IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 11, 2019, accepted December 16, 2019, date of publication December 23, 2019,
date of current version January 8, 2020.

Digital Object Identifier 10.1109/ACCESS.2019.2961513

Environmental and Societal Impact of Nanotechnology

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ABSTRACT The ability to measure, understand, manipulate, organize, engineer and control matter on the nanoscale has been opening up the wealth of possibilities that were otherwise non - existent at higher scales. At this scale, basic research principles and tools in biology, physics, chemistry, and engineering converge and have led to all-inclusive applications of nanotechnology. Despite the innovative applications and promising potentials of nanotechnology, there are concerns about its short and long-lasting impacts on humans, nature and the environment. In an attempt to address these concerns, a number of researches have been conducted. Evaluations of studies addressing the issues of nanotechnologies and their impacts are necessary to give insights for further studies that will advance the technology for the true benefit of mankind and nature. This study, thus, provides a detailed review of studies on nanotechnology applications and the positions of stakeholders on the impact of nanotechnology. Among other things, the outcome of this survey shows that there are numerous successful applications of nanotechnology. Public perceptions are pivotal in determining the extent of revolution and transformation that nanotechnology will have on the environment. Religious beliefs and moral concerns; trust in governmental regulatory agencies and the industry; the level of inclusion of the society in the product design, development, and commercialization process is critical to the extent of acceptance of nanotechnology inventions. Expression of objective views concerning the benefits, limitations & risks, and adequate education of the public, risk regulators & all stakeholders are crucial in determining the fate of nanotechnology.

INDEX TERMS Acceptance, application, economies, environmental interference, ethics, issues, limitations, nanotechnologies, potentials, risks, safety, sustainability.

I. INTRODUCTION

A. WHAT IS NANOTECHNOLOGY?

Nano is a prefix used to show one-billionth of a particular parameter. The prefix is usually applied to the length scale in order to indicate an extremely small magnitude of the length dimension. A nanometer (nm) is a billionth of a meter (10^{-9}m). The diameter of individual atoms is smaller than 1 nm, a DNA strand typically measures 2 nm, a virus is roughly 100 nm in diameter and the thickness of a sheet of paper is around 100,000 nm [1]. The description of some items at the nanoscale is given in Figure 1. The understanding, manipulation, organization, engineering, and control of matter on a molecular and atomic scale can be termed nanotechnology. It involves reduction and refining of bulk materials or artificial combinations of atoms and molecules of materials with at least one dimension ranging from 1 - 100 billionth meter to create materials with modified properties [2], [3]. Matters engineered or which naturally occurs within this range of dimensions are called nanomaterials and can only be seen with the aid of powerful specialized microscopes. Based on dimensionality, they can be categorized as one dimensional (thin films, coatings), two dimensional (nanotubes, nanowires, and nanofibers) and three dimensional (nanoparticles, quantum dots) [4].

Nanoscale particles have ever been part of nature and science. For example, viruses are naturally occurring nanoparticles; carbon particles from combustion processes

The associate editor coordinating the review of this manuscript and approving it for publication was Shashi Poddar.

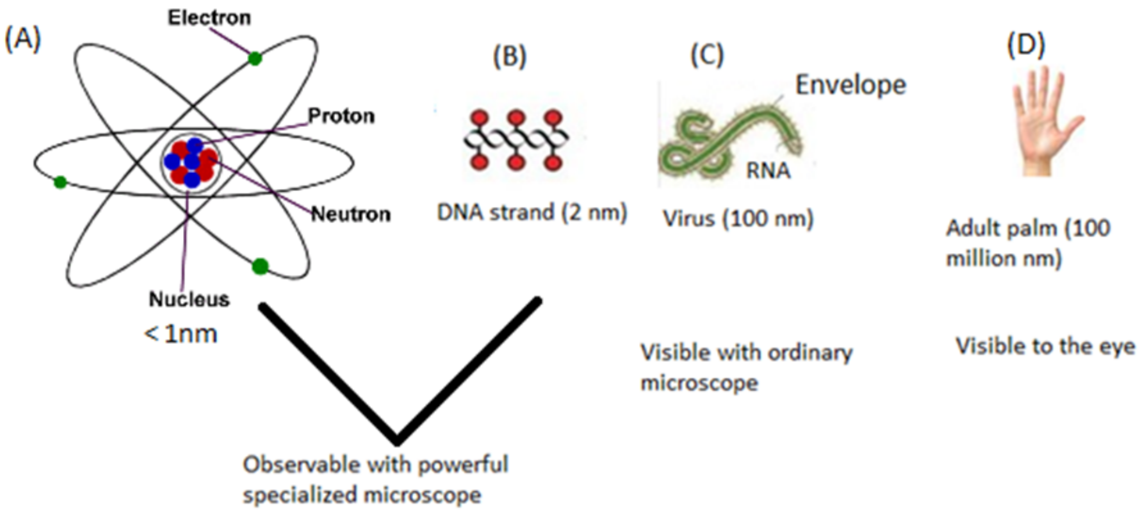

FIGURE 1. Description of items at nanoscale: (A) http://www.ducksters.com/science/the_atom.php; (B) Heerboth et al. [10] (C) https://www.khanacademy.org/science/biology/biology-of-viruses/virus-biology/a/animal-viruses-hiv (D) http://eaconsalt.ru/neyrodermit/neyrodermit-la-foto-de-la-mano.html.

are examples of nanoparticles from human activities and as far back as the 1920s, carbon black has been employed by tyre manufacturers to improve the performance of tyres even without their knowledge of nanoparticles. Also, several of the activities of cells occur naturally at the nanoscale. The quantum leaps in the area of nanotechnology may, however, be credited to the insight gained from the naturally occurring processes at nanoscales. By observing phenomena that characterize the natural organization of materials on the nanoscale, models of nanotechnology are established and nanotechnologists are able to imagine and construct new materials and processes which are applicable in diverse fields.

The properties of nanoparticles and nanostructured materials differ significantly from those of their visible scale counterparts. For instance, gold nanoparticles appear red and not golden and aluminum which is stable on a macro scale becomes combustible on a nanoscale. The unique and unpredictable changes in properties at the nanoscale from that at the macro scale are due to quantum and surface effects that are predominant at the nanoscale. As the size of material reduces to the nanoscale, the percentage of the atom on the surface significantly increases. This leads to an increase in the ratio of surface area to volume. The increased ratio of surface area to volume, among other things, alters the reactive, mechanical, thermal and catalytic attributes of the materials. Reactivity of nanoparticle increases because unlike bulk materials that have only relatively few percentages of the total number of atoms as surface atoms, nanoparticles contain almost all the total number of atoms as surface atoms and these atoms are able to participate in reactions due to the lower coordination number. The surface atoms of nanoparticles are able to interact more easily with the neighboring atoms of other matters. This accounts for high reactivity of nanoscale engineered particles such as gold which is otherwise chemically stable in the bulk form. The increased reactive properties of nanoscale matter are liable for producing both accidental and intended morphological transformations [5].

The basis of the quantum effects is the wave-particle duality behavior of energy and matter. This duality behavior is more predominant at the nanoscale level and it affects the electrical, magnetic and optical attributes of materials. Exploration of the quantum effects at nanoscale increases the possibility of obtaining products with desired properties such as strength coupled with lightness and conductivity without overheating [6]. Discovery and production of nanoscale materials either by building up from single groups of atoms or by refining or reducing bulk materials is a revolution in technology because these materials will possess exceptional physical, chemical, toxicological and biological properties that are different from those of the existing bulk materials.

Without a doubt, in the last few years, considerable research efforts have been invested in the applications of nanotechnology and nanoscience in various sectors of human endeavors. Hence, Nanotechnology has found tremendous breakthroughs in agriculture, water purification, healthcare, transportation, energy, electronics, environmental bioremediation, just to mention a few. Hence, nanotechnology has numerous prospects of positively improving the standard of living in a sustainable manner. Nevertheless, nanotechnology may not achieve its full potentials unless its associated economic impact, societal acceptance (including ethical issues), environmental impact, safety, as well as sustainability, is fully understood. In order to understand these issues, the paper presents a comprehensive review of nanotechnology in various sectors by presenting the latest researches with respect to applications of nanotechnology, the importance of nanotechnology, economic impacts, ethical issues, environmental impacts, and sustainability.

In order to carry out this review, a comprehensive search on relevant works related to nanotechnology applications was conducted on the Google Scholar search engine by specifying the terms ''nanotechnology'', ''applications of nanotechnology'', nano-technology and societal contributions'', and ''nanotechnology and ethical issues''. This led to further searches in other databases such as IEEE Access, the web of science and science direct. In order to streamline and remove irrelevant studies, duplicates of studies were eliminated. Studies that were not presented in English language were also eliminated.

The rest of this article is arranged as follows: Section IB gives the importance of nanotechnology, section IIA presents some ethical issues in nanotechnology, section IIB discusses the economic impact of nanotechnology, section IIC explores the societal acceptance of nanotechnology with special attention given to environmental impact, safety, and sustainability of nanotechnologies. Lastly, section III presents the conclusion of the study and areas that can be considered for further studies.

B. IMPORTANCE OF NANOTECHNOLOGY

Although it has been long predicted that the ability to manipulate matter at the nanoscale will open up a wealth of industrial possibilities [7], the development of tools for imaging, measuring and manipulating matter at nanoscale began as a result of the advances in microscopy in the 1980s [8], [9]. The attending discoveries in nanotechnology have led to an array of developments such as improved agricultural yields to meet the needs of the teeming population, more economical water purification processes, improved medical care and reduction of energy consumption by more than 10% resulting in a cleaner environment. These nano-enhanced developments in various fields are metamorphosing. The current benefits and the projected advantages of nanotechnology in some selected industries are discussed in this section. Figure 2 shows some important applications of nanotechnology.

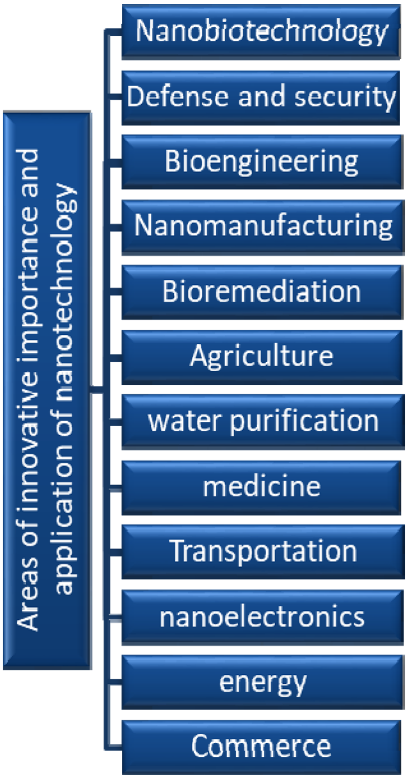

FIGURE 2. **Some important applications of nanotechnology.**

1) AGRICULTURE

Agriculture is the use of biological processes to produce food and many other desired products that are beneficial and essential to man by breeding of crops and animals. Agriculture is vital to human sustenance and it is an important economic driver in most developing countries. With the increasing world population and diminishing resources, the use of new technologies in agriculture is becoming imperative. As it is with many other fields that squarely depend on biological processes, nanotechnology possesses great potential to revolutionize agriculture because biological systems are basically composed of nanostructured materials and biological processes depend significantly on functionality occurring at the nano - level. Currently, the application of nanotechnology in agriculture concerns the use of nanosized particles with extraordinary properties to increase the productive capacity of crops and farm animals. Soil nutrient is a key factor that determines the quality and quantity of the crop. When soils are fertile, they produce crops with higher yields and better quality.

The level of soil nutrients makes some lands more suited for the cultivation of certain crops. Soil nutrients are depleted when the same crops are cultivated on the same soil for several years in a row and some soil nutrients are also removed during harvesting of crops. To obtain optimum yield in the subsequent planting seasons, the soil nutrients have to be replenished. Replenishing of soil nutrients can be achieved either by crop rotation or application of fertilizer. Common methods of fertilization application are remotely leading to inefficient utilization of the fertilizer or even some harmful occurrences such as autrification and pollution of water resources. As against the common traditional methods of fertilizer application, gradual and controlled release of nutrients into the soil through encapsulated fertilizer can improve efficient fertilizer utilization and prevent the associated harmful occurrences [11], [12]. This is because encapsulates, being larger than the nutrient molecules, are not easily transported to unintended soil compartments. Nanotechnology offers ways of encapsulating chemical substances such that the contents are released only at the presence of definite triggers [13]. Through nanostructured fertilizers, target nutrients can be specifically released in response to environmental triggers and biological requirements such as pH, chemicals, light, temperature, and magnetic fields.

