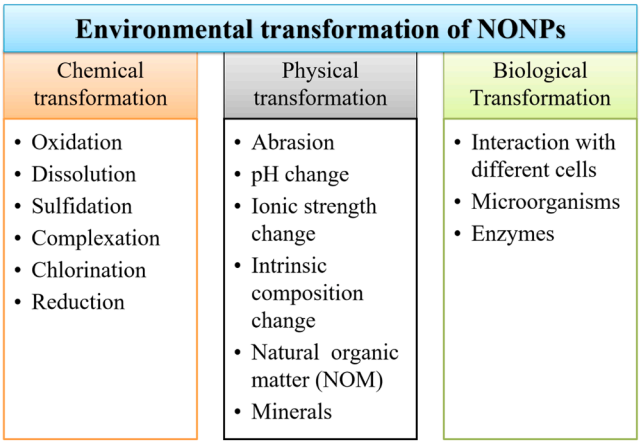

Fig. 7. Environmental transformation of NONPs (Naturally occurring nanoparticles).

ii. Naturally occurring iron nanoparticles (NOFeNPs): Zero-valent iron nanoparticles (nZVI) are a type of NOFeNPs that is made up of a special core-shell structure possessing important chemical properties, such as iron corrosion, particle stabilization, contaminant removal and redox reaction. The aging can alter the shell thus it is considered an important transformation process of nZVI. In humid conditions, nZVI ignites spontaneously on exposure to air and converts into reddish iron oxide particles. This can be inhibited by using inert gases such as argon and other gases such as nitrogen and carbon dioxide. Continuous aging produces minerals inside the shell such as FeO, α-Fe_2O_3 and γ-Fe_2O_3. The reactions are as followed:

$$Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^-$$
$$Fe_2O_{3(s)} + 6\ H^+_{(aq)} + 2e^- \rightarrow 2Fe^{2+}_{(aq)} + 3\ H_2O_{(l)}$$
$$3Fe_2O_{3(s)} + 2\ H^+_{(aq)} + 2e^- \rightarrow 2Fe_3O_{4(s)} + H_2O_{(l)}$$

Depending upon the environmental conditions, the primary product, Fe^{2+}, can be further oxidized into Fe_3O_4, Fe_2O_3 and FeOOH. This multi-step reaction includes the following steps: (i) breakdown of the initial iron oxide shell through hydration and/or auto reduction, (ii) oxidation of the freshly exposed surface together with the reduction of reactive solutes, such as oxygen, nitrate, or coexisting contaminants and (iii) aggregation of nZVI and subsequent cementation by the formation of mixed-valence Fe^{2+}/Fe^{3+} phases. Since these reactions are very fast, it is difficult to detect the intermediates. But one intermediate known is $Fe(OH)_2$ which is quickly converted into Fe_3O_4. For complete oxidation of nZVI to FeOOH, it takes 72 hrs. The oxidation of nZVI is directly proportional to the concentration of dissolved oxygen [58].

7.7. Physical transformation

NONPs undergo physical transformation through abrasion, changes in pH, ionic strength and intrinsic composition, or due to NOM and minerals. The physical transformation causes changes in particle size and porosity of NONPs. NOCNPs derived from fossil coal, biochar or wildfires undergo physical disintegration. Biochar is broken down to sandy soil by the formation of cracks and fractures. Materials with high-lignin feedstocks, for example, wood, disintegrate at a higher rate compared to materials with high cellulose feedstocks like grass. The degree of disintegration is inversely proportional to carbonization and aromaticity. Physical disintegration is prevented when NONPs are exposed to soil where they can interact with colloidal, dissolved and particulate materials. These materials fill the exposed cavities thereby stabilizing particles. In the aquatic environment, the NONPs interact with NOM and mineral particles which affect the size, surface charge and aggregation of particles. The micropores and mesopores of NOCNPs can also be made more accessible through physical processes such as changes in temperature, physical stress and humidity. These processes lead to the disintegration and collapse of pore-networks of NOCNPs. It has been observed that NOCNPs derived from biochar disintegration contain more oxygen and less aromatic structures compared to the original biochar [62].

7.8. Biological transformation

The biological transformation of NONPs is due to their interaction with different cells, microorganisms and enzymes.

i. Naturally occurring carbon nanoparticles (NOCNPs): Fungal hyphae carry out the enzymatic breakdown of large fossil coal and biochar particles to form NOCNPs. These extracellular enzymes include Mn-peroxidase, lignin-peroxidase and laccase which oxidize NOCNPs and convert O-alkyl/alkyl-C groups to carboxyl/carbonyl-C groups. The enzymatic transformations are not studied extensively. Most of the studies focus on single-enzyme in the laboratory. In-depth investigations are required to understand the mechanism of enzymatic transformations in environmental conditions with multiple factors such as the presence of NOM, microbial compositions, microbial activity and nutrient accessibility. These will further help in elucidating the transformation processes of NONPs. For example, the horseradish peroxidase enzyme catalyzes the formation of oxygen radicals which further degrade the engineered NPs. Therefore, there are chances it can also degrade NONPs. Initially, it was proposed that the O-functionalized NOCNPs are generally more degradable than non-functionalized NOCNPs because the irregular structure of O-functionalized NOCNPs facilitates degradation. But later it was observed that the manganese peroxidase was able to transform non-functionalized NOCNPs and not O-functionalized NOCNPs [63]. This is due to the bridging of Mn^{2+} with carboxyl groups on the surface of O-functionalized NOCNPs which interferes with the Mn^{2+}/Mn^{3+} catalytic cycle, thereby suppressing transformation [62].

ii. Biofilms: It has been observed that biofilms are formed on the NONPs thus affecting its surface chemistry, increasing the particle size and blocking pores [62].

iii. Naturally occurring iron nanoparticles (NOFeNPs): Besides chemical oxidation, nZVI also undergoes oxidation through microbial activity carried out by iron-oxidizing and iron-reducing bacteria maintaining the biogeochemical cycling of iron in the environment [58].

