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MINI-REVIEWS

Opportunities and potential of green chemistry in nanotechnology

Ruma Arora Soni[1] · Mohd. Aseel Rizwan[2] · Surinder Singh[2]

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Abstract
Green chemistry and nano-engineering are aimed at increasing products efficiencies in the chemical supply chain and reducing health and environmental hazards. This study stresses how principles and measurements of green chemistry can affect, from design through disposal, the complete life cycle of a chemical. Nanotechnology, as a rapidly developing field, provides an educational framework for investigating the influence and implementation of Green Chemistry in the real world. Both are propelled by a wide range of inventiveness, and both are intended to usher in a new era of technological advancement. In this paper, the application and impact of modern green technologies, as well as future potential for transdisciplinary interaction, are discussed. The 12 Green Chemistry Principles, initially published in 1998, give a framework accepted by not only chemists, but also designers and policymakers. The implementation of the principles was prompted by decades of inadvertent environmental harm and the effects on human health from chemical production and use of dangerous chemicals. But the principles for the synthesis and manufacture of engineered nanomaterials (ENMs) are employed for more than decades. Even while the entire scientific community promotes advancements in nanotechnology, there remain considerable research gaps and a possibility for safe, responsive application of ENMs' great economic, social and environmental benefits. In the context of the notion of the 'Green Economy', the social relationship and economic between the environment and economy can be properly managed. The green nanotechnology concept intends to use nano-innovation in materials science and engineering to support the construction and maintenance of a society to generate energy-efficient products and processes that are environmentally and economically sustainable.

Keywords Nanotechnology · Green chemistry · Sustainability · Engineered nanomaterials

Introduction

Society initiates new requirements for better and novel technologies that are more forward-leaping than the current ones. In the direction of clean and green technological development, green nanotechnology is a subfield of environmental science. Environmentally friendly technology is defined as that technology, which safeguards the environment and prevent the harmful waste production and incorporates the principles of green chemistry and green engineering. It is the future technology and will impact all fields, viz. medical, agriculture, environment, nanotechnology and electronics with unimagined potential [1, 2]. It is a unique multidisciplinary platform that integrates engineering, biology, physics and chemistry. Scientists are working on the development of gadgets that are based on the concepts of quantum mechanics and nanotechnology, and which are predicted to have a profound impact on society [3]. Nanotechnology has emerged in all aspects of synthesis procedures, product development and technological innovations. Nanomaterials or its derived products directly can handle toxic wastes, assist in development of nano-medicines biomarkers and drug delivery, treat saline water and sense organic and inorganic pollutants, monitor toxic gases. Other applications include lightweight materials or components for automobiles, nanocomposites, electronic devices, servers and systems, and fuel cells, clean fuels, light emitting diodes (LEDs), catalytic materials, self-cleaning nano-sized coatings, energy storage devices and bulk chemicals utilizing green synthesis. The potential of nanotechnology is extensive and exciting and

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✉ Surinder Singh
sonuunos@gmail.com

[1] Energy Centre, Maulana Azad National Institute of Technology, Bhopal, (M.P), India

[2] Dr. S. S. Bhatnagar University Institute of Chemical Engineering and Technology, Panajb University, Chandigarh 160014, India