Some of the chemicals that can serve as triggers are produced by the roots of plants. Therefore, with nanofertilizers, the nutrient delivery system can remain intact until the presence of the trigger is detected, thereby increasing the chances of adequate uptake and utilization of nutrients. Nanofertilizers can be encapsulated within nanoporous materials, coated with thin polymer film or delivered in the form of particles or emulsions of nanoscale dimensions. Sheathing of fertilizers with nanomaterials makes the material stronger and ensures the intended controlled release of the nutrients [14]–[16].

Nanotechnology can also be applied in pest control using an approach similar to nanofertilizer technology. Pesticides can also be encapsulated and released only when there is a need for it [17]. For the purpose of improving the effective usage of pesticides, the trigger that would release the pesticides may be conditioned to respond to chemicals produced by the pest or the set of conditions that favour the development of pests. The stickiness of the pesticide encapsulates can be improved to the extent that its loss during rainfall is minimal. However, this will require the inclusion of a trigger to remove unused pesticide capsules prior to the crop consumption or use for other purposes.

Feeding and nutrition, disease prevention and control, conversion of animals' by-products and waste into value-added products, monitoring, and information management are major areas that nanotechnologies are applied to, in animal production [18]. Animal production requires large amounts of vitamin supplements. The common practice is to mix the supplements with animal feed. Inefficiency in delivery of the micronutrients results in loss of the costly supplements because a considerable amount may end up in the urine. Nanotechnologies can be applied to deliver micronutrients to animals in a way comparable to applications developed for human nutrition. Adapting the nutrient delivery systems of human food products guarantees feeding strategies for more sustainable animal production [19].

Toxins and pathogens can be removed by the binding action of surface-functionalized nanomaterials and nanosized additives. Self - healing forces which make animals more resistant to diseases can be activated in animals through nano feed which serves as food supplements. Nanofeeds have also been known to improve phosphate utilization, reduce antibiotics requirement, improve the growth of bones, and reduce mortality rates by serving as antioxidants that help maintain healthy cell activity in animals. Incorporation of nanotechnologies into insemination technology especially in the aspect of sire – fertility testing and semen purification have great potential for improving the reproduction performance of livestock. Sutovsky and Kennedy [20] reported trials of nanoparticle-based technologies for fertility testing and nano purification of bull semen for commercial artificial insemination. Applications of nanotechnology in aquaculture include antibacterial surfaces in aquatic systems, the use of porous nanostructures in the delivery of veterinary products and pathogen detection in water through nano-sensors. Nanoparticles have a high prospect for improving protection against pathogenic diseases in farmed fish. Since oral administration with chitosan/pDNA induced antibody immune response against *Vibrio parahaemolyticus* (OS4) in fish, chitosan may be said to have great potentials as carriers for an oral plasmid DNA vaccine [21], [22].

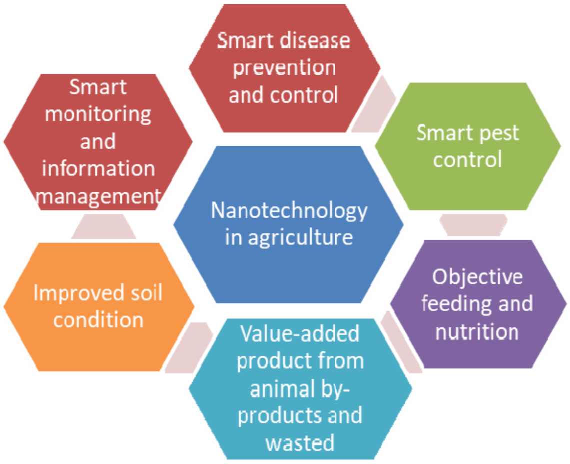

FIGURE 3. **Application of nanotechnology in agriculture.**

Sensors combined with radiofrequency identification (RFID) systems can serve as a veritable tool in monitoring animals for the purpose of obtaining important information on the animals and their production status. By combining nano-delivery of nutrients with RFID and automated feeding, certain processes involved in animal production can be tailored to meet the needs of individual animals based on inferences drawn from available production and health status information. Implantable RFID systems are available that ensure that animals with an RFID transponder can be individualized anywhere on the globe [23]. The transponders can be equipped with sensors capable of measuring definite data. Nanotechnology enabled biosensors are available that can quantify specific substances precisely, economically and reliably. With the unique identification code provided by RFID systems (which ensures the identification of each animal and link information stored in different databases to the individual animal) and nanotechnology-enabled biosensors, the direct monitoring of the reproductive status of animals and early detection of infectious diseases is enhanced.

2) WATER PURIFICATION

The availability of clean, safe water is fundamental to the sustenance of life and it is important to health, environment, and economy. As the global population increases, the demand for water increases and an adequate supply of water becomes great concern especially, in water-stressed areas, leading to the exploration of unconventional sources of water such as seawater and wastewater. The current water purification technologies are therefore gradually becoming inadequate for meeting the need for safe water [24]. A number of technologies like filtration, reverse osmosis, germicidal lamps, chlorination, and ozonation which are modified forms of 19th and 20th-century inventions are being deployed to purify water. These technologies are, however, becoming

TABLE 1. Nanomaterials and their application in water treatment.

Nanomaterials		Application	Probable limitations	Reference
Nano – adsorbent	• Carbon nanotubes (CNTs)	Removal of heavy metals and various organic contaminants from wastewater	Secondary pollution may arise as a result of complications in separation from aqueous solution caused by the smaller size of the particles	[25]
	• Graphene-based nano-adsorbents	Adsorption of heavy metals present in wastewater		
	• Polymeric nanoadsorbents	Removal of organics and heavy metals. Removal of anionic compounds such as dye	Challenge with respect to economic reuse and regeneration	[26]
	• Zeolites	Disinfection of water Hybrid forms remove heavy metals like Nickel and Lead from wastewater		
	• Oxide-based nano-particles	Removal of hazardous pollutants Adsorption of heavy metals		
Nanomembranes		Reduction of hardness, color, odor, and heavy metal ions from groundwater.	The life cycle of some nanomembrane may contribute more to toxicity, global warming and ozone depletion than traditional materials.	[27]
		Low-pressure desalination of seawater Effective elimination of dyes and heavy metals	Increased likelihood of membrane fouling	[28]
Nanocatalysts		Photocatalytic, electrocatalytic and Fenton catalytic purification of water	At the industrial level, the need for UV radiation for photocatalytic activities of some nanocatalysts may predispose workers to skin cancers and DNA mutation	[29]
		Degradation of microbial contaminants in water	Fenton-catalysis is associated with the continual loss of catalyst material and acidic conditions for optimal functioning	[30]

inadequate for water treatments as more than 1000 new industrial wastes that were not envisaged at the conceptual and design stage of these technologies are released into the environment annually. Consequently, new technologies that adequately address the current challenges of water purification are not negotiable. These technologies, among other things, should effectively remove the contaminants, be economically viable, environmentally friendly and energy less intensive [31].

Nanotechnology is one of the methods being explored to address the challenges facing purification of water as it offers possibilities of refining and optimizing currently available techniques to obtain new innovative techniques for purifying water. The nano-based techniques for water purification can be customized for removing a specific contaminant or can be multitasking to address several contaminants. The potential of nanotechnology-based techniques for water purification includes use of nanoparticles as antimicrobial agents for water disinfection; the use of nanomaterials as catalysts and adsorbents for removing pesticides and other organic matter; the use of nanomaterials for removal of heavy metals and inorganic contaminants; and the use nanomaterials as filtering agents. Nano – based purification technologies are poised to have a higher rate of remediation with the generation of lesser amount of harmful by-products because of the higher surface area and surface reactivity which characterize nanoparticles in comparison to macro-sized particles [32]. Although there are uncertainties and concerns about the safety and the potential impacts of nanoparticles, it is expected that nanotechnology would play a sustained role in water purification and orchestrate techniques which can conveniently substitute conventional methods that are energy-intensive and require more raw materials.

The typical stages involved in the usual water treatment are pre-treatment to remove suspended solids; coagulation and flocculation to precipitate dissolved impurities; sedimentation to remove precipitated impurities; disinfection; aeration; and filtration to remove suspended particles. A major limitation of most conventional methods of water treatment is the inability to eliminate dissolved salts and certain soluble organic and inorganic substances [33]. Although reverse osmosis which is one of the conventional remediation techniques prevents all soluble and minutely insoluble substances in water, this is done at very high pressure [34]. Nanofiltration membrane requires low pressure to selectively prevent substances, thereby enabling the preservation of minerals that are present in the water that the human body requires for adequate functioning. Nano-filtration membrane has been shown to remove dissolved salts from brackish water; remove dissolved organic pollutants from surface water and wastewater; remove biological contaminants, nitrates, arsenic and cadmium from groundwater and surface water; and soften water (remove calcium and magnesium) [35]. Favre-Reguillon et al. [36] reported that minute quantities of U(VI) can be removed from seawater through nanofiltration. Evaluation of the use of nanofiltration to desalinate water by Goswami *et al.* [37] reveals that nanofiltration coupled with reverse osmosis could efficiently make brackish water drinkable. Nanoceramic filters have been reported to have a high capacity for particulates with less clogging, chemisorp dissolved heavy metals and have high efficiency for removing viruses and bacteria. Gao *et al.* [38] documented the effectiveness of carbon nanotubes filters at removing bacteria (Escherichia coli and Staphylococcus aureus) from contaminated water. The CNT filters can be cleaned by ultrasonication and autoclaving without impediment. Elimination of metals and organic compounds from water and nano-filtration membranes using nano-sized zero-valent iron have been reported [39].

Reactivity and degradation of contaminants can be enhanced by nanocatalysts. Zero-valent metals, semiconductor materials, and bimetallic nanoparticles are typical catalytic nanoparticles used for degradation of environmental pollutants like PCBs (polychlorinated biphenyls), azo dyes, halogenated aliphatic, organochlorine pesticides, halogenated herbicides, and nitroaromatics [40]. Nano-scale zerovalent iron possesses dual properties of adsorption and reduction and as such is generally preferred for nanoremediation. It has the ability to reduce organic contaminants as well as inorganic anions like nitrate, perchlorate, selenate, arsenate, arsenite, and chromate. Zero valent iron and bimetallic Fe^0 nanoparticles have been efficient in the reduction of metal ions like Cr(VI) into less toxic and mobile Cr(III) [41]. In wastewater treatment, nanoparticles from metal or metal oxides such as manganese oxides, copper oxides, cerium oxide, silver nanoparticles, and ferric oxides are extensively used in eliminating the heavy metals [42]–[47]. Nanostructured silica is also found useful in wastewater treatment to eliminate heavy metal ions [48]. Khan [2] have explored the use of calcium-doped zinc oxide nanoparticles as a selective adsorbent for the extraction of lead ion and several metal-oxidized nanomaterials used in combination with nanosized magnetites and titanium dioxide have been reported to have adsorption capacity greater than that of activated carbon [49].

3) HEALTH CARE

The application of nanotechnology in health care is known as nanomedicine. Applications of nanotechnology in medicine include prevention, diagnosis, treatment, follow-ups of diseases, drug delivery, therapy and disinfection [50], [51]. Tracing diseases to abnormalities at the molecular level through the knowledge of molecular genomics and proteomics theoretically increases the chances of early-stage diagnosis and the possibility of commencing treatment even prior to the appearance of the preliminary symptoms of a disease.

Nanotechnology has the capability of employing molecular genomics and proteomics-based discoveries to achieve this [75], [76]. Since 2003, DNA chip which works based on gene expression profiles is being used to forecast the proliferation of breast tumours to ascertain which patients will be recipients of supplementary chemotherapy after surgical removal of tumour [77], [78]. Similar chips for the diagnosis of leukaemias, mouth and throat tumours are being developed [79]–[81]. Nanotechnology is playing some roles in the production of the chips and also to increase their detection sensitivity and reliability [82]–[85]. Quite a number of the substance that could theoretically be used as medicines are hardly soluble in water, broken down or inactivated before they get to their targets, have difficulty passing through certain biological barriers and distribute non-specifically to all types of tissues and organs. These events make them ineffective, leading to high – dose treatments and ultimately resulting in undesirable side effects [86], [87]. Nanomedicine addresses the challenges of lack of specificity, the toxicity of the therapeutic compounds, poor bioavailability caused by low solubility and reduced efficacy that characterize large size materials in regular drug delivery [88]. Nanoparticles have displayed enormous potential for biological, medical and pharmaceutical applications over the years and are presently being used for delivery of drugs, vaccines, nucleic acids, genes and so on. Drugs or biomolecules can be entrapped into the interior structures of nanoparticles or absorbed onto their exterior surfaces. As drug delivery systems, nanoparticles can permeate the smallest capillary vessels; evade rapid clearance by phagocytes thereby greatly prolonging their residence time in the bloodstream; infiltrate through cells and tissue gap to get to their target organs; improve the utility of drugs, and reduce toxic side effects [89]. Drug delivery using nanocarriers/nanoparticles (liposomes, micelles and polymeric nanoparticles) are of particular interest in overcoming the limitations of the regular delivery system because their biological properties can be manipulated and controlled to meet the desired requirement for pharmacological and therapeutic purposes [90], [91]. Although the use of the nano-carrier system is highly debated in some research communities, there are empirical documentations that indicate that in comparison to the regular drug administration routes, nano-carriers penetrate tissue more efficiently and exhibit increased tissue-specific action of drugs [92]. Researches to improve exclusivity and combination of carrier materials to achieve appropriate rate of drug release; researches on surface modification to enhance targeting ability of nanoparticles; researches on optimization of the preparation of nanoparticles to increase drug delivery capability, clinical applicability and the possibility of industrial production; researches on in vivo dynamic process to unveil the interaction of nanoparticles with blood, targeting tissues and organs are all ongoing. Not only can nanoparticles function as drug delivery systems, in certain situations they function as active substances. It has been reported that once metal-containing nanoparticles find their way through the bloodstream into a tumour or when they have been directly injected into a tumour, they can be heated using near-infrared radiation or a rapidly oscillating magnetic field to kill the tumour cells [93].

