# Assessment of health, safety, and economics of surface-modified nanomaterials

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## 11.1 Introduction

Nanomaterials (NMs) have at least one dimension of 1 to 100 nm size range (Hasan, 2015). These possess ability to exhibit quantum effects and high surface area (Wang et al., 2015). NMs and surface-modified NMs are employed in various applications in different fields like catalysis, construction, aerospace, agriculture, semiconductor devices, optoelectronic devices, food packaging, optics, cosmetics, textiles, water treatment, and medicine (Kaur et al., 2023; Kumar et al., 2023; Pokhriyal et al., 2024). As the size, morphology, and dimensionality changes, the fundamental characteristics also show significant variation like magnetism, electrical properties, temperature, and chemical reactions (Sudha et al., 2018). NMs are prepared from various materials like inorganic compounds, polymers, metal oxides, and metals. The novel NMs synthesis is rising constantly. The applications of NMs can also be increased by their surface modifications (Joudeh & Linke, 2022). Surface modification refers to refitting material surface through biological, chemical, or physical changes. This will produce nanoparticles (NPs) of desired size, shape, and property (Tharmavaram et al., 2018). Surface modification of NPs is performed in accordance with the requirement and massive technological and economical expectations have been sparked by its applications. Surface modifications may lead to the change in functional groups, surface crystal structure, electric property, surface adsorption, surface wettability, etc. (Lin et al., 2015).

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Consequently, it has been demonstrated that surface modification of NMs can be used to greatly increase their applications for better inertness and/or stability as well as adsorption capacity, efficiency, and dispensability. It is demonstrated that surface modifications also blocks the issue of particle aggregations (Afkhami et al., 2010). Moreover, applications of surface-modified NPs have a significant impact on daily life. These include the ability to produce strong, light materials, clean energy, and pure water, as well as a variety of medical applications for severe human diseases (Savolainen et al., 2010).

Growing global population, overuse of natural resources, fast industrialization and growth as well as recurrent droughts are some of the factors that have been connected to these rising pollution levels (Zahoor et al., 2021). Industrial effluents from industries like battery manufacturing, mineral processing, ceramics and glass, petroleum refining, tanneries, pharmaceuticals, fertilizers, paints and dyes, textiles, and metal plating use heavy metal in different chemical and manufacturing processes, and these have eventually found their way into water bodies (Gupta, 2018; Hao et al., 2012; Singh et al., 2022;). These heavy metals are a threat to both humanity and aquatic life. Metals like arsenic, chromium, and lead contaminate drinking water and cause several health issues and skin diseases. So, there should be environment-friendly techniques or zero pollution techniques to lessen pollutant concentration (Sathish et al., 2023). The traditional methods to remove heavy metals and other contaminants from water like flocculation/coagulation, reverse osmosis, biological treatment, electrochemical treatments, chemical reduction, electro dialysis, sedimentation, filtration, ultra-filtration, ion exchange, as well as adsorption requires high energy consumption, operational costs, lower sensitivity to operational condition as well as high sludge generation (Adeleye et al., 2016; Gupta & Gupta, 2016; Gupta & Singh, 2018; Kumar & Gupta, 2020; Singh et al., 2018; 2020). The development of nanoscience has opened new ways in the field of research. Application of nanocatalyst is not new but our ability to view and characterize catalytic ability has increased with time (Gupta & Dhiman, 2023; Gupta & Gupta, 2015; Gupta, 2016; Gupta et al., 2017). Nanocatalysis plays an important role in both academic as well as industrial research and development. Traditional catalysts have less surface area that is accessible for reactant molecules and hits high consumption of expensive catalysts. But nano-scaled catalysts solved these problems by increasing the surface-to-volume ratio (Zach et al., 2006). Advances in nanoparticles in the past few years with present day's developments open a new vision for NPs and its future aspects such as surface-modified design (Nabgan et al., 2023). The requirement for materials with a higher surface area, a higher adsorption capacity, and affordability which can effectively handle pollutants at even very low concentrations has been met by nanomaterials. Surface-modified NMs maximize the applications of NMs. They modify the adsorption efficiency and surface of the nanomaterials to enhance the adsorption capacity and investigated the undeniable importance and significance of NMs. Adsorption of heavy metals is mainly emphasized to the materials that are silica, alumina and iron (Manyangadse et al., 2020). NM surface modifications may be mainly divided into two parts, that is, physical modifications of surface and chemical modifications of surface. Surface modification improves the performance of nano-adsorbents to a higher extent. Surface modification crucially enhances the performance of nano-adsorbents. The adsorption capacities of modified and pure particles were compared, and the results indicated that the modified particles had greater capacities. The performance of the various nanomaterials in the removal of heavy metal ions from aqueous systems was also found to be altered by the modification techniques used on them. With increasing modification and/or functionalization, it was found that the specific surface area decreased while the adsorption capacity generally increased. Finally, it has been discovered that surface modification improves the stability of nanomaterials, particularly magnetic materials. This chapter emphasizes different introductory matters related to surface-modified nanomaterials and also gives information about health, safety, and economics of surface-modified nanomaterials. The different methods for the surface modifications are discussed briefly in the following manner.