attracts considerable interest and research. Although nanotechnology is described in numerous ways, simply defining, it is the design or use of materials having nano-dimensional structures generally in the size below 100 nm. In comparison to conventional materials, nanoscale compounds have a higher surface-to-volume ratio, which is the primary cause for their reactivity, magnetic, optical, and electrical capabilities, that's why they are more effective and more sizeable, as well as reactive [4–6]. Despite considerable progress in nanotechnological arena, the toxicity and danger associated with the nanomaterials are a point of critical concern. These nanomaterials can enter our body and can cause many health hazards; hence, nano-toxicology continues to be a source of key concern and deciding factor across the broad field of nanotechnology. The environmental, health, and safety consequences of exposure to nanoparticles and their associated hazards remain unresolved and there is less data on toxicological studies of nanoparticles investigations. The two biggest problems: poor knowledge of the novel risks of nanotechnology and the absence of regulatory legislation about nanotechnology are key obstacles to the widespread deployment of nanotechnology in the sectors of human existence. The notion of 'green chemistry' is gradually emerging to address some of the possible hazards related to nanotechnology. Green chemistry is an environmentally friendly means to synthesize products from biodegradable and safe components with less use and minimized creation of hazardous chemicals. Green approaches of synthesizing, though not entirely effective, can address a wide range of challenges relating to nanotoxicology. [5–8]. Green synthesis, sometimes referred to as green nanotechnology, has the potential to alter large-scale processes into nanosynthesis and represents a new platform for the development of innovative products that benefit human and environmental health. In the future, the environmental and biological segments of nanotechnology applications aim to be improved by these methods to green nanomaterials. According to Wu yan et al., the perovskite-type $LaFeO_3$/g-C_3N_4 photocatalyst of the Z-scheme supports the growth of photocatalysis and has great promise for environmental remediation [9]. When it comes to the development of sustainable green energy systems, the investigation of extremely reliable photocatalysts for hydrogen evolution reaction is a major concern. [10, 11]. For photocatalytic materials in the future, nanostructures with doping will be evaluated as interesting candidates for further investigation [12]. Green Chemistry's major pillars are the use of resources that are harmless, biodegradable, eco-friendly, energy-efficient and bearing low cost. These green and eco-friendly synthesis properties benefit swiftly from nanotechnology and the research is underway. Nanoparticles from plants, micro-organisms, or other natural resources have been produced in a large number [4]. Even though green nanotechnology portrays a rosy vision of a clean, ecologically friendly, and safe future, there are some concerns, as it faces challenges not only to address the potential toxicity problems but also of building a new ground for the production of sustainable nanomaterials while taking into account of the environmental and health issues [13].

Clean and green nanotechnology

The nanomaterial quality developed by the technique of green synthesis is comparable to its chemical equivalents, and the properties of nanomaterials can be manipulated in the same manner by modifying reaction parameters such as temperature, and pH. But there are many barriers and activities that must be solved in this context [9]. The main challenges in green nanotechnology have been:

(i) Stability of the nano-products and structures
(ii) Handling and managing nanomaterial toxicity,
(iii) Regulatory guidelines for nano-material synthesis and
(iv) Industrial applications of methodologies used to increase scale-up.

In order to characterize nanomaterials and determine their effects on in vitro and in vivo functions, nanotoxicology relies on a variety of analytical methodologies, which include attempting to define and categorize the health consequences induced by artificial nanomaterials, to ascertain structural and functional links among nanoparticles and the associated toxicity. As seen from the standpoint of analytical chemistry, this burgeoning discipline presents numerous interesting issues that will call on the experience of both nanomaterial and bio-analytical chemistry experts in the field to solve those [14]. The investigation of in vitro nano-entities accumulation and localized effect is strongly intertwined to cyto-toxicological impacts related to nano-entity organism-cell interaction. Transmission electron microscopy, elemental analysis, and fluorescence spectroscopy are some of the analytical procedures that are utilized for characterization of nanomaterials along with XRD, FTIR, XPS analysis [15, 16]. When it comes to nano-toxicology, in vitro toxicity evaluation is a crucially significant tool. If compared it to in vivo investigations, the advantages of in vitro analysis include being fairly rapid, less expensive, providing control over method and decreasing ethical problems by limiting the test animals used in research and development.

This green (clean) issue of nanosynthesis is not yet implemented, and the change from concept to reality continues to be an important milestone. Excellent applications for green nanomaterials production have been proposed by researchers around the world e.g. solar energy storage and nano-sensing, nano-catalysis and nano-medicine. On the other hand, due to paucity of defined frameworks for manufacturing, fast toxicity analysis for determining health friendly nano-entities and uncertain market requirements limit the extent of the usage and marketing prospects of nanomaterials [6].

Although there appear to be numerous obstacles and issues related to green nanotechnology, the promise of this new and sustainable method does not appear to be diminished. [17, 18] The least routed approach is green nanotechnology, yet it can modify the faces of the traditional production of nanomaterials. The combination of nanotechnology and green chemistry is progressively bringing technology advancements into tandem and can be seen as the future of sustainable nanosynthesis. Dr. James Hutchison has clubbed both these as "Green chemistry is an excellent method to do nanotechnology responsibly". [19]. It takes time for the new technologies to develop, similarly green nanotechnology happens to be yet in its infancy. The face of traditional synthesis processes, as well as the use of industrial protocols for the commercial production of nanomaterials, needs to be transformed far more into greener practices. The foundations will be laid for environmentally sound and sustainable nanotechnology via green synthesis with a better understanding of the underlying processes of green approaches and improved characterization techniques and data analyses. Nanotech and nanotechnology are the art and science in which the components are measured in nanometres produce complex, usable devices with atomic precision [20].