Photocatalytic properties of titanium dioxide nanoparticles make it exhibit bactericidal effect. Nanoparticles of titanium dioxide form highly reactive molecules (radicals), such as hydroxyl and perhydroxyl radicals in the presence of water, oxygen and ultraviolet radiation. The radicals formed are known to kill microorganisms [94]. In the presence of light, fullerenes also have an antimicrobial effect [95]. Antimicrobial wound dressings containing nanocrystalline silver and several other antimicrobial products based on nanoparticles are now commercially available [96].

4) TRANSPORTATION

Transportation involves the conveyance of people, goods and other things over macroscale distances. The role of transportation in economic development cannot be overemphasized. An effective transportation system requires a sustainable facility for the conveyance of goods and people and is expected to be safe, durable and economical. There are

TABLE 2. Some applications of nanotechnology in health care delivery.

Area of Application	Nanoparticle/Nanomaterial	Specialization/Enabled Technology	Reference
Wound dressing	Silver nanoparticles (AgNPs)	Anti-bacterial agent for the treatment of burns, open wounds, and various chronic infected wounds Antimicrobial activity against strains of *B. subtilis, E. coli*, and *S. aureus* and diverse skin pathogens Anti-inflammatory properties, and improved outlook of healed wounds	[52]–[54]
	Gold nanoparticles (AuNPs)	Speed up normal and diabetic wound healing	[55]
	Copper nanoparticles (CuNPs)	Effective against *E. coli* and *S. aureus* present in burn wound infections and diabetic foot-ulcer Antimicrobial activity and improved rate of wound healing	[56]–[59]
	Titanium dioxide nanoparticles	Significantly associated with the process of wound healing	[60]
	Zinc oxide nanoparticles	Function as a wound-healing material in the cosmetic and pharmaceutical industry	[61]
		Support angiogenesis, cell proliferation, and chemotaxis	[62]
	Cerium nanoparticles	Exhibit antioxidant properties and faster wound closure	[63]
	Nitric oxide nanoparticles	Improves the process of wound healing	[64]–[66]
	Nanosized bioactive glass particles	Stimulates cell proliferation, angiogenesis, and wound closure	[67]
	Chitosan, Collagen, and Polylactic acid (Tissue-engineered nanofibers and nanoparticles)	Protects wound from bacterial infection; adequate nanomaterial for wound dressing, particularly for diabetic ulcers and burns; enhances the pace of wound contraction and epithelialization	[68]
	Antimicrobial peptides on gold Nanodots	Hinder the growth of multi pathogenic drug-resistant bacteria and also enhances wound healing	[69]
		Treatment of diabetic foot ulcer	[70]
Drug delivery	Ethosomes	Enables drug to reach deep skin layer/systemic circulation	[71]
	Hydrogel NP	Transportation of large amounts of drugs to the desired site through an external magnetic field.	[72], [73]
	Dendrimers	Suitable for unimolecular micelles for drug encapsulation Reproducibility of biodistribution of polymeric prodrugs use as scaffolds Act against prion diseases, Alzheimer's disease, inflammation, HIV, herpes simplex virus (HSV), bacteria and cancer More suitable drug delivery carrier in comparison to other polymers due to their highly controllable structure and size, and the terminal functional groups	[71]
Therapy	Buckyballs	Capture free radicals produced in the course of an allergic reaction and block the inflammation that results from an allergic reaction	[74]
	Nanoshells	The concentration of heat from infrared light to kill cancer cells with the least damage to surrounding healthy cells as a better alternative to radiotherapy	[74]
	X-ray activated Nanoparticles	Produce electrons that effect the destruction of cancer cells to which they are attached Purposed to be used alternatively to radiation therapy with far lesser harm to healthy tissue	[74]
	Nanofibers	Activate the production of cartilage in injured joints	[74]

several opportunities for the application of nanotechnology to adequately meet these requirements in the transportation industry [97], [98]. Although nanotechnology involves use of phenomena on atomic and molecular scale to offer structures and materials that perform tasks that would be impossible if the materials in their usual macroscopic form were rather used, the technology is relevant in the process of providing, operating and managing the needed infrastructure (routes) that allow vehicles to travel; maintenance of the routes and management of the vehicles that make use of the routes. A considerable number of research into the development of transportation application focus on the large operational dimensional difference existing between nanoscale of nanotechnology and macroscale of transportation systems.

Safety is the most important necessity in transportation and as such, researches that enhance the safety of the transportation system are pertinent. Safety in transportation, among other things is connected with the properties of the surface of the facility as it is the platform of interaction between the vehicle using the facility and the facility itself. This translates to improving the properties of materials used in the construction of the facility and improving the interfacial stresses and strains that occur between the facility and vehicles. Visibility and signage are also considerations for the safe use of transportation facilities. In these regards, nanotechnology has potential applications in improving hardness, durability, skid resistance and water resistance of existing materials in the transportation sector. Nanocatalysts, fuel additives, tribological coatings, and lightweight, carbon nanotube-reinforced composites have been linked to increased sustainability of transportation systems [99]–[102]. Application of ZnO_2 can make surfacing hydrophobic and gives the possibility of hydrophobic road surfaces with quicker runoff from the road and lesser chances of hydroplaning [103], [104]. Improved performance (abrasion resistance and grip) are some of the leading reasons for applying nanotechnologies in tyres and this has led to a reduction in fuel consumption (by decreasing rolling resistance). Although the inclusion of carbon black and silica in tyres to improve mechanical strength, braking distance, and rolling resistance is not new, further developments of silica in the last decade have led to an improvement in the rolling resistance and braking distances in the wet, through nanoscale interactions with the rubber matrix [105].

Development of nanoscale rubber particles that improve the binding of silica to the rubber matrix and their incorporation in new eco-tyres are more recent advances. Nanostructured coatings are also being applied to the surface of tyres to reduce heat generation and nanoclays are being incorporated into tyres to improve stiffness, wear, and handling properties. Improvement of wet skid resistance and about 50 % decrease in tyre abrasion by incorporation of nanoscale silicon carbide into tyre manufacturing elastomers have been documented [106]. The application of nanotechnology in the aspect of visibility is promising. The technology is being used to incorporate signage into transportation facilities and also to improve material used in signage through the use of materials like nanophosphor. The possibility of making infrastructure surfaces auto - luminescent in order to provide guidance to traffic at night has been shown [107].

With respect to durability and sustainability, nanotechnology can be applied to improve the strength of construction materials, engine components, sensors, and avionics systems, and obtain functional coatings [97], [98]. Research interest on the replacement of structural materials with lighter composites with the intent of achieving weight reduction is increasing. Inclusion of nanoparticles of silica within the polymer matrix and application of thin-film coatings containing inorganic oxides are respectively being used to eliminate the drawbacks of poor ultraviolet (UV) and scratch resistance that limits the use of polycarbonate composites (which offer about 50% weight savings) as an alternative to conventional glass. Developments in this area have led to a prediction of polycarbonate constituting about 20% of the automotive glazing market by 2020 [108], [109]. To a large extent, research into how flexural and shear strengths of concrete can be improved through the application of various nano-sized particles have been conducted and up to 50 % increase in shear strength of concrete has been documented [110]. The use of nano-sized SiO_2 and TiO_2 as additives to cement mortar have been reported to increase the abrasion resistance of concrete pavement applications by about 90 % and 180% respectively [111]. Nanoparticulates additives containing CeO serve as fuel catalysts for improving the combustion of diesel fuels and also decreases the emission of particulates [101]. With nanotechnology, the activity of catalytic converters can be improved resulting in a reduction in exhaust gas emissions, a decrease in the use of noble metals such as Pt, and probably allow the replacement of noble metals with more readily available materials [112]. Nanotechnological innovation aimed to improve the performance of fuel cells may be used in addressing the current technical and economic limitations in automotive applications [113].

5) ENVIRONMENTAL BIOREMEDIATION

Several daily human activities, industrial processes, and agriculture inherently release chemicals and harmful substances into the environment. At sufficient concentrations, these chemicals and harmful substances disrupt the ecosystem and have destructive effects on humans and organisms in the environment. In the bid to address environmental contamination issues, several environmental remediation technologies have been developed and bioremediation proves to be more effective and reliable because of its eco-friendly features [114]. Environmental bioremediation simply means the process of solving environmental problems using biological agents. Bioremediation may be in-situ which involves the treatment of contaminants in the location where it is found or ex-situ which involves the treatment of excavated contaminants. Despite the advantages of bioremediation over other conventional methods of remediation, bioremediation is limited by the non-instantaneous nature of the process and the presence of inhibition in recalcitrant and non-biodegradable forms of compounds [115]. Nanotechnology allows the development of techniques that helps ameliorate the deficiencies of traditional bioremediation [116]; although the behavior of materials existing at the nanoscale may not necessarily be deducible from what is known at the macroscale, more often than not, materials and particles at nano-level possess desirable properties. Ease of diffusion into contamination zone where microparticles cannot reach and higher reactivity to redox – amenable contaminants are some of the reasons nanoparticles and nanomaterials are gaining vast applicability in bioremediation. The applications of nanotechnology in environmental remediation include denitrification, dechlorination, degradation of organic pollutants, removal of heavy metals, and anodic remediation.

The breakdown of carbon tetrachloride (CCl_4), a toxic, carcinogenic and stable chemical compound into methane, carbon monoxide or formate using oxide-coated Fe^0 has been reported [117]. CCl_4 is a typical solvent used industrially for degreasing operations, for fumigation of grains and is an intermediate chemical in refrigerant production. Inefficient use and improper disposal make CCl_4 a widespread environmental pollutant. The oxide-coated Fe^0 forms weak and outer-sphere complexes with CCl_4, reactivity is increased by the oxide coating and CCl_4 is broken down through electron transfer. Studies have also shown that an extensive range of common environmental contaminants such as chlorinated organic solvents, organochlorine pesticides and polychlorinated biphenyls (PCBs) can be transformed and detoxified effectively with nanoscale iron particles. As such, derivatives and modified forms of iron nanoparticles like catalyzed and supported nanoparticles have been synthesized [41]. The potential for an enhanced increase in remediating efficacy of highly reactive iron oxide nanoparticles when employed in combination with microorganisms has been established by the reduction of a highly contaminating organic compound, 4-nitroacetophane using *Geobacter metallireducens* bound to macro particulate ferrous oxide [118]. The remediation of sites contaminated with chlorine solvent using nano-scale zero-valent iron particles may be enhanced by concurrent or subsequent action of bacteria that exploit cathodic depolarization and reduction [119].

Degradation of pentachlorophenol (PCP) has been accomplished in the laboratory through photoelectrocatalytic reaction using TiO_2 nanotubes [120]. De Windt *et al.* [121] demonstrated the use of nanoparticles as biocatalyst for reductive dechlorination of organic contaminants by depositing zero-valent palladium on the cell wall and inside the cytoplasm of *Shewanella oneidensis* charged with $H*$ radicals. The radicals are from various substrates such as hydrogen, acetate and formate and function as the electron donor in bioreductive assay containing Pd (II). The dechlorination of chlorinated compounds is catalyzed by the H^* radical on the Pd^0.

6) ELECTRONICS

The currently predominant electronic technology for manufacturing chip is known as lithography or etching and is based on Moore's law which permits enhanced functionality,

TABLE 3. Some selected use of nanotechnology in environmental remediation.