## 11.2 Surface physical modification

In physical modification, surface depositions are employed to fix the modifier on NMs surface. The NMs surface of different inorganic as well as organic materials is modified using different types of chemical bonds like van der Waal bond, electrostatic bond, hydrogen bond, or covalent bonds (Ngouangna et al., 2022). The dispersion of the NPs can be improved by reduction in activity of surface and change in properties of surface-by-surface modification (Lin et al., 2015). The nano technological advancement provides designing and generation of NMs engineered with the controllable physical properties (Moku et al., 2019).

### 11.2.1 Surfactant method

Surfactants may also be applied for physical modification of NMs. Surfactants work as stabilizers which prevents aggregation due to production of coating around NMs during manufacturing process or application. The commonly applied surfactants in the present method are polyvinyl alcohol (PVA), didodecyldimethylammonium bromide (DDAB), cetyltrimethylammonium bromide (CTAB), sodium cholate, and polysorbate 20. Based on the activity of surface, PEG-PLA or PLGA-PEG (poly(lactide-co-glycolide)–polyethylene glycol), amphiphilic block copolymers are applied in some reports (Uğur et al., 2010).

### 11.2.2 Surface deposition method

Surface deposition method is a process for improvement of NMs surface characteristics. For instance, Cu coating is applied in order to prepare ceramic/metal composite NPs. Against Staphylococcus aureus bacteria, excellent antimicrobial activities were reported by films of nano zinc oxide deposited on the cotton fabrics. The cotton fabric protection from UV radiations was also found to be enhanced in presence of multilayers of nano-ZnO on the cotton fabrics (Uğur et al., 2010).

## 11.3 Surface chemical method

One effective way to increase the dispersion of nanoparticles is to modify their surfaces chemically by absorption of silane coupling agents, for example, stability of nanoparticles in different liquid environments. The reaction between the surface of NP and modifier results in the attachment of chemical groups (Upadhyaya et al., 2018). The chemical methods for the modification of surface of NMs include *in situ* modification method, surface grafting improvement method, phosphate ester method, coupling agent method, and esterification reaction method.

### 11.3.1 Esterification reaction method

Esterification reaction is the chemical reaction of alcohols and metal oxides. Under the mild reaction conditions of atmospheric pressure, moisture, and ambient temperature, the direct facile esterification reaction can be applied to the silica NPs surface to graft the chains of poly (methyl methacrylate) (PMMA). The produced NMs have core–shell structure with higher glass transition temperature and better thermal stability. The NMs surfaces consist of PMMA molecular segments attached with covalent ester bonds with the NPs core (Feng et al., 2009).

### 11.3.2 Coupling agent method

Coupling agent modification uses those groups which form chemical bonds with the surface of nanoparticles and the molecular end react with different NP so as to improve the performance of NP. Various coupling agents like carboxylic acids (Dinari & Haghigi, 2017), polymers (Qi et al., 2017; Xie et al., 2010), silanes (Salarizadeh et al., 2016), and organo phosphorous molecules. Usually silane modifiers are used as coupling agents as they have extrusive characteristics. The functional groups of different types are available on the silane modifiers. In order to improve the characteristics of NMs, one group may bind with inorganic materials, whereas other group may bind with organic materials (Maji et al., 2017; Lin et al., 2015).