8. Human health hazard from NONPs

Unique properties of NONPs has made them an efficient candidate for various application since ancient times. However, there are health risks associated with NONPs. NONPs enter the human body through the gastrointestinal tract, lungs and skin causing adverse effects. These risks largely depend on exposure level, frequency and duration of exposure and the composition of the particle [57]. The Human health hazard from NONPs are mentioned in Table 2 and are explained in detail below:

8.1. Carcinogenic

Dust is estimated to contain several millions of tons NONPs collected globally every year and can be transported over thousands of kilometers. Dust particles include asbestos minerals or erionite nanoparticles which are of great human health concern. Inhalation of asbestos can cause carcinogenic pulmonary diseases, mainly asbestosis, pleural plaques, lung cancer and mesothelioma [57]. Multi-walled carbon nanotubes are also observed to be carcinogenic [65].

Table 2
Human health hazard from NONPs.

Sr. No.	Adverse Effects	Description	Reference
1.	Carcinogenic	NONPs like asbestoses present in dust are carcinogenic	[57]
2.	Cardio-vascular disorder	NONPs enhances vascular thrombosis in the cardiovascular system	
3.	Filtration	NONPs can pass easily through HEPA filters so difficult to eliminate	[4]
4.	Immunological	NONPs increases oxidative stress and causes cell apoptosis	[4,57]
5.	Allergy	NONPs ions causes dermatitis	[64]
6.	Cosmetics	NONPs present in cosmetics can easily penetrate through the stratum corneum (SC) layer of the skin	[53]
7.	Pathogenicity	NOCNPs in the dust cloud increases the risk of exposure to pathogenic bacteria/fungi.	[61]

8.2. Cardio-vascular disorder

Dust particles containing hazardous NONPs, on entering the circulatory system, cause platelet aggregation and enhanced vascular thrombosis [57].

8.3. Infiltration

It is difficult to eliminate nanoparticles because of their nano size as it can easily pass even through HEPA filters. NONPs has adjuvant properties and so can carry indoor and outdoor allergen causing various diseases. Thus infiltration of NONPs is a threat [4].

8.4. Immunological effects

NONPs like TiO_2 NONPs, quartz and carbon black NONPs are observed to increase interstitial fibrosis, airway inflammation and oxidative stress leading to apoptosis [56]. These can induce cellular damage and micronucleus formation in the cell resulting in severe health conditions such as pulmonary fibrosis and lung tumor. Cerium oxide nanoparticles were inoculated on human lung epithelial cells lines such as BEAS-2B which showed immunogenic effects such as an increase in reactive oxygen species, reduction in glutathione levels and the induction of OH^{-1}, catalase, glutathione-S-transferase and thioredoxin reductase, all markers of oxidative stress, production of cytosolic caspase-3 and chromatin condensation. These immunogenic effects lead to apoptosis [4].

8.5. Allergy

Metal NONPs for example, gold, palladium, cobalt, mercury, beryllium, chromium, silver and nickel NONPs are reported to cause allergies. Metal implants and jewelry are shown to produce NONPs which enter via the skin surface causing dermatitis. NONPs elicit immune responses involving T cells, B cells and NK cells [64].

8.6. Skin concerns

To protect skin from these UV radiations several cosmetics are made such as face creams and sunscreens. These cosmetics consists of metal NONPs such as TiO_2, maghemite and iron of size less than 15 nm which can easily penetrate through the stratum corneum (SC) layer of the skin. The entry of these NONPs into the human system can cause adverse effects such as increased aging of the skin, pathological effects in the liver and particle accumulation in the brain [53].

8.7. Pathogenicity

A substantial fraction of atmospheric brown clouds containing NONPs and aerosol particles originating from the incomplete combustion of fossil fuels and biofuels. This heightened exposure to particulate matter not only escalates the risk of encountering pathogenic bacteria and fungi but also exacerbates health issues. The health impacts associated with these particles encompass an elevated incidence of cardiovascular diseases, pulmonary illnesses and chronic respiratory problems, along with an increased susceptibility to fungal and bacterial diseases [61].

9. Conclusion & future aspects

NONPs, prevalent in the environment, play a pivotal role in maintaining ecological equilibrium and have demonstrated considerable benefits for human applications. Their exceptional properties, including a substantial surface-to-volume ratio, adsorption capabilities, electron-donating characteristics, robust electrostatic interactions and distinctive optical, magnetic and catalytic attributes, have broadened their applicability across diverse domains. Notably, NONPs exhibit biocompatibility, making them promising candidates for cancer treatment, antiviral medications and various biomedical applications. As products of natural synthesis, NONPs contribute to bioremediation processes, aligning with environmental conservation efforts.

However, alongside their advantages, NONPs also pose environmental and human health concerns. Their influence extends to climate alteration and potential human health hazards, encompassing carcinogenicity, cardiovascular disorders, immunological effects, allergies, skin-related issues and pathogenicity.

Looking ahead, NONPs hold promise for future applications, particularly in agriculture and food production. With a historical presence in the food industry, NONPs can contribute to addressing the contemporary challenges of increasing food demand due to population growth. In agriculture, they may enhance biomass production, serve as pesticides and herbicides, extend shelf life during transportation and boost the nutritional content of food. Additionally, NONPs could play a role in food processing and preservation to meet the demands of modern lifestyles, where convenience and efficiency in food preparation are paramount. Despite significant strides in nanotechnology research, there remains a vast realm for exploration to further advance human well-being and foster environmental sustainability.

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

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