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Environmental Benefits and Toxicological Risks of Nanomaterials

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ABSTRACT

Environmental biotechnology is the application of scientific and engineering knowledge used for the study and regulation of natural biological systems. It is used for the reduction in levels of environmental pollution. With the use of biotechnological applications like biotreatment, biomonitoring, and bioremediation, pollution levels in solid, liquid, and gas phases can be minimized. Nanotechnology is the application of science which focuses on designing, synthesis, characterization and applying materials on the nanoscale. At the nanoscale level, properties of materials (physical, chemical, and biological) provide number of advantages. There are benefits from the development of nanotechnology to environment, like energy consumption, cost saving on materials, less waste on raw materials, environmental monitoring and protection, biological applications, biomedical applications etc. There are many ways to reduce air pollution by using nanotechnology, of which major is nanocatalyst and nano-structured membranes. The conventional water purification systems are difficult to treat, including bacteria, viruses and heavy metals. New technologies consist of reverse osmosis, nanofiltration and ultrafiltration membranes which are using emerging products as nanofiber filters, carbon nanotubes and various nanoparticles. Uses of nanostructures and techniques involving nanoscale materials are safe, reliable, and cost-effective for the bioremediation of contaminated soil.

Recent developments of nano-wires make oil recovery possible. A major limitation for use of nanotechnology is the manufacturing processes as they are expensive and not very environmentally friendly. Choosing the right nanoscale materials is one of the vital parameters for the future of nanotechnology.

Key words: Environment, Nanotechnology, Biotreatment, Nanoscale and Graphene.

INTRODUCTION

Nanotechnology is application of science which focuses on design, synthesis, characterization and application of material on the nanoscale.

Nanotechnology is the engineering of functional system at the molecular scale. It is the understanding and control of matter at dimensional size of material between approximately 1 and 100 nanometers or nanoscale. At the nanoscale level properties of materials (physical, chemical and biological) provide new advantages. These properties may differ from the properties of bulk materials and single atoms or molecules in important ways. Applications of nanotechnology include manufacturing, measuring, imaging and manipulating matter of various products on the nanoscale [Mansoori et al., 2008]. Scientists have major interest in nanotechnology for the fields of nanocomposites, biocomposites, optical, biomedical and electronic manufacturing. Now day's researchers are intensely working on applications of nanotechnology as this can be applied widely in various fields. The applications are used for advances in medicine, computer science, ecology and even sports, during last few decades.

Nanotechnology provides solution for certain environmental problems as nano scaled materials have increased their limits and capabilities. Many new and better techniques for pollution control are emerging. Nanotechnology is able to create many new devices with a wide range of applications such as in medicine, electronics, energy production and many other production industries. Encompassing nanoscale science, engineering and technology, nanotechnology involves imaging, measuring, modeling and manipulating matter at this length scale. Nanotechnology has many applications [Aher et al., 2012]. Some of them can be very significant in improvements of technologies which can be used for protection of the environment. This involves materials and processes on an ultra-small scale.

Nanoscale devices are used for enhancement of treatment and remediation of environmental contaminants. Nanoscale materials differ from bulk in some properties such as surface area and quantum effects. Nanoscaled particles have much larger surface area per unit mass. This is the critical factor to increase mechanical and other physical and chemical properties. Basic properties of material are changed at nanoscale due to more quantum effects and less imperfections.

On comparison of polymer composite materials to traditional structural materials made up of metals, they have a reduced weight, high modulus and more resistance to environmental effects. However, polymer composites with nanoparticles reinforcement to composite materials offer more options to the material properties to meet design specifications. Different forms of nanoscale materials are used as nanoparticles, nanofibers, buckyballs, carbon nanotubes and graphene. These are having a vast range of applications in fields such as medicine, electronics, energy production, many other manufacturing industries etc. These devices consume less energy, reduce material wastes and help in monitoring environment. It can also be used to reduce and prevent the toxicity of contaminants in environment more efficiently [Dunphy Guzmán et al, Verdejo et al., 2011]. There are benefits from the development of nanotechnology to environment like energy consumption, cost saving on materials, less waste on raw materials, environmental monitoring and protection, biological applications and biomedical applications. Graphene based coatings are applied to the blades used in wind turbines or on the body of an airplane. It keeps safe the weight increasing efficiency because it does not require a multifunctional film coating, only one layer is needed. Hybridization of automobiles will be able to reduce the price by novel developments in nanotechnology. Nanoscale chemical reagents (or catalysts) fasten the rate of reaction and other efficiency of chemical reactions.