Nanoparticle/Nanomaterial	Specialization/Enabled Technology	Reference
Nano iron oxides	Removal of lethal ions and organic contaminants from water	[122]–[124]
Fe^0 nanoparticles	Transformation of chlorinated organic pollutants without leaving the chlorinated intermediate byproduct	[125], [126]
	Reduction of polychlorinated biphenyls	
	Debromination of diphenyl ethers by reduction	[127]
	Alachlor and pretilalachlor removal	[128]
	Chlorinated ethenes catalysis	[129], [130]
Bi-metallic nanoparticles	Detoxification of water bodies from contaminants such as heavy metals, hexachlorobenzenes, chlorinated and explosive compounds	[131]–[133]
	Immobilization of bimetallic nanoparticles in Polyacrylic acid/Polyvinylidene fluoride membrane matrix for complete dechlorination of harmful chlorinated organic compounds	[134]
Carbon nanostructures	Removal of inorganic and organic contaminants and radionuclides from wastewaters	[135], [136]
	Adsorption of heavy metal ions from aqueous solutions on the surface of the oxidized carbon nanostructures	
Carbon nanotubes	Removal of heavy metals such as Cr^{3+}, Pb^{2+}, and Zn^{2+}	[137]–[140]
	Removal of metalloids like arsenic compounds	
	Removal of organic biological contaminants, dioxins, and volatile organic compounds	
Nanomembranes and nanoplatelets	Oil spill remediation	[141]
Microbes-derived nanoparticles	Effective degradation of organic compounds	[142]

a higher speed of computations, savings in raw materials, weight, and power consumption through continued miniaturization of electronic devices. It is opined that in the nearest future, the technology will no longer be sufficient to handle the demand for new chips as there is a limit to the extent of miniaturization and improved performance attainable through Moore's law [143]. Three obstacles that have been identified in the current scaling down approach used in the electronic industries are the increasing costs of fabrication, the limits of lithography, and the size of the transistor. For instance, already there are transistors that are only a few atoms thick and scaling down will have to cease when the thickness reaches about 1 - 2 atoms and moreover, the continued reduction in size comes with increased complexity. Nanoelectronics may be adopted to achieve circuit integration beyond the limits obtainable from the current predominant technology and may also be used to tackle the challenges of increasing fabrication costs associated with it. Some of the nanoelectronic digital devices from nanotechnology include nano transistors, nano - memory, nano circuitry, nano diodes, organic light-emitting diode (OLED), plasma displays, quantum computers, nanosensors, nanorods, Ipods, and nanogears.

Nano-electronics have the potential of making computer processors more powerful than what is achievable through traditional semiconductor fabrication techniques. New forms of nanolithography, the use of nanomaterials such as nanowires as an alternative to complementary metal-oxide-semiconductor (CMOS) components are being researched into. Carbon structures are of great research interest and importance to the electronics industry. Carbon atoms can be arranged in a crystalline lattice (graphite and diamonds) and also exist in the amorphous state (coal and carbon black). The discovery of carbon 60 opened the door to the discovery and study of various forms of carbon.

Carbon nanotubes (CNT) are one of the allotropes of carbon discovered after carbon 60. CNT is a lattice of carbon atoms that are coupled to create a cylinder and has multiple variations which include single-walled tubes, multi-walled tubes, and tubes with different arrangements of individual carbon atoms. Multi-walled CNTs have multiple concentric tubes of carbon and have significant applications in the electronics industry. A major importance of nanotubes is the provision of a significant increase in the strength of materials. Automotive bumpers that have nanotubes integrated into them have strengths that are many times greater than steel even though they are several times lighter than steel. The reduction in weight that characterizes materials that have nanotubes incorporated into them lowers transportation cost and reduces fuel usage in the lighter weight automobiles. Properties of material vary with how the tubes are connected together. It determines whether the nanotubes will be conducting or semiconducting. The single-walled carbon nanotubes are very promising in electronics. Semiconducting carbon nanotubes and heterostructured semiconductor nanowires have been used to produce field-effect transistors (FETs) [144], [145]. Carbon nanotube field-effect transistors (CNTFET) appear very similar to metal oxide semiconductor field-effect transistors (MOSFET) which serve as a switch and have been the building block for most computing devices for the last several decades. In CNTFET, the silicon channel is replaced with a CNT. Electrical conductivity and small diameter of carbon nanotube can be explored to obtain field emitters with extremely high efficiency for field emission displays (FED) which operates on a principle similar to that of the cathode ray tube but on a much smaller length scale. Research efforts towards creating nano-electronic devices have greatly increased; these nano-electronic devices could interact with single cells for use in basic biological research [146] and nano-electronic devices that could detect the concentrations of biomolecules for use in medical diagnosis [147]–[149].

7) ENERGY

Nanotechnology is being used and is being considered for increased sustainability of the energy sector. Nanotechnology has the capability to provide cleaner and more efficient supplies and usage of energy. Even though not all applications of nanotechnology in the energy sector necessarily affect energy transmission directly; they, however, possess the potential for reducing the need for electricity, natural gas and other fossil fuels. In the energy sector, nanotechnology plays significant roles in the areas of lighting, heating, renewable energy, energy storage, fuel cells, and hydrogen power generation and storage.

The current artificial lighting in many countries is mainly of incandescent and fluorescent sources. For instance, in Nigeria, the urban areas have a larger share of electricity consumption from household lighting. In 2010, only 1% of the urban household lighting was achieved using LED bulbs while incandescent and compact fluorescent technologies were correspondingly used to achieve 41% and 58% of the urban household lighting in Nigeria [154]. Based on 2010 data, it is speculated that the demand for electricity in urban households will increase from 17.4 billion kWh to 75.3 billion kWh by 2040, with lighting requirements amounting to about 37.8% of the projected value [155]. Ordinary incandescent lamps are based on a heated tungsten filament and generate about 10–18 lumens (lm) of light output per watt of electrical power consumed whereas fluorescent lights produce about 60–80 $\mathrm{lm \cdot W^{-1}}$. The excessive heat from incandescent lamps may sometimes be undesirable and the need to counteract it (perhaps through air conditioning) may arise. As such, their use is being discouraged in some nations through enacted legislation. Compact fluorescent lamps (CFLs) on the other hand contains up to 5 mg of mercury which is a very toxic element. The breakage or disposal of CFL devices, therefore, presents some challenges. Also, the manufacturing of a CFL requires twice the energy for making halogen incandescent and generates 108 g of waste, of which 78 g could be considered hazardous as against only 5 g of nonhazardous waste generated by halogen incandescent [156]. When frequently switched on and off, the life of CFL devices is also rapidly shortened if used in a dimmer circuit [157]. In more recent times, light-emitting diodes (LEDs) are being acclaimed as the solution to clean and energy-efficient lighting. LEDs comprise of very precisely deposited layers of nanoscale semiconductors and the light-emitting process itself takes place within a nanoscale volume of material. LED chips have smooth layers and generate light internally and it is very unlikely that much light will escape due to total internal reflection except in special cases where special surface structures or chip shapes are used. Generally, light-emitting diodes (LEDs) are compact, durable, generate low heat and are electrically efficiency and can compete with incandescent light sources in many areas of the visible spectrum and are found useful in displays, automobile lights, and traffic lights. There are projections that nanotechnology-based lighting advances may lessen global energy consumption by more than 10% [158]. By exploring the ability of nanocrystals (otherwise known as quantum dots) to produce distinct colors of light which varied with the size of individual crystals, hybrid LED that gives warm, white light similar to that of an incandescent lamp has been produced by coating LED with a thin layer of quantum dots. As an advantage over excessive heat that accounts for a large percentage of energy inefficiencies in incandescent light bulbs, this discovery can be extended to produce light without heat for residential, commercial and industrial applications [159]. LED-based lighting devices with efficiencies between 10 to 60 $\mathrm{lm \cdot W^{-1}}$ are already commercially available. In comparison to incandescent lamps, LEDs are more energy-efficient and have a lower environmental impact which may be credited to a reduction in resource consumption as a result of their durability.

In terms of efficiency and cost, LED-based lighting devices have lower luminous output and are more expensive than fluorescent lamps [157]. Nonetheless, LEDs last quite longer and improvement on the technology is continuous. The use of novel phosphors and low-dimensional nanostructures can greatly enhance their performance [160]. High-intensity emission over the whole visible spectrum can be achieved and efficiency during high-power operation can be maintained [161] through innovative researches.

Several review articles on the thermal conductivity enhancement of nanofluids [162], [163] and their probable benefits on heat transfer applications [164]–[166] are available. The use of nanofluids boiling enhancement in the areas of pool boiling [167]–[170] and convective boiling applications [171], [172] are being explored. When nanoparticles (which may be metallic, metallic oxides, carbon, glass or other material) are added in very small quantities to base fluids (such as water, light oils, and ethylene glycol), they disperse to form a nanofluid. Using CNTs, nanofluids with rates of forced convective heat transfer that are four times better than the norm have been developed. Nanofluids have the potential of making the central heating device 10% more efficient if added to the home's commercial water boiler [173].

Solar energy, wind energy, and geothermal energy are energy from renewable sources. Electricity generation from these sources, particularly from the solar source, goes a long way in ameliorating the problems of the greenhouse effect associated with the generation of electricity from conventional sources [174]–[180]. Currently, only a small fraction of the world electricity is generated from solar photovoltaic cells. This could partly be accounted for, by the cost of solar panels which is the principal component in photovoltaic systems. A way of making solar-generated electricity popular is by reducing the price of solar panels as this will, in turn, reduce the price of generating electricity from solar energy, and ultimately make it more attractive compared to electricity generated from conventional sources.

TABLE 4. Some current and potential use of nanotechnology in electronics.

Technique/Technology	Reference
Future extensive use of nanofabrication to fabricate microprocessor chips that are smaller, faster, reliable, efficient and lighter	[150]
Development of CNT based wires with lower resistance than the high-tension wires presently used in electric grids in view of reducing power loss during transmission	[151]
Nanomagnetic tunnel junctions enabled MRAM (magnetic random access memory) for the quick and effective saving of even encrypted data during a system crash or shutdown and; the gathering of vehicle accident data;	[151]
Incorporation of nanostructured polymer films (organic light-emitting diodes) in display screens of electronic devices (such as TV, computers, digital cameras, and cell phones) for longevity, lesser power consumption, lighter weight, wider viewing angles, brighter images, and improved picture density	[151]
NanoDesign software system for the purpose of designing and simulation of materials based on nanotechnology	[150]
Higher speed data transmission between integrated circuits (compared to what is obtainable with electrical signals) through the integration of silicon nanophotonics components into CMOS integrated circuits	[152]
Deposition of cadmium selenide nanocrystals on plastic sheets to generate flexible electronic circuits which have low power requirements and simple fabrication process	[153]

The solar industry has been deploying the knowledge of nanotechnology to increase the efficiency of solar panels and achieve a continuous reduction in its price through the production of new photovoltaic materials. Researches have shown that single-wall carbon nanotubes are an ideal photovoltaic material because it possesses a wide range of direct bandgaps that match the solar spectrum, has strong photoabsorption ability, high carrier mobility and reduced carrier transport scattering [181], [182]. Solar cells with ultrahigh-performance can be obtained from a combination of conductive polymers with high-performance semiconductor nanocrystals (nanodots) that are active over the entire visible spectrum and into the near-infrared. The function of the nanocrystals is to harvest a larger portion of the energy spectrum, thereby improving efficiencies of solar cells. The importance of nanotechnology also extends to improved techniques in the manufacturing of solar cells such as advancements in the use of ultra-precision tools. These have been helpful in tackling the kerf loss associated with cutting solar cells into individual panels which has a direct impact on cost reduction. Transmission loss can be reduced by putting energy from renewable sources into use at or near the source. Nanotechnology can facilitate this through simple, practical and automated sensors that are nanofabricated [183]. The amount of electricity generated in areas with abundant renewable energy sources can be increased and more efficiently transmitted to areas with high energy demands through the nano-enhanced transmission.

The ability to store energy locally reduces the quantity of electricity required to be transmitted over power lines and it is fundamental to meeting peak electricity demands. Nanotechnology plays certain roles in facilitating energy storage. In batteries, electricity output can be increased with the use of CNT-based electrodes in place of traditional electrodes. This is possible because CNTs have good electrical conductivity, extraordinarily high surface areas with linear geometry that makes their surface areas highly accessible to a battery's electrolyte. The increased electricity output gives room for the development of smaller, lighter and powerful batteries for a wider range of applications. An increase in electrode surface area of a capacitor by covering its electrodes with millions of nanotubes and consequent increase in the amount of energy that they can hold has been reported. The resulting new technology is acclaimed to combine the strength of modern batteries with the longevity and speed of capacitors and has vast applicability [184].