Due to the absence of common substantive knowledge, this is not a traditional scientific discipline; the unifying attribute is "smallness", which means it is more ideal for nanoscale research and development to be a strategy, instead of a field. “There's plenty of space in the base” as said by Cal Tech, Nobel laureate Richard Feynman in his1959 talk. Richard Feynman had widely recognized the possibility to work on non-radioactively active materials at the atomic level, and he was without a doubt an inspiration for working on the nanoscience, which began to evolve gradually [21]. Now, much of this kind of study is quite common, whereas nanotechnology enthusiasm and fear are mostly due to the dramatic notions initially formulated in K. Eric Drexler's Engines of Creation: The Coming Age of Nanotechnology, a then MIT graduate student. This visionary/fictional 1986 account of non-technical readers created a production system that would produce functional things from the ground up and position individual atoms precisely where the makers wanted to. He contrasted this to modern manufacture, starting with large, readymade chunks of raw materials, then clumsily mixing, moulding, cutting, and transforming into useful stuff [22].

The green economy

In the mainstream of policy decisions, the concept of the “green economy” has been brought to fore by the global financial crisis, with an expected increase in over one third of world energy demand between 2010 and 2035, increased commodity prices, and urgent challenges in energy, environmental and health sectors [23–25].

In a breakthrough, in an United Kingdom Government study in1989, a group of top environmental economists coined the term "green economy" which refers principally concerning to the concepts of sustainable development. The United Nations' definition of green economy is most widely and trustworthy. It includes along with sustainable production, the lowest carbon footprint, efficiency in resources and social inclusion [26].

A series of concepts, aims, and actions can alternatively be classified as the green economy:

(i) equality between and across the different generations,
(ii) firmness and stability towards sustainability principles,
(iii) social and environmental precautionary approach.

The concept of green economy can change the way economies and people manage the environmental, social and wealth issues. Nanotechnology, generally defined as the material management within 1–100 nm dimensions—provides the chance to create new, energy-efficient and economically and eco-friendly green innovations in the form of small, large-scale surface to mass-related structures [27–30].

But the sustainability of green nanosolutions is now unclear and should be addressed with caution, although it is expected to have a major influence on society, economy and industry. Indeed, it can result in environmental and health hazards, ethical problems, market uncertainty and customer receptiveness, and stiff competition for traditional technologies, as well as the benefit of incorporating nanomaterial (NMs) into processes and products which contribute towards sustainable outcomes [31].

Concerning green economy principles, this review focusses on several perspectives and practical issues that nano-applications face when they are applied to the environment. Examples of the some nanoapplications, include, but not limited to, energy production and storage. Decreasing raw materials burdens the production cycles, clean-up technologies are required and support for sustainable manufacturing products are needed. [32].

The possible impact of nanotechnology on green initiatives

The meretricious features of NMs which are incorporated into nanoproducts and NM applications must take into account green nanotechnology as relevant to the entire value chain [27]. But most prospective green technology remedies are still at the stage of laboratory/start-up, while only a limited number of products are available in actual market. For evaluating the applicability, effectiveness, and long-term viability of nanotechnology in more realistic contexts, additional research should be carried out, along with validation of nano-enabled products vis-a-vis to traditional/existing technologies. Nanomedicine, nano-manufacturing and nano-catalysts are some of the prospective areas for green nanotechnology breakthroughs [33]. Nanotechnological goods, processes, and applications, as well as the reduction in greenhouse gases and hazardous wastes, are predicted to contribute greatly to environmental and climatic protection. Therefore, the use of nanomaterials promises some environmental benefits and sustainability consequences. However, notice that, in research or actual implementations, nanotechnology plays a very minor role in environmental protection. Nanotechnology is of modest value to environmental engineering companies themselves. Increasing raw material and energy prices, as well as increased consumer environmental consciousness, has resulted in a glut of goods in the market promising specific climate and environment friendly benefits in exchange for a premium price. Nanomaterials have unique physical and chemical properties that make them appealing for use in the development of new products that are both environmentally friendly and useful. Some examples here include e.g. enhanced durability of substances subjected to fatigue, mechanical stress or ageing, which contributes to extending the life cycle of the product. Similarly, dirt proof and water-resistant films/coatings based on nanotechnology for anti-ageing purposes; new insulating materials for improving heat transfer and building energy efficiency; the addition of nanoparticles to materials for weight reduction and energy efficiency has provided savings in the transport sector. Nanomaterials in the chemical industry are used to enhance energy and resource efficiency based on their particular catalytic capabilities and nanomaterials can replace chemicals with environmental problems in some application domains [34]. Nano-optimized products and processes are now in the development phase and are intended to make substantial contributions towards climate protection and to solve our energy concerns in the future.