Due to this, there is less wastage of raw materials, it also saves time. A detector used for detection of a nuclear leak is much faster and more accurate using applications of nanotechnology. Development of ultra-small probes on planetary surfaces can be used for agricultural applications and control of soil, air, and water contamination. Biomedical applications include the newly developed medical diagnostic and treatments [Jagdale et al., 2010, Chabukswar et al., 2014]. Applications of nanotechnology are able to prevent environmental damage. On the contrary, it also creates negative impact on the environment. Its unique characteristics may also lead to some environmental problems. Therefore, evaluation of the positive and negative impacts of nanotechnology is necessary for the safety of society. Nanotechnology improves the strengths of many materials and devices. It also enhances efficiencies of monitoring devices, remediation techniques for pollution control, and renewable energy production. Undoubtedly, nanotechnology continuously developing can be a benefit to society and improve the environment. Although there are many obstacles to overcome in implementing this technology for common usage, researchers are constantly taking efforts for refining, developing, and making new developments. Nanoscale materials will make the products better in terms of functionality, weight savings, less energy consumption and a cleaner environment. With the help of nanodevices, scientists are able to develop more sensitive pollution detection systems for air and water quality monitoring. These systems can measure multiple parameters like a real time response capability, simplified operation and lower running costs, simultaneously when compared to conventional methods [Aher and Jagdale, 2015, Jagdale et al., 2009].

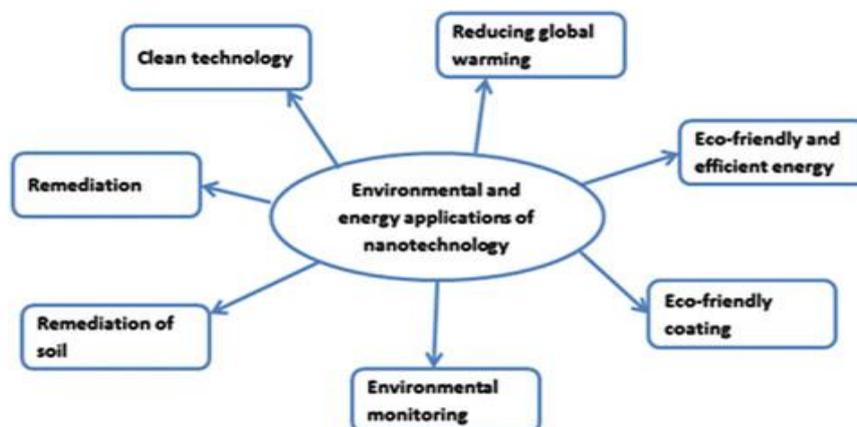


Fig. 1. Applications of nanotechnology on environment [Zhang et al.].

Environmental Cleanup

Environmental remediation eliminates or minimizes pollution or contaminants from environment. It removes pollutants or contaminants present in environmental medium. Reduction of pollution of air, soil, groundwater, surface water is important for the general protection of human health and the environment. Nanoremediation is use of nanoscaled reactive agents for removal of contaminants [Sellers, 2009]. Use of nanotechnology for environmental cleanup became effective and so used frequently. The diagrammatic representation of environmental nanotechnology used in minimizing soil, water and air pollution is shown below in figure 2.

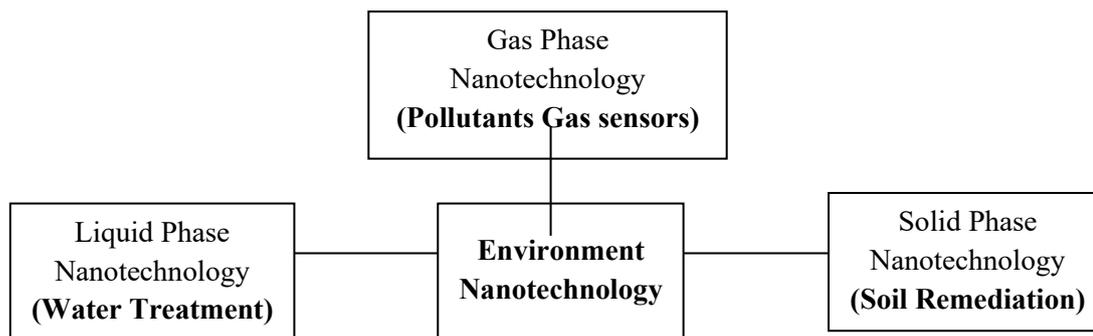


Figure 2. Environment nanotechnology on solid, liquid and gas phase [Dunphy G. et al].