Fuel cells convert chemical reaction energy involving hydrogen and oxygen into electricity, heat, and water. It is designed to continuously replenish continuous reactants, has no moving part and thus can be compact and portable. It has been found useful in providing power for remote locations such as weather stations and spacecraft. Nanotechnology can proffer solutions to the problem of the cost of materials and complicated manufacturing processes that have restricted the development of fuel cells such that eventually, fuel cells could possibly be used for powering almost everything, ranging from handheld electronic devices to cars, buildings and utility power plants. Nanoengineered membrane materials can be used as a catalytic medium to increase the volume of hydrogen conversion for more energy generation [185]. Application of the concept of controlling and manipulating structures of materials on the nanoscale could result in the development of extra powerful fuel cells and electrode that enable the direct use of natural gas or biogas (generated from waste) in fuel cells in more efficient ways [186]. High strength and toughness-to-weight characteristics of CNTs can be harnessed for the durability of composite components in fuel cells that are deployed in transport applications.

Adequate electricity sources for hydrogen production, ease of transportation and storage are major challenges that have to be tackled in making hydrogen economy (the use of hydrogen as the major form of stored energy for mobile applications and energy load balancing) a reality. Hydrogen, which may be considered as the smallest element has the propensity to easily escape from pipes and tanks. In solving the storage problems, hydrogen can be absorbed in nanotubes. A major consideration in the absorption will be to optimize the absorption behavior of the tube and control the diameter of the nanotube in a way that the absorption energy of hydrogen within and on the outside of the tube is sufficiently high to meet the intended storage capacity at a permissible pressure. Single-walled CNTs have been identified as principal alternatives for effectively dealing with the storage problem for hydrogen-fueled cars and trucks [187]. The storage system can be protected against corrosive environments using core-shell cobalt nanoparticles with structured chemical compositions. Nanowires may be employed for increased efficiency in the area of transportation.

II. SOCIETAL ISSUES IN NANOTECHNOLOGY

A. ETHICAL ISSUES IN NANOTECHNOLOGY

Ethics promotes the responsible development of technology. In light of the present understanding, nanomaterials and their applications may possess potential inherent hazards. The probable hazards depend on the particular nanomaterials and applications. It is, therefore, very necessary to properly conduct examinations on the potential consequences of nanotechnology principles, processes, and applications to identify instances of nonconformity to safety standards and regulations. Currently, the principal challenge is basically related to the development and validation of methods & instruments for detecting, characterizing and analyzing nanomaterials; assessment of exposure to nanomaterials and the development of comprehensive information on the risks connected with nanomaterials and nanotechnologies [188]. According to Sandler [189], ethics in nanotechnology ensure that what is meant by enhancement of lifestyle, justice, and sustainability are clarified. Through ethics, ways of achieving the goals of nanotechnology and the hindrances to achieving them are identified; restrictions on the pursuit of the goals are set out; instruments and resources for making ethically substantiated judgments are established, and assessment standards for potential nanotechnologies are also developed. As explained by Schummer [190], it is proper to classify nanotechnology ethical issues into specific and general issues because of its fuzziness and diversity, and the current exaggerations about the technology. In his opinion, the specific ethical issue may arise from certain research processes, products, and applications of the technology. While general ethical issues may arise from the mode in which nanotechnology programmes are generally initiated, controlled and administered, in addition to how they are perceived in the wider scientific and societal viewpoint.

According to Schummer [190], the most exigent ethical issues of nanotechnology seem to be the likely health and environmental hazards of nanoparticles. Particles having very same chemical composition exhibit dissimilar characteristics by virtue of their size and shape at the nanometric scale. One of such dissimilar properties is the manner in which the particles transport in the environment and through organic membranes. The focus on chemical composition and the disregard of size- and shape-dependent properties by national and transnational regulations will make particles that are hazardous at the nanoscale to successfully scale through the required toxicity tests for emerging chemicals if larger particle sizes are used for the test. As research and development in the field of nanotechnology exploit the unique properties (such as improved mechanical, optical, thermodynamic and catalytic properties) exhibited at nanoscale for large-scale production of new and improved materials, there will also be the risk of new exposure to nanoparticles. A responsible thing to do is to genuinely consider the new industrial prospects associated with nanoscale particles, jointly with the new environmental and health hazards [188]–[193].

Issues associated with the control of and the responsibility for new devices emanating from nanotechnology is also very germane. As nanotechnologies are continuously being used for miniaturization of several devices, the ability of devices and systems to execute highly complicated tasks independently is being reinforced. With this development, there is the possibility of these devices causing undetectable alterations, the intrusion of privacy, and unintended surveillance. At a particular level of complexity, it is possible that nano-miniaturized devices in a system interact with one another in such a way that their combined performance cannot be predicted or controlled. These devices may take quasi-independent decisions that warrant moral and legal responsibilities. Ethical issues will arise in these circumstances when these devices become uncontrollable and cause damages in which no one can be vividly responsible for. It is, therefore, pertinent that firm regulations that stipulate the extent of the permitted tasks of devices, the required human control and the responsibilities of makers and users of such devices are put in place and enforced. Furthermore, as these devices are being developed, there is the need to accompany them with techniques and tools that enable the detection and disabling of the devices [188]–[193].

Another area of nanotechnology where ethical issues arise is nanomedicine. Nanomedicine may be presumed not to differ much from conventional medicine without the notion of immortality, robots that repair DNA, super-intelligence and other hypes. But then, there is the tendency of giving false hopes to patients who may be persuaded that by some sort of wonders of nanomedicine they will be cured of their acute ailments. It is not impossible that in the bid to obtain funds and gain some publicity, there will be some instances of false propagation of impressive tales ranging from nanotherapy, diagnostic biochemical sensors, to genetic diagnosis by researchers and organizations. This, on its own, constitutes a critical ethical issue. Also, the development of devices that automates medical delivery reinforces the issue of responsibility regarding the operation and failure of nanotechnology-enabled devices. Furthermore, with automation in nanomedicine, there will be the need to redefine the expertise, duties, and responsibilities of medical personnel who would virtually be replaced by robots automating medical delivery. The fear of shift of the medical system from the curative to the enhancement of human capacities beyond the limits of health using nanotechnology, which could be the political plan of some nations is also an issue of concern. The concept of enhancement of human capabilities beyond health level subverts nearly all medical ethics.

With the availability of relatively abundant resources in the area of capability enhancement with nanotechnology, more research capacities will be diverted to that area, thereby creating an imbalance in the area of curative researches. Without effective preventive measures against the shift, it is speculated that the poor may suffer more from the imbalance that the shift will create [188]–[193].

In relation to material resources used in nanotechnologies, there are issues of sustainable use of materials to prevent the dearth of materials and a profusion of unusable waste in the future. Generally, nanotechnologies that evade the use of critical material resources or substitute technologies that make use of the critical resources are more attractive. It is desirable that products obtained from critical materials can be recycled with ease but this may, however, be difficult with nanostructured composites. With the aid of nanotechnologies, as industrially developed countries tends towards unravelling and utilization of alternatives to imported and costly critical material resources, the developing countries where most of the critical materials are resident and whose economies are predominantly dependent of the export revenues from the material resources are faced with the challenges of taking drastic and pragmatic measures to save their economies from imminent failure [188]–[193].

The issue of rights to intellectual property is not peculiar to nanotechnology but it is of weighty significance in nanotechnology because of the relative newness of the technology. With increased liberation pertaining to what can be patented and with the increased revenue accruable from patent licenses, knowledge emanating from educational institutes, which were previously published in academic journals and made available in the public domain are now increasingly being patented and licensed [2], [190], [193]. On one hand, this development has engendered the transfer of knowledge between academic institutions & the industries and created new sources of income for the institutions. On the other hand, industrial advancement has become expensive and more complex because each piece of knowledge virtually has to be paid for, and this has further widened the technological gap between the advanced and developing nations which previously benefited from knowledge made freely available to the public [188]–[193].

Although the instance of ethical issues in nanotechnology highlighted are in no way exhaustive, it is evident that ethical issues related to nanotechnology are engendered not just by the fundamental fact of the exhibition of downright difference in properties at the nano-scale by nanomaterials but also by factors, like certain social conditions prevailing in specific nanotechnology laboratories, nature of time-dependent job markets where researchers structure their research and search for jobs & funds, the priorities & levels of research funding for nanotechnology made available by the government, and the nature of the systems of incentive & penalty that dominate nanotechnology research communities. It is pertinent that ethical issues relating to nanotechnology be taken seriously and the extensive gaps in every national and transnational regulation be closed in order for nanotechnology to be of true benefit to humanity. Researches that impart the required knowledge for purposeful policymaking are to be supported; education of citizens on the different advantages and drawbacks of a particular technology in order to facilitate informed public technology evaluation should be powered and people should be involved in the governance of technology in order to reduce cases of nanotechnology-related disputes. In all of these, the government has a pivotal role to play.

B. ECONOMIC IMPACT OF NANOTECHNOLOGY

Nanotechnology as a field has grown to a level where it has the potential to help societies in achieving the aim of efficiency improvement and progress acceleration in different sectors of the economy such as medicine, energy, and manufacturing [194]. Therefore, there arises the need for quantitative data to assess the economic impact of nanotechnology in order to guide policy decisions and investments. Public investment in nanotechnology is extremely significant and required for: gaining fundamental knowledge through basic research; supporting industrial competitiveness and economic growth; addressing societal issues like health and environmental concerns; and accelerating the commercialization of new technologies & products [195].

In a symposium organized on assessment of the impact of nanotechnology, several challenges which could affect the economic impact of nanotechnology were raised and these include the multipurpose nature of nanotechnology which presents difficulty in measuring the economic impact; the often case of mixing the impact of many other technologies with that of nanotechnology thereby making it difficult to understand and determine the precise role of nanotechnology; difficulties encountered in meaningfully manipulating and cleaning data linked to nanotechnology due to largeness and variation of data; confidentiality and proprietary which businesses put in their product and services which makes it difficult to obtain data from industry; inadequacy of information obtained and difficulty in assessing the value of the technology because data is mainly collected through surveys; complex relationship that exist between science, innovation and the economy, between public and private actors interaction; and the long-time periods between investments and their returns [196].

Quantitative measures like cost-benefit analysis, life cycle analysis and qualitative measures like input indicators (such as research and development investments and infrastructure) are very essential in valuing the economic impact of nanotechnology. The public is highly needed for the economic impact of nanotechnology as the absence of the public's acceptance of nanotechnology, could potentially mean the failure of even high value/low-risk applications commercially. High quality of data is also important for the assessment of the economic impact of nanotechnology while impact analysis on a quantitative and qualitative basis is important for addressing issues of risks, costs, and benefits [197].

Undoubtedly, the fundamental understanding of how materials can be manipulated at the nanoscale, the incorporation of nanostructures and the introduction of nano processes into technological innovations will make cheap products with better performance available [198]. The economic implication of this is however still hanging as there is currently a dearth of nanotechnology research from an economic point of view. Economic insight on nanotechnology is currently evolving and is based more on experience with earlier technologies. Typically, new applications of existing technologies initially cost more than existing applications of such technologies and the initial higher cost is compensated for by improved performances. Implementing entirely new technologies may however cost less, such as manufacturing of nano-electronic circuits from chemical as opposed to the current method of using lithography in microelectronics. By analogy, it is opined that the implementation of nanotechnology will offer substantial advantages and will also require a huge investment in new production facilities and raw materials. This will relatively cost higher until economies of scale are achieved. Although there have not been in-depth researches on the economies of nanotechnology, it is certain that incorporation of nanostructures and nano processes into technological innovations has the ability to generate products with highly enhanced performance; based on the common paradigm, implementing newer technologies are usually initially more expensive than existing technologies as it will involve huge investment in new production facilities, machines, equipment, and raw materials; and achieving economies of scale may, therefore, take time. Inasmuch as technological capabilities play a crucial role in the difference in economic development across regions and countries, to maintain economic competitiveness, massive financial aids have to been made available in support of research and development and these funds have to be put into judicious use [195].

There exists difficulty for government agencies and policymakers in the evaluation of investment returns from nanotechnology and by extension, the economic impact. The economic value of nanotechnology is usually measured in terms of education, employment, research activity, and commercialization of products and processes which vary widely from country to country. Evaluating research by counting the number of published articles and papers is also considered as a means of assessing the economic impact of nanotechnology. A drawback of this approach is the variation in terms of importance and value that exists in the assessment of the economic impact of research. While University degrees in the field of nanotechnology, research projects and outputs provide a good yardstick for checking the value of academic work, they are not adequate as economic metrics. Investments in nanotechnology should be examined in terms of contribution to export industries, reduction of manufacturing costs, job creation, creation of new products or services and new company formation [196].