### 11.3.3 Surface grafting method

The method through which the polymer chain gets attached with NMs is referred to as surface graft modification. Grafting polymerization is not responsible for change in crystalline structures of NMs. The reactive bonds onto ZnO NPs are introduced by treating the NM with KH570 coupling agent. Now, the free-radical polymerization may be employed to achieve PMMA grafting on zinc oxides NPs surface (Ayanoğlu & Dogan, 2020; Canché-Escamilla et al., 2014; Hong et al., 2006).

### 11.3.4 In situ method

Surface fabrication through *in situ* method is quite attractive and convenient for the generation for surface-modified NMs. Broadly two categories of in situ methods are reported for the modification of thin films of polymers. In one method, cast is mixed into composite film and precursor in solution, while, in the other method, cast is the polymer film with the introduction of precursor in it. It provides unique control over distribution, shape, and size of nano structures, reunion, and high dispersion (Ramesh et al., 2009). It is considered as ideal surface modification method as chemical modification, post processing, and production cost of nanometer unit is highly decreased (Lin et al., 2015).

## 11.4 Surface-modified nanomaterials for health, safety, and economic applications

### 11.4.1 Surface-modified gold nanomaterials for higher cell uptake and radiation therapy by x-rays

X-ray radiation therapy can harm healthy cells because of its poor tumor selectivity and has unfavorable side effects. Many beam technologies were reported to maximize dose to cancer cells and minimize dose to normal cells; however, techniques have limitation of low spatial resolution during treatment due to motion of patient, low precision in planning and positioning, and inability to treat tumors with unclear boundaries or hard-to-reach tumors. The distance between production sites and nucleus may be shortened if radio sensitizers can be inserted into cancer cells or nuclei. There will be more free radicals available to damage DNA (Wang et al., 2015).

As a radio-sensitizer, gold nanoparticles (Au NPs) are thought to be both biocompatible and promising. Because of electrostatic attraction, cationic modifications in Au nanoparticles have increased their attachment to cell membranes, increasing the possibility of nanoparticle endocytosis. The single-step modification of gold nanoparticles with a thiol-based cationic molecule has a high destruction rate in cancer cells. Cancer cells are destroyed by X-ray radiation at a far lower dose. The altered nanoparticles have a high yield of cell membrane penetration. The total dose of X-rays required for killing cancerous cells was lowered by bringing radio-sensitizing Au NPs nearby to nucleus, which stores DNA. Auger electron contributes higher in comparison to photoelectrons, according to the simulation of the interaction between Au NPs and X-rays (Wang et al., 2015).

### 11.4.2 Surface-modified cellulose nanomaterials for drug delivery

A wide range of NPs are present in the form of drug carriers including micelles, liposomes, dendrimers, and others. The majority of nanocarriers were found to be spherical in shape but it was found that nonspherical NPs used for nanomedicine have superior qualities. As elongated nanoparticles can align in the bloodstream and change how they interact with phagocytes, it has been discovered that they have longer circulation times. A large variety of NPs were prepared to treat cancer and several nanomedicines to treat other diseases are under the development process. But cellulose NPs have gathered great attention scientifically due to its exceptional chemical, mechanical, structural, and biological qualities. The fibrous, tough, and water-insoluble material known as cellulose can be isolated through any plant, including hemp, coconut, bamboo, wheat, sisal, cotton, hard wood, soft wood, bagasse, ramie, and jute. Biomedical applications of cellulose-based NMs include tissue engineering, wound healing, diagnosis, and drug delivery. Cellulose-based formulations have been used to prepare tablets, hydrogels, aerogels, and nanoparticles. Thus, therapeutic agents or ligands that target cellulose nanomaterials can be added to them to create a drug delivery system. Because they can align in the bloodstream, elongated nanoparticles have been found to have longer circulation times (Khine and Stenzel, 2020).