Nanostructures affect on environment in following ways:

Nanostructures transportation occurs through particle-mediated transport due to its nano size, high distribution, high surface area, porous nature and surface chemistry (hydrophobic nature). They have potential for bio-assimilation as there are direct consequences and associated contaminants. The state of dispersion for nanostructures is agglomeration/aggregation. Their physical and chemical properties, like crystalline phase and crystallite size, water solubility, and electro-optical properties, affect faster than other materials. Their surface chemical properties, such as reactivity, surface composition, catalytic properties, adsorption/desorption of molecules, and surface charge, etc., also affects environment [Rickerby and Morrison].

Air

Air pollution is the result of production and consumption of wasteful resource. Cars, fires, various manufacturing plants produce a complex variety of chemicals in the air. This low quality air often harms the environment and human health. Traditional methods for determining the chemical makeup of the air requires expensive equipment and experts for preparation of the sample to be tested. Most of the waste cannot be restored into the environment effectively and cheaply [Ian Sofian Yunus et al., 2012].

Air pollution can be minimized using nanotechnology in several ways. There are two major ways to reduce air pollution by using nanotechnology i.e. nanocatalysts and nano-structured membranes. Nanocatalysts are currently in use and nano-structured membranes are under development.

Nanostructured membranes are developed to separate carbon dioxide from industrial plant exhaust streams. This designs a method which can be implemented in any power plant inexpensively. Nanosensors used to detect and track pathogens (germs), contaminants, nutrients, environmental characteristics (like light/dark, hot/cold, wet/dry), heavy metals, particulates, and allergens. The nanospray Desorption ElectroSpray Ionization (nanoDESI) developed to fasten the process. It helps to make measurements easier for analysis, provides detailed analysis of molecular content of sample. This process involves dissolution of the sample into a solvent (liquid), and then aerosol is formulated from the dissolved sample by using nano-electro spray ionization. It requires very small amount of sample. Now the particulate matter is analyzed using a high resolution mass spectrometer as the sample is in aerosol form [Ian Sofian Yunus et al., 2012].

Recent research is on development of new material which can record accurately carbon dioxide (CO₂) efficiently, selectively and inexpensively. Researchers have used materials based on metal organic frameworks (MOF) for preparation of tiny cages which are capable of capturing the CO₂. These MOFs have 2-3 times more capacity to absorb CO₂ when compared to conventional sorbents. It requires the pull of a vacuum to release the CO₂ from the MOF. Other technologies require high temperature to release the gas. CO₂ can be pumped deep into the Earth where it becomes stable in the form of carbonate minerals [Air Pollution and Nanotechnology].

Water

The surface water, waste water and other water sources are mainly contaminated by toxic metal ions, various organic and inorganic solutes, microorganisms etc. The present nanotechnology application is used in water treatment for purification. Some novel nanomaterials are being used for the treatment of polluted water resources. Due to their unique activity toward resistant contaminants, scientists are able to develop new techniques. Many nanomaterials are under active research for their consumption in the treatment of water and contaminated sites. Thus, due to chemical reactions, harmful pollutants in water can be transformed into harmless chemicals [Cloete et al., 2010].