NanoMedicine has lots of economic benefits in aspects of society and welfare with the provision of healthcare systems and technologies used in prevention, diagnosis or therapy. Globally, the nanomedicine market is known to be growing at an annual rate of 7 - 9% varying from country to country, technologies, and segments of markets. The application of nanomedicine includes medical devices like surgical implant machines and medical imaging like nano-metric systems for cardiac activity monitoring and minimally invasive surgery sensors [197]. Zucker and Darby [199] captured the impact of nanoscale processes on a large scale, multi-year project that provides a resource on public data which creates a link between individuals and organizations involved in the creation and use of nanoscience and technology (nano S&T) in different activities such as patenting, research funding, publishing, innovation & production, and commercial financing. The project of Zucker and Darby [199] is designed to track the technological progress and economic growth in which nanotechnology is expected to significantly account for that which would occur over the next several decades. The project is organized based on knowledge transfer, commercialization, and industry change. Nanotechnology was observed to have characteristic features of breakthroughs and scientific discoveries capable of creating technological opportunities that could transform existing industries whilst creating new ones.

Nanotechnology is known to provide value-added components that are essential in providing enhanced consumer products, for example, transparent electrodes from silver nanowire or carbon nanotube networks which is used for the manufacture of touchscreens. Other value-added components provided by nanotechnology include functionalized ink dispersions, raw nanomaterials resulting in thin films, and the printing or roll-to-roll nanomanufacturing methods [194]. According to Morse [194], nanomanufacturing is a platform for the transition of innovations from simple and ineffective to enhanced consumer products. Therefore, the development of specific models and methods is very important in the assessment of the economic impact of nanotechnology.

C. SOCIETAL ACCEPTANCE OF NANOTECHNOLOGY

Safety in nano-technology is a very important theme that needs to be addressed in order to determine the boundary between adverse and normal. For example, the main issue with the safety and efficacy of nanomaterials in environmental and medical contexts is uncertainty. This uncertainty cut across many fields of human sectors. Most forms of calculation in these fields deal with calculable risk – for instance, dose effects in toxicology and related researches. A lot of the issues around social acceptance revolve around the difficulties of dealing with uncertainty. Many of these issues will only be resolved through large scale population studies either through longitudinal cohort studies or big data linkage.

As established in the previous sections, through innovations in areas such as agriculture, water purification, healthcare, transportation and environmental bioremediation, nanotechnologies have the potential to improve lives; and these potentials come with responsibilities on the part of the government, private sectors and the public. From history, several technologies have been racked with societal contentions which led to the disapproval of the applications of such technologies. Societal disapproval of technologies has often given rise to negative impacts on the commercialization of such technologies [200]. For instance, literature revealed that the massive public debates which ensued after the market introduction of the earliest generation of genetically modified staple crops were unfavorable to their endorsement and commoditization at least in certain parts of the globe [201]–[207]. Moreover, unforeseen events and accidents having negative impacts on the public have a way of instilling fear in the minds of prospective consumers. The incidence of such unintended events and contentions about the application have far-reaching effects on the rejection/acceptance level of technologies. Consequently, it is imperative to be cognizant of the factors determining the societal acceptance of evolving technologies.

As in the case of other evolving technologies like the genetic modification of crops or organisms, the conveners of innovations in nanotechnologies are also saddled with responsibilities of identifying diverse factors that affect responses of the society to the development, use, and commercialization of nanotechnologies. The identification and understanding of these factors will foster strategic development and commercialization of nanotechnologies. As the first batch of nanoproducts such as nutritional supplements, cosmetics, drugs, and pesticides gain entrance into the market, it is normal for the society to raise questions related to the health, environmental and safety implications of these materials. In light of the aforementioned society's wariness of unintended events and accidents that could occur when emerging technologies are adopted, researches on understanding factors that drive societies acceptance of nanotechnologies to a large extent have focused on the perception of risk and benefits [200], [208]–[212]. In a number of surveys that have been conducted to understand the perception and acceptance of nanotechnology-based applications in various domains, it has been posited that demography, age, gender, income level, education, level of awareness play some roles in how nanotechnologies are perceived [200], [209], [212]–[216]. Furthermore, concerns on environmental impact, safety, and sustainability of nanotechnologies will be critical to the acceptance.

1) ENVIRONMENTAL IMPACTS OF NANOTECHNOLOGY

Advancements made recently in material science and nanotechnology have brought about numerous developments, resulting in calls from different walks of life for research into the impacts of nanomaterials on the environment. These advances that have given rise to concerns regarding the potential adverse environmental impacts of nanomaterials have grown over the past decade. As there are documented positive impacts of nanotechnology on the environment (such as the reduction of a thousand tons of gasoline via the weight reduction property of graphene-based nanocomposites in airplanes, prevention of direct and indirect effects of lightning strikes in airplanes through the use of nanocomposite graphene thin films or graphene bucky papers, weight reduction of wind turbine blades, and increase in energy conversion efficiency due to the eminent properties of nanocomposite graphene), there are also negative environment impacts (such as difficulty in the removal of graphene from waste due to the toxic property of nanocomposite graphene and fire outbreak risk of nanocomposite graphene due to their thermal conductivity and fire retardancy properties). Also, there are agitations concerning unknown deleterious impacts of nanomaterials and the harmful effects of toxicity of nanomaterials (for instance, carbon nanotubes inhaled into the lungs are deleterious to the human body and has more toxicity than carbon black and quartz once it is present in the lungs) [217]. Goel [218] divided the impact of nanotechnology on the environment into two aspects: The first involves the potentials for innovations in nanotechnology for the improvement of the environment, while the second deals with new possible types of pollution which the release of nanomaterials might cause in the environment. For example, magnetic nanoparticles provide methods that are effective and reliable for the removal of heavy metal contaminants from wastewater through the use of magnetic separation techniques. Nanoscale particles are also cheaper and more effective in absorbing contaminants compared to traditional filtration and precipitation methods. Nanoscale iron particles have also been known to potentially act as an agent of detoxification for cleansing of environmental contaminants from brownfield sites. While efficiency in industrial processes, detection and elimination of contamination for improvement of soil and air quality, reduction of waste for high and precise manufacturing, clean power through highly efficient solar cells, and elimination of greenhouse gases and pollutant are some of the positive effects of nanotechnology stated by Goel [218], the negative effects include complexity in synthesizing nanoparticles resulting in high energy demand, the toxicity of nanosubstances causing environmental damage, and low recycle & recovery rates Goel [218].

Although nanotechnology has brought about improved environmental solutions, there exist environmental problems associated with multiple cases of complications that require analysis and solutions that are multidimensional. Understanding the fundamental physical interactions between nanomaterials and the ecosystem is very crucial in understanding the impact of nanotechnology on the environment. Dreher [219] gave a brief overview of the issues emerging from risk assessment of manufactured nanoparticle, highlighted the results and contributions of nanomaterials from companion articles, and placed the contributions of these articles into different perspectives with regards to the evolving issue of manufactured nanomaterial toxicology. It was highlighted that the ability of nanomaterials to improve the performance and quality of many public consumer products and the development of medical tests and therapies which will use manufactured nanoparticles will lead to a dramatic increase in the effects of occupational and public exposure to manufactured nanoparticles in the near future. A number of crucial risk assessment issues related to manufactured nanoparticles brought forward by the National Science Foundation and the US Environmental Protection Agency as highlighted by Dreher [219] include

- Assessment of exposure to manufactured nanoparticles
- Manufactured nanoparticle toxicology.
- Ability to use existing particle and fiber toxicological databases to extrapolate manufactured nanoparticle toxicity.
- Transport, transformation persistence, environmental and biological fate of manufactured nanoparticles.
- Overall sustainability and recyclability of manufactured nanomaterials.

Dreher [219] reckoned that the potential for nanoparticle exposure will increase as the quantity and types of nanoparticles used in society increases.

Stander and Theodore [220] addressed the issues of concern arising from existing & planned environmental regulations, and procedures for quantifying both the health and hazard risks of nanotechnology. It was explained that nanomaterials posed health risks by eluding the body's defense mechanisms and gaining entry to the body either through inhalation, skin absorption, and ingestion, which could occur by acute & short-term exposure, and long-term exposure (e.g. immersion or contaminated air). Nanotechnology was also said to have hazard risks through accidents in manufacturing activities and plant operations. They noted that the success or failure of achieving the goal of controlling, reducing or eliminating the environmental and environmentally-related problems associated with nanotechnology depends on answers provided to key environmental questions such as: a) What potential concerns of the environment are associated with nanotechnology? b) Should there be expectations of the environmental release of toxic/hazardous material during either the manufacture or use of nanoproducts by industry and society? c) Is there a possibility that nano applications particularly bioaccumulation of nanoproducts in living tissue could lead to environmental degradation? d) What is the impact of regulations on nanotechnology?

These questions provide insight into the risks of environmental health and hazard related to both nanoparticles and the nanotechnology applications for commercial and industrial uses.

Colvin [221] carried out a technical assessment of the environmental impact of engineered nanomaterials to determine if the environmental and social costs via unknown risks outweigh its many benefits. It was noted that the lack of technical data gives enough backing for proponents and critics of nanotechnology alike to make conclusions that are contradictory to the safety of nanotechnology. According to Colvin [221] extrapolations from better understood molecular species and larger particulate matter, coupled with an analysis of the routes of exposure for nanomaterials, and their relative importance are considered necessary for characterizing the environmental risk of nanomaterials. It was noted that a wider exposure of the ecosystem to engineered nanomaterials existed through the water and soil; thereby signifying that increasing amounts of nanomaterials in groundwater and soil present significant avenues of exposure and environmental risk assessment.

A risk assessment and full life-cycle analysis for products of nanotechnology at all stages to comprehend nanoproducts hazards and to obtain knowledge that is useful for predicting probable positive and negative impacts of the products obtained from nanotechnology was conducted by Zhang *et al.* [222]. Some points which need to be considered to understand the potential risks present in using nanoparticles were raised and these include:

- Problems arising from the analysis method of nanoparticle as a result of lack of information on shape and size of nanomaterials (which are important factors in determining the toxicity) and methods for characterizing nanomaterials thereby making it extremely difficult for existing technology to detect the nanoparticles in the air for environmental protection.
- Lack of information on nanomaterial chemical structure which is a critical factor in determining the toxicity of nanomaterials as minor changes in chemical functions could change its properties drastically.
- Evaluation of full risk assessment of safety on human health and environmental impact at all stages of nanotechnology. The risk assessment should include persistence risk, toxicological analysis, transport risk, exposure risk and its probability of exposure, transformation risk and ability to recycle.
- Use of life cycle risk assessment for prediction of environmental impacts.

Use of proper experimental design for the reduction of material waste and the advancement of manufacturing in nanotechnology-based products

Notably, the first two points (as highlighted above) raised by Zhang [222] seems to negate the efficacy of using extrapolated data of better understood molecular species and larger particulate matter for handling issues related risks of nanomaterials/nanoparticles as proposed by Colvin [221].

2) SAFETY IN NANOTECHNOLOGY

Judging by the unique characteristics possessed by nanomaterials, nano-enabled products, and processes, it is not an overstatement to say nanotechnology has a very high tendency to impact civilization in no small measure just has certain novel inventions such as electricity and automobiles have done [223]. Nanotechnology is a very important scientific discovery and a very renowned modern world due to its promising attributes which all other treatment methodologies before it failed to deliver. Besides, nanotechnology also had various applications in different areas separate from the fields it was planned for, making it a field with lots of prospects and potentials. These great potentials notwithstanding, the flip side of the nanotechnology inventions has to be objectively considered before they are deployed. For instance, the size of nanoparticles which is the major source of the unique characteristics they possess also poses a risk factor. The extremely small size of nanoparticles allows them to possess a high penetrative ability, easily airborne and easily conveyed in droplets and aerosols. As a result, the benefits of nanotechnology vary with the possible risks that come with it [224].

Due consideration of the possible effects of exposures to these materials is therefore germane in assessing all nanotechnology inventions. Nanoparticles gain access to humans and animals through three basic channels which are inhalation, ingestion, anorption. When adequate personal protective equipment is not put into use, nanoparticles can be absorbed through the skin and inhaled during industrial operations like drilling, sanding, grinding and welding, during cleaning and maintenance of dust collection devices, through improper handling of un-enclosed systems containing nanoparticles and through aerosols generated during some process [197]. Available research findings have shown that exposing animals to certain carbon nanotubes resulted in rapid lung inflammation than when exposed to ''typical'' carbon. Fullerenes, in cosmetics, have been reported to rapidly penetrate the skin, thereby constituting harm to various cellular structures and activities in humans. Also, when foods are prepared under poor hygienic conditions or when foods are kept in the work environment, there is a high possibility of food contamination with nanoparticles and the ingestion of such food opens up the consumer to the attending risks. Although there are limited researches in the area of risk associated with exposure to nanotechnology, and there are neither clear exposure limits nor known long – term effects of exposure, it is rational to suggest limited exposure to nanoparticles and nanomaterials.