### 11.4.3 Surface-modified catalysts for splitting of water

Hydrogen energy is a viable replacement for fossil fuels with zero carbon dioxide emission and lack of contaminants. Water splitting by electrochemical means is an efficient way to generate $H_2$ and $O_2$ (El-Temsah & Joner, 2012). At present standard catalysts are used for water splitting. Iridium or ruthenium oxides are used for oxygen evolution reaction (OER) and elemental platinum is used for hydrogen evolution reaction (HER). Their limited availability and high cost prevent them from being applied in large-scale uses. Due to the lower hydrogen adsorption energy, high electrical conductivity, and chemical resistance, transition metal phosphides, or TMPs, have become highly effective catalysts for electrochemical water splitting (Beltran-Suito, Menezes, & Driess, 2019).

The high HER electrocatalytic activity of cobalt phosphides (CoP or $Co_2P$) has drawn attention recently among them. Subsequent research also showed that negatively charged P atoms have the ability to trap protons and encourage the release of $H_2$. Additionally, efforts were made to use such resources as OER catalysts to enable overall water splitting. Here, the negatively charged Pd centers can serve as catalysts for the positively charged $Co^{\delta+}$ sites to function as hydroxyl acceptors, promoting $O_2$ evolution through desorption and discharging. To create amorphous and crystalline CoP electrocatalysts and increase its activity, a number of cutting-edge synthetic techniques have been used. These include aerosol spraying from Co-P precursors, electrodeposition, and combining with carbon nanostructures or other transition metals (Beltran-Suito, Menezes, & Driess, 2019; Crane & Scott, 2012).

### 11.4.4 Surface-modified nanomaterials for fast removal and recovery of chromium

The impacts of heavy metal pollutants in the environmental segments are known and there is a need to remove these pollutants from industrial wastewater streams as well as natural water sources. The industrial sector generates a large amount of chromium-containing wastewater annually. Cr(VI) is highly toxic for plants and animals while Cr(III) is thought to have lower toxicity. In biological systems, Cr(VI) species function as potent oxidants which can cause cancer, mutagenicity, and teratogenicity. The hexavalent form can cause allergic skin reactions, dermatitis, and ulcerations on the skin. Cr(VI) compounds when inhaled may cause perforations in mucous membranes of nasal septum, ulceration, irritation of the larynx and throat, bronchospasms, asthmatic bronchitis, and edema. The respiratory symptoms include wheezing, coughing, itching in the nose, and breathlessness. To recover and remove Cr(VI) from wastewater, a novel technique combining magnetic separation and nanoparticle adsorption was developed. The synthesized, characterized, and investigated $MnFe_2O_4$ nanoparticles with surface modification as Cr(VI) adsorbents. The findings demonstrate the effectiveness of surface-modified $MnFe_2O_4$ nanoparticles as efficient sorbents for quick extraction of hexavalent chromium from aqueous media. Metal ions may be quickly and cheaply removed by the adsorption process followed by magnetic separation; additionally, these materials can be recovered in highly concentrated material form (Hu et al., 2005).

### 11.4.5 Surface-modified nano-hydrotalcite to enhance crude oil fluidity

Crude oil has poor flowability under low temperatures and is one of the main problems which affects crude oil transportation after extraction. During the extraction process, the crude oil temperature drops, causing wax to gradually precipitate. The wax crystals join to create a 3-D network structure which holds liquid constituents of crude oil, and as a whole, fluidity of crude oil decreases and begins to gel (Chang et al., 1998). This results in a sharp rise in viscosity and a large decrease in crude oil's fluidity, which greatly increases the difficulty of transporting oil. Also, the wax accumulates on the pipe thereby decreasing effective diameter of pipe and may also cause blockage in oil pipeline (Huang et al., 2021). Moreover, about 40% of high-wax crude oil is heavy oil, which has a high colloid and asphaltene dosage. For precisely this reason, heavy oil has low fluidity, high viscosity, and high pour point. Therefore, the economic costs associated with producing, shipping, processing, and storing heavy oil will be higher (Ansari et al., 2022). Thus, flow improvers or viscosity reducers are added to heavy oils for improvement in pour point of the oil. Four broad categories can be used to classify viscosity reducers: nanoparticles or nanofluids, surfactants, oil-soluble polymers, and other chemicals (Du et al., 2024).