Nanotechnology is expected to deal more efficiently with contaminants. New technologies consist of reverse osmosis, nanofiltration and ultrafiltration membranes which are using emerging products like nanofiber filters, carbon nanotubes and various nanoparticles. The conventional water treatment systems are difficult to treat, including bacteria, viruses and heavy metals. The efficiency of purification techniques generally originates from the very high surface area of nanomaterials which automatically increases dissolution, reactivity and sorption of contaminants [Water Pollution and Nanotechnology]. Because of insertion of nanoparticles into underground water sources, water purification process becomes cheaper and more efficient. This nanotechnology eases the water cleansing process. Nano-sized fibers as electrodes used in the method of deionization are cheaper and more energy efficient. Traditional water filtering systems use semi-permeable membranes for electro dialysis or reverse osmosis. On decreasing the pore size of the membrane to the nanometer range, it allows only selected molecules to pass through it. These molecules can filter out later easily. New nanoscaled materials widely used in separation, purification, and decontamination processes for water purification. Newly developed ion exchange resins are used for softening and purification of water. These resins are having pores which are of nanoscaled and organic polymer substrate on the surface. On these types of surfaces ions get replaced with others easily, e.g. sodium or potassium gets exchanged with heavy metals, removes poisonous elements present in water. However, damage or contamination of these resins is due to iron, organic matter, bacteria, and chlorine [Air Pollution and Nanotechnology, Water Pollution and Nanotechnology]. New technique Functionalized Nanoporous Thin Films (FNTF) is highly-selective for detection of heavy metals in water. It allows testing for every heavy metal (including mercury, lead and cadmium) which can affect human health and the environment negatively. It increases sensitivity more than a thousand times and is also available in low cost. Another recent development is super paramagnetic nanoparticles. These are capable of absorbing heavy metals as they are coated with chemicals which can capture metal ions.

These are tested in river water as it contains all heavy metals which are relevant environmentally. Rapid and reliable identification of pathogens present in water is necessary for maintenance of public health. Traditional laboratory techniques like culture tests take more time for detection. The methods involving enzymes, immunological or genetic tests can be faster are under development.

Biofilms can be mats of bacteria wrapped in natural polymers. These are difficult to treat with antimicrobials or other chemicals used for water filtration. They can be cleaned up mechanically, but involves more cost, time and labour. With the use of nanofiber membranes and nanobiocides purification of water can be more easy, faster and effective.

Soil

Now days, with the huge growth of human population, food demand from crops also increase. So soil conservation is a vital parameter. Deforestation, over-development and pollution from man-made chemicals and many other are consequences of human activity and carelessness. Application of increased amounts of fertilizers and other agricultural chemicals to soil led to soil pollution. Industrial and domestic waste-disposal practices add to the pollution. Soil pollution is due to use of persistent toxic compounds, chemicals, salts, radioactive materials or disease causing agents. All these have combined adverse effects on growth of plants, animal and human health. Use of nanostructures and other techniques involved nanoscaled materials not only used safely, but is also reliable and cost-effective for bioremediation of contaminated soil. This is environment friendly method for degradation of various pollutants. Catalysts are molecules used to fasten or speed up chemical reactions. Due to nanoscale, more chemicals can interact with the larger surface area of catalyst simultaneously. This makes the catalyst more effective and lead to even faster reactions. Nanocatalysts can be used to enable a chemical reaction (which changes one type of molecule to another type) at lower temperatures. These can be used more effectively to process waste into food, feed, industrial chemicals, biofuels and energy [Ehsan Olyaie and Hossein Banejad, Krishna et al., 2015]. Nanoparticles can be beneficial in catalytic and remediation application. Nanocatalysts made up of metal oxides can prevent pollution due to industrial emissions (e.g. DeNOx catalysts used to remove nitrogen oxides from fossil fuel power plant emission gases). The benefit can be derived from titanium dioxide nanoparticles to manufacture self-cleaning surfaces as it is having photo-catalytic properties [Lamba, 2005] .

Oil spills

Traditionally, dispersing agents, gelling agents and biological agents are most commonly used for cleaning up oil spills. However, none of the traditional methods can recover the oil lost completely. There are many proposed ways that nanotechnology can be applied to oil spill cleanup. A mat of nanowires is just one of many. Recent developments of nano-wires make oil recovery possible. The nanowires made up of potassium manganese oxide can clean up oil and other organic pollutants. These nanowires form a mesh that absorbs hydrophobic liquids up to twenty times its weight and rejects water due to its water repelling coating. Since the potassium manganese oxide is very stable even at high temperatures, the oil can be boiled off from the nanowires. Also both the oil and the nanowires can then be reused [Lamba, 2005, U.S. Environmental Protection Agency, 2008].

In 2005, Hurricane Katrina destroyed many oil platforms and refineries. New oil remediation and recovery application successfully launched. These used water repelling nanowires to clean up the oil spilled by the damaged oil platforms and refineries [Jingna Zhao, 2009].