The concerns regarding safety with nanotechnology expressed by experts and the population, in general, must be addressed to make the technology safe for everyone. Some of the expressed concerns include pollution of the environment, triggering harmful effects instead of intended benefits in health and medicine, alteration of human life and lifestyle, use by criminals and misguided individuals, etc. Nanopowders and nanofibres are known to cause the most likely hazards such as catalytic effects (speeding up reactions), toxic effects and fire or explosion. Asbestos fibres which contain nanofibers have been linked with ill-health in humans. To access the risk posed by nanoparticles on human health, the likelihood and extent of exposure, the ability and strength of nanomaterials to penetrate the external and internal protective barriers of the body and toxic effects after penetration should be considered. Studies have revealed that nanoparticles can penetrate the main barriers to larger-sized particles due to their small size.

As explained by Madhwani [225], the two factors which make nanoparticles a serious occupational risk include the size of nanoparticle and massive surface area. The size of nanoparticles cannot be seen by the eye or detected by a light microscope. It can, therefore, be inhaled by the lungs and can pass through the brain and placenta. They can cause structural damage if present in the cell mitochondria and can lead to cell death if present in the cell nucleus. 1 g of nanoparticles have a surface area of 1000 m^2. The harmful effects of nanomaterials become intense as the nanoparticles become smaller and more reactive, in this case, harmless substances become very harmful and hazardous. Laboratory studies of toxicology carried out by Morris [226] on animals showed that exposure to nanomaterials had harmful effects such as inflammation and lung fibrosis. Carbon nanotubes were also classified to have harmful effects as they are suspected to cause cancer and respiratory system damage due to exposure from prolonged inhalation.

Dimou and Emond [227] reviewed the process of control banding and available models used around the world (control banding qualitative approach of risk assessment and management to promote occupational health and safety) for safety in nanotechnology. They observed that the control banding models which they reviewed and evaluated did not have the required hazard information in their material Safety datasheet, this, therefore, means that expert judgment is often required in decision making. They, therefore, proposed a method for human health assessment based on control banding for health hazard characterization of engineered nanomaterials. The method involves evaluating the health hazards resulting from the use of engineered nanomaterials using the method of control banding to classify different levels of toxicological hazards from engineered nanomaterials by focusing exclusively on the relevant physical, chemical (physico-chemical) and biological characteristics of engineered nanomaterials. The toxicological hazard levels are then combined into four or five physico-chemical characteristics to carry out toxicological tests. Finally, the combination develops a decision matrix tool used for the establishment of a control level which is used to make recommendations for workers who make use of engineered nanomaterials and the general population who could also be affected by engineered nanomaterials. The scope of the method is limited as the tests must be validated before a decision can be made.

Groso *et al.* [223] used the concept of a decision tree as a risk assessment support tool for safety in nanotechnology. It classifies Nano-laboratories which contain nanomaterials into risk hazard classes determined by the decision tree and a list of risk mitigation measures are provided for each hazard class or level. The work of the decision tree considers human activities with nanofibers and the risk involved, human activities with nano-objects in powder and the risk involved, human activities with nano-objects in suspension and the risk involved, and human activities with nano-objects in the solid matrix and the risk involved. The measures suggested included preventive, technical, organizational, personal and cleaning management.

Schmidt [228] in his article examined the strategies used for checking and ensuring safety in nanotechnology. According to the article, no case of human toxicity has been directly linked to the over 2000 nanomaterials used commercially today but responses found in carbon nanotubes have been observed to be similar to those seen in fibers of chrysotile asbestos thereby bringing forward the high possibility of risk and danger. The article stressed the need for a national strategy which is health based on research in nanotechnology with defined milestones, goals and mechanisms for progress assessment, and properly organized around questions of public concern. The need for data on nanoparticle toxicity to be made more widely available to ensure public support for the technology was also stressed; this makes the process of nanomaterial use and all aspects of safety more transparent. Above all, avoiding exposure was given as the best way to avoid risks thereby making strategies and studies on exposure assessment more important than those on toxicity assessment.

Youtie *et al.* [224] examined the impact of research works and studies carried out on the environment, health and safety of nanotechnology. Their work used the method of bibliometric analysis (a statistical analysis of publications) of publications on Environmental, Health, and Safety (EHS) of nanotechnology. The publications were divided into four categories: a) Potential positive effects of nanotechnology; b) Potential negative effects of nanotechnology; c) Implications of both potentially positive and negative effects of nanotechnology; d) Characterization and description of nanoparticles. The result of their research showed that publications on nano Environmental, Health, and Safety (nano EHS) although growing rapidly were small compared to publications on nanoscience and Technology (nano S&T) suggesting the potential of nano EHS broadening its impact on nano S&T research. They, however, highlighted the challenge of scope broadening which nano EHS publications would face due to the smaller size of nano EHS publications as compared to publications on nano S&T. They, therefore, stressed the need for greater emphasis on nano EHS works if the goals of nanotechnology governance for the impact and success of nano S&T are to be met. They also explained that the spread of research on nano EHS across multidiscipline is crucial to the development of nano S&T, they, therefore, called for continuous monitoring of the existing relationship of nano EHS among different disciplines to help the ongoing development of nano Research and Development (R&D).

Maynard *et al.* [229] recognized the need for systematic risk research for emerging nano industries to thrive. They identified that researches on risk understanding and prevention in the competitive worlds of intellectual property, research funding and technology development are often less prioritized even though the need for strategic and targeted risk research is huge. In order to prevent unanticipated ill occurrences, they canvassed for appropriate action to be taken by the research community and proposed five grand challenges to stimulate imaginative and innovative researches that will be relevant to the safety of nanotechnology. The challenges include: a) Developing instruments for assessing exposure of humans to engineered nanomaterials in air and water within three to ten years; b) Developing and validating methods of evaluating the toxicity of engineered nanomaterials within five to fifteen years; c) Developing models to predict the possible effects of engineered nanomaterials on human health and the environment within ten years; d) Developing robust systems to evaluate the environmental and health impacts of engineered nanomaterials over their entire life within five years; e) Developing strategic programmes that will enable risk-focused researches which are relevant within twelve months. They, therefore, emphasized the need to develop communication activities for the enabling of technical information to be summarized, critiqued and synthesized ultimately for different parties interested in the safety of nanotechnology including policymakers and consumers. They advocated the need for a global understanding of nanotechnology-specific risks and proposed the establishment of mechanisms, networks, and meetings that enable the sharing of information and coordination between the public and private sectors internationally.

Sargeant Jr. [230] in a report prepared for the United States Congress highlighted issues on health, environment, and safety in nanotechnology which required consideration. Some of the highlighted challenges included potential harmful effects on cells and body parts of humans and animals, concerns of unfair indictment of nanoscale materials by some scientists, absence of generally accepted standards for toxicity testing of nanomaterials and concerns on lack of proper understanding of the properties of the various nanoparticles and their various impacts on humans and other organisms. He, therefore, raised issues on the absence of a single and centralized source of EHS research funds allocated to individual agencies for effective funding of EHS research, poor management of EHS research through lack of research priorities and strategies, and the need for budget development, coordination, and integration of efforts to develop research priorities and strategies. He, therefore, called on Congress to spearhead a cooperative and collaborative approach between government and organizations to promote EHS research. He advocated for the implementation of recommendations made by The Project on Emerging Nanotechnologies (PEN) which includes: a) the creation of a NanoSafety Reporting System where people working with nanotechnology can anonymously make reports on issues and concerns of safety; b) creation of technologies providing an early-warning system which allows risk assessment early in research effort; c) information dissemination to small businesses, start-ups, and laboratories due to the challenges they experience in devoting significant resources to EHS issues as a result of their size and resources; and d) Applying lessons learned from other technology areas to make nanotechnology more inherently safe e.g. learning from failures, awareness of operations and building resilience to prevent succession of errors.

Dhawan *et al.* [231] explained that making safety an integral aspect of running the business of nanotechnology meant a comprehensive understanding of the safety benefits of achieving the promises of nanotechnologies. They, therefore, gave a guideline for safe handling of nanomaterials which includes:

- Developing monitoring methods for nanomaterials and the creation of a database on nanomaterials.
- Exploring the process of nanotoxicology and other related safety systems.
- Cooperation and partnerships between different bodies and organizations crossing the local regions and going international.
- Proper identification and assessment of the hazards connected with the production and handling of nanoparticles,
- Measuring the level of exposure amongst workers, consumers and the environment.
- Ensuring risk characterization and risk management by control banding.
- Using approaches such as safety design (ensuring prevention through design) involving critical thinking and forecasting of the life-cycle of these materials starting from planning to production.

Since various countries have put down different standards and regulations for exposure assessment of nanoparticles, it is in the best interest of the society at large that the World health organization (WHO) has established a Guideline Development Group to develop guidelines on standards and regulations of exposure assessment that would appeal universally to all countries. Collaboration between health parastatals, groups, and organizations in any country is also very crucial to ensure the safety of nanomaterials in the country. On a global scale, ensuring the sustainable development of nanotechnology requires the establishment of a proper governance system. A worldwide agreement on safety harmonization and hazard governance of nanotechnology and engineered nanomaterials is essential to realize this objective. The safety of nanotechnology is a global challenge that demands global approaches and a global solution.

3) SUSTAINABILITY OF NANOTECHNOLOGY

The valuable applications of nanotechnology in medicine, electronics, energy production, and consumer products as well as the concerns about the toxicity, the impact on the environment by nanomaterials and the potential effects of nanotechnology on world economics gives enough reason to determine whether the activities of nanotechnology are sustainable for human development and progress. The availability and commitment of professionals in the fields of humanities, sciences and social sciences (this consists of scientists, environmentalists, businessmen, governments, economic planners and policymakers) is very vital for the sustainability of nanotechnology as they are responsible for creating visions in form of standards, regulations, and knowledge to express how economy and environment should be managed for human development and progress. As scholars in their own right, they are bounded by professional ethics and when they give due diligence to be adequately informed about a particular nanotechnology, they would be able to evaluate the nanotechnology without prejudice, represent the public interest even as they contribute fresh perspective without failing to respect the professional integrity of nanotechnologist and nanoscientists.

One of the United Nations Sustainable Development Goals (SDGs) states that sustainable development is linked to the social, economic and environmental climate [232]. It is therefore important that sustainable nanotechnology addresses economic needs, the safety of the human race and conservation of the environment. This can only be achieved by creativity and innovation from professionals in all fields having a relationship with nanotechnology. Making nanomaterials safer for use by people, making manufacturing using nanotechnology less energy-intensive and the minimization of wastes are the key areas in which focus is needed to ensure sustainable nanotechnology. Sustainable nanotechnology may, therefore, be defined as the application of nanotechnology for human development whilst considering the economic feasibility on a long-term basis, proper use of natural resources and the minimization of the negative effects on the environment and health of humans.

Serrano *et al.* [233] in their paper reviewed instances of advances in nanotechnology with respect to sustainable energy production, storage, and use. Their study limited its focus to solar, hydrogen, new generation batteries and super-capacitors which have the most significant contributions to nanotechnology in the energy sector. The presence of nanoscale components in PV cells, production, storage and transformation processes of hydrogen, batteries, and super-capacitors provides lots of benefits thereby showing the sustainability of nanomaterials and phenomena [233]. Currently, nanomaterials make it possible for the efficiency of PV solar cells to be increased while reducing the costs of manufacturing and electricity production at a rate that is unprecedented.

Rechargeable lithium batteries have high economic value in the global market due to their storage capabilities in weight and volume which are higher than the aqueous batteries, they also have shortcomings linked with low energy density, large volume change in reaction, safety and costs which can be minimized with the application of nanotechnology e.g. Toshiba corporation produces nanobatteries which can recharge 80% of a battery energy capacity in only one minute which is nearly 60 times faster than the typical lithium-ion batteries in wide use today, this fast recharge time ensures performance-boosting improvements in energy density [233].

According to Agrawal and Pandey [234], the introduction of nanoparticles of alumina, silicon or zirconium to non-aqueous liquid electrolytes increases electrolyte conductivity up to six times. Nanocomposite polymer electrolytes are, therefore, capable of assisting in the fabrication of highly efficient, safe and green batteries. For instance, the use of ceramic nanomaterials as separators in polymer electrolytes causes a room temperature increase in the electrical conductivity of these materials by 10 to 100 times the electrical conductivity of an undispersed solid polymer electrolytes (SPE) system. Graphite nanoparticles and carbon nanotubes have been shown to be effective for nano structuration of the anode for rechargeable lithium batteries thereby preventing the adverse effect of lithium deposition and other safety problems from occurring [235].