Due to their low cost, nanosilica and nanomontmorillonite are currently the materials of choice for most researchers. The modified hydrotalcite containing anionic surfactants was created. The efficacy as a flow improver was examined, and the mechanism through which the interaction between modified hydrotalcite and the wax and resin in crude oil improves flowability was investigated. Crude oil is highly viscosity-reduced by anionic surfactant-modified hydrotalcite; on the other hand, poplar oil sample (YL) viscosity is most significantly affected by sodium dodecyl sulfate-modified hydrotalcite (12S-MNH). More investigation was done on viscosity-decreasing properties of 12S-MNH, which may lower the pour point of YL crude oil by a maximum of 14.0°C and reduce its viscosity by 96.6% (31°C) (Du et al., 2024).

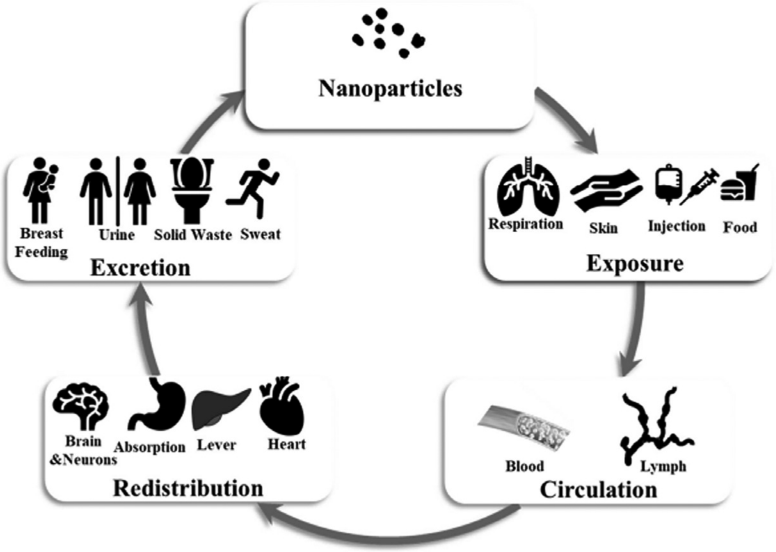

**Figure 11.1.** Routes of exposure, toxicity, and excretion of NPs in human beings. *(From Malakar et al. (2021), with permission from Elsevier through RightsLink).*

## 11.5 Risks associated with surface-modified nanomaterial exposures

There are severe health risks associated with exposure to NMs. All new nanomaterials are potentially hazardous and should be managed in a consistent manner. The nature, scope, and risk probability posed by NMs and their organized application will be recognized and explained through an efficient risk management procedure (Schulte, 2008). NMs may enter the body by various routes, including ingestion, skin penetration, and inhalation. In spite of their small size, NMs can have a negative effect on organisms at the cellular level, as well as on the transportation, redistribution, and excretion pathways of the body (Ma et al., 2016). Nanomaterials have the potential to interact with various biological systems, including the liver, kidneys, lungs, brain, colon, bone, skin, blood, and so on. They may also cause different kinds of deformation, impede the growth of cells, and even cause diseases in both humans and animals.

The exposure route, the chemical and physical properties of NMs, and their life cycle can all have a significant impact on how various human organs are affected by NMs, as well as how long they stay in the body. Many concerns regarding NMs' fate, life cycle, and potential toxicity to both individuals and the environment have been raised by their widespread production and use (Fig. 11.1). Because of the wide range of nanostructured materials that are available, their toxicity and interaction with biological systems are mainly influenced by size, concentration, solubility, stability, and chemical and biological features. The primary factors contributing to the toxicity of NMs to humans are their size and chemical makeup. A large number of the characteristics found in NMs are brought about by size confinement, which alters the physical and chemical characteristics of particles and exponentially increases the surface area of given volume. The reactivity and toxicity of NMs can be enhanced by these modifications, independent of composition and shape. NM with a diameter of less than 100 nm has the capability to bypass blood-brain barrier, enter nuclei at a diameter of less than 40 nm, and readily penetrate cells (Ganguly et al., 2018; Malakar & Snow, 2020). Chemical processes like composite formation, functionalization, and surface treatment may decrease toxicity of nanostructured materials (Singh & Nalwa, 2007).

Fig. 11.1

## 11.6 Adverse effects of surface-modified nanomaterials

Various kinds of surface-modified as well as unmodified NMs pose serious threat to the living beings and the environment. In mammals, fibrosis and inflammation like pulmonary toxicity are observed due to the inhalation of multiwalled or single-walled carbon nanotubes (CNTs). The multiwalled CNTs reported to generate oxidative stress, whereas single-walled CNTs cause hazard to the cell wall.