Solar Energy

Major research is being done on the development of nanotechnology in solar cells. Solar energy is a renewable resource. The price per watt of solar energy is very less. Nanotechnology is used to provide improved performance coatings for photovoltaic (PV) and solar thermal panels. Due to nanoscale, hydrophobic and self-cleaning properties combination increases efficiency of cells. When PV coated with nanoscaled materials, they can remain cleaner for longer duration and ensure maintenance of maximum energy efficiency [Jingna Zhao, 2009]. Nanotechnology is making solar power cheaper. New technique is organic photovoltaic cells (OPV) instead of the more common silicon crystal solar cells made from light-sensitive polymers. These polymers can be dissolved in liquids, and so they can be used in various processes and can cut down the cost. Though conversion efficiency is typically on the order of 5%, research is carried out for improving that through controlling nanoscale morphology [Leo Stander, and Louis Theodore, 2011].

Energy Generation and Storage

The use of nanomaterials leads to significant savings in resources and efficiency increases in manufacturing and related applications. There are many applications related to energy related include nanostructured electrode materials for improving the performance of lithium ion batteries and nanoporous silicon and titanium dioxide in advanced photovoltaic cells [Hyder, 2003]. There are currently many nanotechnology based projects in the area of energy generation and storage. Some examples are solar cells, better rechargeable batteries, hydrogen fuel cells. More durable gas turbines cost effective and sustainable biofuel production.

Green nanotechnology

This refers to the use of nanotechnology or products developed using this technology to enhance the environmental sustainability. This reduces the production of negative externalities from processes. Use of nano-products supports the environmental sustainability. It is used to minimize potential environmental and human health risks occurred with the manufacturing process and use of nanotechnology products. It helps to replace the existing products with new nano-products which cause less damage to environment throughout their lifecycle [Barbara Parish Karn, 2007]. This involves incorporation of nanotechnology, for efficient, controlled manufacturing would drastically reduce waste products. The use of nanomaterials as catalysts in manufacturing processes gives greater efficiency. This minimizes or eliminates the use of toxic materials and the generation of undesired by-products and effluents [Tratnyek and Johnson, 2006].

Benefits of Nanotechnology on Environment

Nanotechnology provides many environment benefits and also has the potential to help reduce the human interventions on the environment. It offers solutions for energy consumption, air-soil-water pollution, green gas emissions etc.

Nanosensors used for identification of pollutants faster and cheaper. Nanocatalysts and nanoparticles utilized for clean up pollution in the ground, air or water. Nanoscience is making great strides in manufacturing and use of fossil fuels more environmentally friendly. Its applications are also in advancing alternative energy sources like solar energy, batteries, fuel cells, and biofuels [Hester and Harrison, 2007]. To reduce the weathering effects on composites carbon nanotube and graphene based coatings are used. This is used in wind turbines and aircraft. For a better nanoscale inclusion to reduce the degradation of UV exposure graphene is the material of choice. For longer lasting and retention of longer initial strength, a nanoscale coating is applied on materials. For improvement in the performance of data information system carbon nanotubes have been used [Dreher, 2003].

Use of nanomaterials helps to remove greenhouse gases and other pollutants from the atmosphere. It reduces requirement of large industrial plants for water purification and provides cleaner, more efficient processes. It reduces amount of waste created from manufacturing industries. It minimizes damage to environment. It helps in detection and elimination of pollutants from air, water and soil [Dreher, 2003].

Potential Environmental Effects

There is need to consider few potential risks while using nanoparticles. The larger surface area of nanoparticles damages more to human and environment. Therefore, concern for the risk involved to the society has attracted national and international attentions. Nanoparticles are beneficial to tailor the properties of polymeric composite materials and environment in pollution monitoring. They also reduce material consumption and remediation [Dreher, 2003].

The effects of environment and risks associated with nanotechnology are very limited and inconsistent. The major problem of nanomaterials is the analysis method. With improvement of nanotechnology, various new and novel nanomaterials are developed. However, important factors in determining the toxicity are variation of shape and size of material. There is not much information on methods of characterizing nanomaterials. Also critical factor is chemical structure for toxicity determination. This makes difficult detection of nanoparticles in air for environmental protection with existing technologies. Advanced experimental designs for products based on nanotechnology reduce the waste. Minor changes in chemical function groups have major impact on properties of nanomaterial. Risk assessment is important factor for prediction of the environmental impacts. For safety of human health and environment evaluation of nanotechnology requires. Risk assessment includes various types of risks involved like exposure, transport, persistence, transformation, toxicological analysis and ability to recycle [Gillett, (2009)].