Interests in the use of Electrochemical Capacitors (EC) have increased due to the contributions of nanotechnology [233]. Nanotechnology is credited as having the capability of solving the drawbacks of classical capacitors especially the case of low efficiency which is caused by the low surface area of the electrodes; nanostructured materials can, therefore, increase the surface area [233]. A transition from the use of activated carbon electrodes to the use of carbon-based nanostructures electrochemical double-layer capacitors (EDLCs) is being done in order to improve the performance of these devices. Nanostructures like Carbon nanotubes (CNTs) can achieve higher specific power, higher specific capacitance and higher conductivity in capacitors, while the use of carbon Aerogels could lead to an improvement in both capacitance and cyclability due to their low electronic charging and ionic resistance [236]. The production, storage, and transformation of hydrogen into electricity in fuel cells have been made more effective with the use of better-nanostructured materials for cheaper and simpler fuel cells, efficient catalysts for water splitting, and higher capacity of hydrogen adsorption.

Nanotechnology is very important for overcoming some technological limitations involved in using different substitutes of non-renewable energies. For a transition from a carbon-based energy economy to a more viable energy economy, a lot of technological advances are necessary to solve vital scientific and engineering challenges. In several instances, materials presently available today are unable to solve the problem of efficiency required at a feasible cost [237]. The field of nanotechnology is already overcoming some of these challenges with the provision of novel materials with unique properties of unparalleled control over the structure, size, and organization of matter discovered from research carried out by nanotechnologists. This gives an excellent example of how the development of nanomaterial science can support the development and the welfare of the current and upcoming generations [238].

Fleischer and Grunwald [239] in their study reviewed how nanotechnology can be made sustainable and how to assess and realize its potential; they considered nanoscience and nanotechnology as a central enabling element of sustainable development when used judiciously and when the social context of its application is given due consideration. Some of the potentials of nanotechnology mentioned were in energy technologies in terms of solar and hydrogen as discussed above, in water technologies (via treatment of wastewater and water remediation using catalytic nanoparticles and nanomembrane, nanoscale sensor elements for contaminants and pathogen detection in water [240], [241], water purification and desalination using nanoporous polymers [242] and in chemistry (via nanoporous zeolites for slow release and efficient dosage of water and fertilizers for plants, nanoparticles for improvement of the efficiency and reduction of specific emissions in the catalytic converters of cars, and nanosensors for improvement of the quality and reduction of cost in continuous environmental monitoring). The sustainability of nanotechnology can be assessed using life cycle analysis (LCA) which evaluates environmental risks associated with a product, process, or activity. This is achieved through the identification of waste matter released to the environment, the energy and the material used for a process, production or activity, thereby evaluating and implementing opportunities affecting environmental improvements [243]. LCA also uses future technology analyses (FTA) to investigate claims regarding the potentials of the role of nanotechnology for sustainability thereby facilitating a rational process for strategic thinking and decision-making. This drives policies and strategies aimed at shaping nanotechnology through sustainability assessments [208].

Dhingra *et al.* [244] in their paper emphasized the necessity of conducting assessments based on life cycle analysis (LCA) in the early stages of the new product development process to get a better understanding of the potential consequences of nanomaterials on environmental and human health throughout the entire life cycle of a nano-enabled product. They used industrial ecology to link life-cycle analysis whereby industrial ecology gives a holistic view of environmental problems and provides an understanding as to how humans make use of natural resources in the production of goods and services while LCA is a tool which accesses the impact of the environmental problems (identified by the industrial ecology process) on the lifecycle of a product. Difficulties are encountered in conducting life-cycle assessments for nanomaterials as a result of lack of data for inventory on the materials, because of the new manufacturing processes associated with nanomaterials and confidential constraints. The paper, therefore, put forward frameworks that combine LCA with Risk Assessment (RA) to solve the difficulties encountered using LCA for nanomaterials. The frameworks include nanoLCRA (Life Cycle Risk Assessment) where risk assessment solves problems tradeoffs in terms of order of significance of quantities of pollutants discharged to air; water; and land which LCA has difficulty in solving, and Comprehensive Risk Assessment (CRA) which uses the combination of the ‘‘environmental impact focus’’ attribute of LCA with the ‘‘exposure focus’’ attribute of Risk Assessment (RA) while considering the toxicological effects of nanomaterials. They also proposed the solution of ‘‘greener alternatives’’ which can be viewed in the form of greener nanosynthesis methods to solve the problem of the production of nanomaterials being environmentally burdensome and addressing the potential health and safety concerns which are associated with their production.

Wiek *et al.* [245] critically explored the ideas of a nano-enhanced city and its benefits and limitations in terms of urban sustainability. They provided a model that explained the nano-enhanced city and its governance oriented towards sustainability. The model had a supply-side and a demand-side where the supply side reviewed a spectrum of new and developing urban nanotechnologies, key stakeholders, and the mechanisms which govern these technologies in the city. The demand side reviews the challenges of sustainability encountered by the city. The model provides foresight research for demand and supply to explore new social dynamics, outstanding architectural possibilities, surprises in governance, new patterns of benefit or perception of risk, and systemic perspective capable of causing accidents. The model also investigates and tests governance strategies, engages stakeholders through real-life experiences and virtual environment to understand different cases of diversity and to discuss the opportunities and risks of urban nanotechnologies. The model then integrates all the considerations, factors and inputs into a design. The model uses a combination of anticipatory governance principles and the science of transformational sustainability to overcome complex operational theories.

Ciemleja and Lace [246] explored the implementation of smart specialization strategy concepts using innovation from nanotechnology. They considered the market dimension related to innovative multifunctional materials manufacturing using nanotechnology in Small and Medium Enterprises in Latvia. Their results found out that the commitment of the management of the few nanotechnology enterprises in addressing the issue of sustainable development of nanotechnology in Latvia remains topical due to losses incurred by half of the enterprises in two years of operation. This signified the importance of funding and collaboration. They, therefore, considered cluster development as an important requirement for strengthening weak cooperation between academic and business structures in the field of nanotechnology.

Drobne [247] in his work summarized the future perspectives, issues, and tasks of regulations of nanotoxicology. His paper presented a discussion on the mechanism of the toxic action of nanoparticles and how the size and composition of particles affect the overall toxicity of nanoparticles. Surface area and quantum chemistry which have effects on nanosciences were said to be crucial in deciding the manner in which biological systems behave and interact with the physical world. Various ways of assessing the risks of nanomaterials were suggested which include a) identification and characterization of chemical and physical properties of nanomaterials; b) understanding the environmental fate of nanomaterials, c) environmental detection and analysis of nanomaterials; d) human and ecosystem exposure of nanomaterials and; e) human and ecosystem effects of nanomaterials. He concluded that more research and study needs to be carried out in the area of nanotoxicology in order to underpin the potential negative impacts of nanotechnology and as new discipline nanotoxicology has the potential of contributing to the safety and sustainability of nanotechnology. Having an improved and comprehensive understanding of the factors of risk related to nanomaterials in the body of humans and the ecosystem will assist the development and exploitation of different types and forms of nanomaterials in the future.

In adopting nanotechnologies for solving existing problems in developing countries, a level of caution has to be exercised because there may be danger or risk when nanotechnology is viewed as the all in all solution to challenges existing in such countries. This is because the application of nanotechnology in some cases undermines more appropriate approaches and locally available alternatives to solving problems at hand [218]. Wide consultations are therefore needed in developing countries before the application of nanotechnology to solve problems in order to prevent unfavorable situations. Moreover, the sustainability of nanotechnology in developing countries is affected by some peculiar difficulties. Some of these challenges include

- Poor or weak industry base
- Inability to convert research and development investments into economic outcomes due to poor planning and funding
- Lack of resources for research
- Weak scientific base and platforms which negatively affects the competitiveness and agility of nanotechnology development which in turn affects the economy
- Absence of comprehensive standards, regulation, and frameworks for risk and life cycle assessments in nanotechnology
- Absence of tools to evaluate and mitigate risks and hazards
- The high cost of acquiring intellectual property rights in nanotechnology, high cost of acquiring nanotech infrastructure, absence of public policy and political instability
- Poor awareness and sensitization of the public
- The demand for infrastructure for development in developing countries overrides the interest for innovation especially in nanotechnology

Setting up trust funds to provide financial support for research and innovation in the field of nanotechnology and partnership between developed and developing nations can support the application of nanotechnology to solve sustainable development challenges which are very critical in developing countries.

III. CONCLUSION AND FURTHER STUDIES

Without any iota of doubt, nanotechnology has diverse successful novel applications in many fields and has the capability of causing a great technological and economic revolution that has never been recorded. It plays a vital role in the development of novel techniques and new materials with exceptional abilities as better alternatives to or modification to existing ones. Numerous discoveries and products in the field of nanotechnology are already available commercially while some still need to cross the hurdles of technical limitations, cost-effectiveness, and potential risks. The numerous utilization of nanotechnology for improved performance in various fields notwithstanding, nanotechnology comes with drawbacks that have to be given due attention.

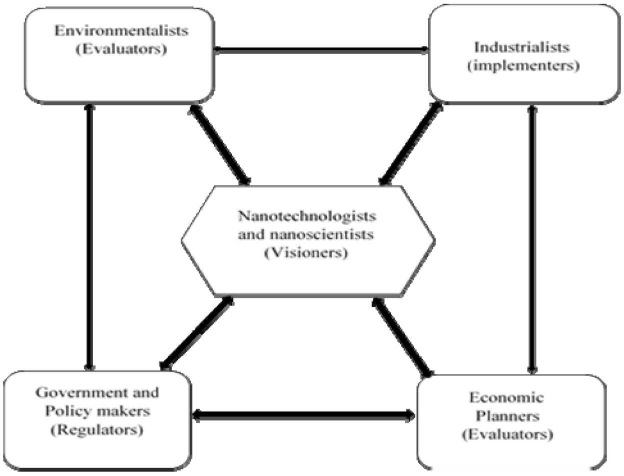

FIGURE 4. **Stakeholders Involved in sustained nanotechnology developments.**

Nanoparticles, which forms the bedrock of the technology may be unintentionally released and accumulated in the environment in the process of utilizing them in various application. Workers may be exposed to the nanoparticles and certain process conditions in an unhealthy manner. These and many more constitute risks associated with nanotechnology. Unarguably, as it is not possible to prefigure all the future applications of nanotechnology because the technology is still evolving, it is thus difficult to determine what the future impacts will be. Proactive steps, however, have to be taken in view of mitigating the undesirable impacts of nanotechnology even as the technology unravels because doing this is key to sustaining nanotechnology developments and maintaining a competitive national economic position. Diverse issues relating to large scale revolution has to be understood, the important decision relating to nanotechnology have to be strategically made and plans to handle arising complex societal issues have to be formulated. To overcome the risks and other challenges associated with nanotechnology, the collaboration between researchers, industrialists, policymakers, policy enforcers, the public and government is non - negotiable. Adequate funding must be available to facilitate researches. Researches to minimize or eliminate health risks and negative impacts of nanomaterials on the environment should be intensified. Globally acceptable schemes for objective evaluation of nanotechnology inventions, risks, and lifecycle assessments have to be in place.

With the expectations of overcoming the hindrances to the adoption of nanotechnologies and maximizing the benefits thereof, numerous researches have been conduction and several symposia have been held. It is recommended that some research efforts should be tailored towards harmonizing the research outcomes and submissions of researchers and research bodies. This will make the research findings go beyond the shelves and be actually useful in closing the extensive gaps in every national and transnational regulation. Some of the major challenges militating against the process of impact assessments of nanotechnology are incongruous approaches to exposure assessment, validation methods and discrepancy in instruments for detecting, characterizing and analyzing nanomaterials. As an analogue to convertibility and universality of scientific units and measurements, researchers and stakeholders in the field of nanotechnology, in the interim, could focus on developing universally acceptable approaches to impact assessments. This will foster the development of nationally & globally relevant and adequate schemes for unprejudiced appraisal of nanotechnology inventions.

On account of the relative newness of nanotechnology, one of the cogent ethical issues that have been identified is the deception to give false hopes to consumers of nanoproducts, deception to accrue research funds and misappropriation of research funds. To address this issue, proponents of nanotechnologies can put considerable efforts into studies aimed at developing efficient value systems and control schemes that promote responsible research practices in the field of nanotechnology and deter shady conduct. This may involve defining what constitutes inappropriate practices; placing clearly defined responsibilities on researchers, research institutions, and funding bodies in relation to fallouts in nanotechnologies; and designing equitable, clear cut, a knowledge-based system for allegation investigations and sanctions.

ACKNOWLEDGMENT

The authors acknowledge and appreciate the Management of Covenant University for the publication funding support provided for this article.

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