### 11.6.1 Health effects of manufactured carbon nanotubes in rats

CNT toxicity information was first reported on the guinea pigs in the research conducted in Warsaw University by Huczko et al. (2001). The researchers found no adverse effect on the health of the pigs upon exposure to CNTs. Warheit et al. (2004) and Lam et al. (2004) showed the production of granulomas and lung lesions in rats by CNTs. Shvedova et al. (2005) indicated that with the increasing CNT concentration, functional respiratory deficiencies increase in mice. Furthermore, slower bacterial clearance was observed in mice treated with CNTs. It was also reported that the increase in CNTs may cause an increase in cell counts, protein concentration, glutathione depletion, $\gamma$-glutamyltranspeptidase activities, lactate dehydrogenase, and concentration of transforming growth factor beta. The researchers concluded the intrinsically toxic nature of CNTs and the risk of lung lesions among workers exposed to respirable single-walled CNTs. Muller et al. (2005) reported that multiwalled CNTs cause fibrosis, granulomas, and inflammation of lungs in rats. The two biomarkers of fibrosis, soluble collagen and hydroxyproline were found to be enhanced in dose-dependent manner in lung tissues (Lam et al., 2006).

### 11.6.2 Effect of manufactured nanomaterial on human beings

Shvedova et al. (2003) investigated human skin cells to examine the effect of single-walled CNTs in culture medium. Immortalized human epidermal keratinocytes were incubated with CNTs and the results suggested the decrease in vitamin E content, reduction of total sulfhydryls, accumulation of peroxidative products, and formation of free-radical species. The researchers also attributed the presence of iron in CNTs may cause oxidative effects. Later, these cytotoxic effects were also observed with iron-free CNTs (Shvedova et al., 2005). Multiwalled CNTs were tested on human epidermal keratinocytes by Monteiro-Riviere et al. (2005). The authors revealed that in a time-dependent manner, the proinflammatory cytokine interleukin 8 was released in the culture media. It was also confirmed that the effect observed on cells was not due to iron content (Lam et al., 2006).

The human epidermal keratinocytes were subjected to amino acids based on fullerenes by Rouse et al. (2006). The results indicated that cytokine production was induced less below 0.04 mg/mL concentrations, and it also found to retain the viability of the cell. Yamawaki and Iwai (2006) investigated endothelial cells for the first time to examine water-soluble fullerene toxicity. In the dose-dependent manner, fullerenes changed the morphology, and the maximal doses of fullerenes were found to cause cell deaths as well as inhibition of growth of cells. The potential effects of graphene-related materials were studied by Drasler et al., 2018 using 3D human lung model. The results suggested that harmful effects to the human lung model were not observed during acute exposure for two different doses (1000 and 300 $ng/cm^2$) (Kanel et al., 2022). Due to the limitation of size, the surface-modified or unmodified NMs are difficult to separate from the final products. The release of different NMs including metal-oxide and metal nanoparticles along with the final products may cause toxic effects to the ecosystem and can be detrimental to human health (Kanel et al., 2022).

## 11.7 Economics of surface-modified nanomaterials

The economics of surface-modified NMs depends on the type, grade, functionalization as well as purity of NMs. The NMs can be of different types such as carbon NM, graphene, nanocomposite, CNTs, etc. The reported range of prices for different NMs include single-walled CNTs (per gram) for \$25 to 300, multiwalled CNTs (per gram) for \$0.10 to 25, graphene and derivatives (per gram) \$2.50 to 1000. Assuming adsorption capacity for lead (Pb) on an average as 75 mg Pb per gram of CNTs, the removal cost for lead from water is estimated to be \$2.2/g-Pb, if the cost of single-walled CNTs is considered. The cost of the process may be decreased depending on various other factors such as recycling, recovery, and reusability of the material. The benefit of any technology should also be ascertained after analyzing different prevailing studies such as stability, eco-friendly nature, toxicity, etc. The cost of nano zero-valent iron is in the range \$0.05 to 0.10 per gram, whereas the production cost of bulk or micro zero-valent iron is <\$0.001 per gram (Crane & Scott, 2012). The modified NMs based on titanium oxide are reported to be available in the price range (per gram) of \$0.03 to \$0.16 (Lu et al., 2011). Titanium is a more abundant metal in the Earth's crust, therefore, it is difficult for other metal NMs to be available at similar prices as well as similar efficiency. The surface-modified or unmodified NMs are reported not to be degraded during the reaction process and can be regenerated as well as reused, which may reduce the overall application cost of the NMs (Adeleye et al., 2016).