Applications of carbon nanotubes use in many materials for memory storage, electronic, batteries, etc. Concerns are due to unknown harmful impacts by inhalation to the human body. It shows toxicity similar to asbestos fiber. Graphene has a good thermal conductivity and fire retardancy.

Though there are benefits of graphene to the environment and economy, the graphene based composites harm the environment due to toxic properties. It is difficult to separate graphene from waste and may cause fire risk if contamination occurs. It could react with materials and biological systems in environment [Gillett, 2009, Arti Goel, 2014]

Though there are several positive benefits of nanotechnology, the classic example of its harmful effects on environment is a semiconductor plant contaminated the ground-water in Silicon Valley, California in the 1980s. The potential environmental effects of nanotechnology can be summarized as: For synthesis of nanoparticles high energy require, which demand high energy. The less information is available on actual size, shape, chemical structure and environmental implications of nanomaterials. The recovery and recycling rates are very low for nanomaterials. Also there is no proper training to engineers and workers, cause of some manufacturing concerns [Arti Goel, 2014].

Limitations

Major limitation for use of nanotechnology is manufacturing processes is that there are expensive and not very environmentally friendly. It requires strict purity for starting materials, involves repetitive processing steps and processing requires extreme environments such as high temperatures, cryogenics (extremely cold), clean rooms etc. The process involves use of some toxic chemicals and solvents also, high usage of energy and water. Manufacturing gives low yield compared to starting materials and involves generation of greenhouse gases which can harm environment [Arti Goel, 2014]. A major concern is nanoparticles cannot be detected after their release into the environment, which can create difficulties. More information is needed regarding the structural and functional characteristics, in relation with surface area, size, and toxicity. Complete risk assessments should be performed on newly developed nanomaterials which might get exposure during manufacture or use. Such assessments should be considered for toxicological hazard, probability of exposure and environmental and biological fate, transport, persistence. The transformation of nanomaterials into the finished product and recycling of it is also important. This analysis is useful for assessing impacts of nanomaterials on environment. An effective strategy for recycling and recovery of nanoparticles is necessary. Overall, nanotechnology avails significant opportunities for improvement of the environment. For achievement of sustainable and safe environment, further research on the potential risks is required [Arti Goel, 2014].

Educational Issues

Researchers or college students do not fully realized and understand how nanoparticles affect a system. Universities should provide nano safety seminar and conference which can be beneficial for college students, engineers and also industrial manufacture scientists in other fields. Having organized education and training systems to college students and researchers in laboratories will reduce the negative impacts of nanotechnology. Research funding should be raised from government agencies. Public media is an ideal way to populate the information of nanomaterial and to educate public of advantages and disadvantages of nanomaterial for the commercial products [McLaughlin, 2007].

Concerns

The special properties of nanoparticles inside the body are unclear and unpredictable. Also, many are worried about the effects of nanoparticles on the environment. In 2009, the European Network on Health and Environmental Nanomaterials held its first conference to study the impact of nanomaterials on health and environment.

The small size of nanoparticles warrants investigation of the consequences of inhalation and absorption of these particles and their effects inside the body, as they are small enough to penetrate the skin and diffuse through cell membranes [McLaughlin, 2007].

New branches of science such as eco-nanotoxicology emerge to study the movement of nanomaterials through the biosphere. Research is going on to know how much will be absorbed by the soil, air or water, and how severely the widespread presence of nanoparticles in the environment will impact the ecosystem [McLaughlin, 2007]. To address these concerns, there is need to set up regulations and legislation to ensure that nanoparticles, with so much potential for cleaning up pollution, will not become a new form of pollution themselves.

CONCLUSION

Nanomaterials help to clean certain environmental wastes, but also can contaminate environment in other ways. Engineering ethics need to be defined before the commercial use of nanotechnology. Risk assessment is important to evaluate potential risk to our environment when the products are in use. Full life cycle evaluation and analysis for all difference applications should be conducted with constant attention. Potential effects such as increased toxicological pollution on the environment are due to the uncertain shape, size, and chemical compositions of some of the nanoscale products. Choosing right, less toxic materials (e.g., graphene) will make huge impacts on the environment. This can be very useful for the training of students, scientists, engineers, policymakers, and regulators working in the field. It is important to conduct a risk assessment and full life-cycle analysis for products of nanotechnology to understand the hazards and the resultant knowledge that can be used to predict the possible positive and negative impacts of nanoscale products.

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