## 11.8 Future aspects of surface-modified nanoparticles

The mixed-composition nanomaterials with surface modification are continuously being synthesized for applications in various fields. The simple synthesis techniques will yield the targeted size, shape, and property of the NMs which are resistant to the outside elements but they still require a little betterment. Recently, extensive research into the domains of sensors, electronic storage devices, and biomedicine has been reported. These materials have a basic multifunctional feature that makes modified NMs potentially useful in a variety of high-value applications. Such applications include artificial membranes for gas separation, ultra or nanofiltration, adsorbents of toxic metal ions, catalysts, nanoscopic reactors, biomaterials for corrosion protection, and abrasion resistance. In view of the inorganic nanoparticles' strong propensity to aggregate during the development of these composites, inorganic nanofillers' surfaces should be altered either by absorbing silane coupling agents like smaller molecules, or by grafting polymers, to improve their dispersion stability and compatibility with organic solvents or polymer matrices. Surface modification enhances inorganic nanofillers and polymer matrices interfacial interactions, leading to special qualities like extremely high mechanical toughness and other optical, electronic, gas-barrier, and flame-retardance characteristics. Therefore, to create high-performance organic–inorganic nanocomposite materials, the surface modification of inorganic nanofillers is required. More environmentally beneficial and nontoxic nanomaterials still need to be developed. The degrees of risk are additionally affected by the conditions of synthesis, processing, chemical composition, and dosages. Therefore, further research on the relation between the physical and chemical properties as well as toxicity of nanoparticles is required to be accomplished. The toxicological studies are still required to be done to further provide a detailed description of toxicity from surface-modified NMs and their mechanism of action. A strong guideline is also required for safe applications of such materials. Future research should also be done to estimate the actual economics dealing with surface-modified NMs, based on stability, eco-friendly nature, and toxicity of such materials.

## 11.9 Conclusion

The chapter presents an assessment of health, safety, and economics related to various surface-modified NMs. The single-step modification of gold nanoparticles with a thiol-based cationic molecule has a high destruction rate in cancer cells. The altered nanoparticles have a high yield of cell membrane penetration. Biomedical applications of cellulose-based NMs include tissue engineering, wound healing, diagnosis, and drug delivery. cellulose-based formulations have been used to prepare tablets, hydrogels, aerogels, and nanoparticles. Thus, therapeutic agents or ligands that target cellulose nanomaterials can be added to them to create a drug delivery system. Surface-modified NMs were also found to be economical for water splitting, removal, and recovery of heavy metals as well as enhancing the fluidity of crude oils. The primary factors contributing to the toxicity of NMs to humans are their size and chemical makeup. The reactivity and toxicity of NMs can be enhanced by these surface modifications. NM with a diameter of less than 100 nm has capability to bypass blood-brain barrier, enter nuclei at a diameter of less than 40 nm, and readily penetrate cells. Multiwalled CNTs cause fibrosis, granulomas, and inflammation of lungs in rats. The two biomarkers of fibrosis, soluble collagen and hydroxyproline were found to be enhanced in dose-dependent manner in lung tissues of rats. Immortalized human epidermal keratinocytes were incubated with CNTs and the results suggested the decrease in vitamin E content, reduction of total sulfhydryls, accumulation of peroxidative products and formation of free-radical species. The reported range of prices for different NMs include single-walled CNTs (per gram) for $25 to 300, multiwalled CNTs (per gram) for $0.10 to 25, graphene and derivatives (per gram) $2.50 to 1000. The cost of processes may be decreased depending on various other factors such as recycling, recovery and reusability of the material. The benefit of any technology should also be ascertained after analyzing different other parameters such as stability, eco-friendly nature, toxicity, etc.

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