Nanomaterials for energy conversion

The photovoltaic technology happens to be the most capable and trustworthy renewable energy technology. Sunlight can be instantly transformed into electricity. Carbon nanomaterials such as C-60-fullerene, nanotubes and graphene are used to evaluate effective electron receivers in solar cells, polymer and quantum dot cells [35]. At its nascent phase, dye sensitizing solar cells still have great potential. The nanofilm is deposited on the nanocrystalline mesoporic titanium dioxide (TiO_2) film into a transparent, conductive substrate with the charge dye's monolayer associated with their surface [36, 37]. The enormous NM surface area for colouring chemisorption is due to their strong energy conversion efficiency and the short period of migration. Nanotechnology, other than solar cells, has had a significant effect on the direct transformation of chemical electricity into fuel cells [4, 38–40]. When it comes to key electrode based oxidation/reduction reactions in fuel cells, nano-metals bearing high surface area, lower specific density, and a high concentration of surface chemicals, can be very effective electrocatalysts. While the platinum-based electrode exhibits time-modulated drift and CO_2 deactivation, platinum nanoparticles (PtNPs) have been identified as the most effective catalyst material for fuel-cells. Miniature metallic-Pt alloys prove to be extra efficient with their improved electro-catalytic activity and resistance [41]. CNTs and graphene based catalyst-supported devices for fuel cells are currently used as metal-free catalysts, which reduce loading of precious metals, and increase catalytic activity. Their advantages include a large surface area, meso-porosity, high conductivity, improved mechanical strength, small weight and exceptional corrosion resistance, among other characteristics.

For energy conversion and storage technology there are at least two main factors. To solve the intermittent availability of renewable resources, whether geothermal, wind, or solar, it is important to convert and store energy using highly efficient devices. Renewable sources of energy should also be turned into diverse types of energy, such as chemical energy in batteries that may be extracted as energy wherever needed to facilitate sustained acceptance in our daily lives. Second, the availability of electricity on demand is crucial to satisfying increasingly mobile social needs. Also chemical storage devices, like fuel cells, batteries and super capacitors, have been explored and utilized. The development of energy conversion and storage technologies depends on the availability of appropriate materials, as is true in many other domains. The dependence on the themes described may be particularly significant because the performance of conversion and storage devices is limited by the problems associated with normal materials. New materials such as 2D nano-materials are now available and are emerging. Although the parameters that characterize ideal energy conversion and storage materials are different, they typically share a striking commonality, i.e. the characteristic charging length scale. The nanoscale is this length scale. There have been considerable attempts to synthesize, characterize and utilize nanomaterials [42]. Control of nanoscale materials is certain to be decisive for any breakthrough in the future, based on and driven by renewable energy sources. Figure 1 depicts the nanoscale entities that can be produced for various targeted applications [43].

Principles of green chemistry

(i) **Prevent waste**: Preventing waste is better than treating or cleaning trash after production [44–46]. Design chemical syntheses to prevent waste and to avoid the waste that can be processed or utilized.

(ii) **Atom Economy**: To maximize assimilation into the finished product of all processing ingredients, synthetic procedures should be created. The reactants are covered, however, frequently other materials like solvents or separators are utilized in the synthesis, also with a chemical reaction. These materials normally constitute the bulk of the material input, and hence, the waste produced by them must also be taken into account. To be entirely successful, chemical products must have minimal toxicity [47].

(iii) **Design non-hazardous chemical synthesis**: The product synthesis design formulated for targeted application should be least toxicity. Synthetic procedures should always be conceived wherever practical for the usage and generation of compounds with minimal or no environmental toxicity [13, 17, 47]. The chemical substances and materials used in the manufacture of chemicals are of great importance and chemists must pay greater attention towards the selection and use of materials and chemicals; ideally go for green materials and synthesis. All the other things can be easily managed, but great care about choosing the correct synthetic pathway must be taken so that it leads to the production of the green products.

(iv) **Use renewable feedstocks**: Utilize renewable and non-depletable raw materials and feedstocks. Feedstocks are usually obtained from agricultural or other process wastes; waste feedstocks can either obtained from industrial residues or obtained from fossil fuels (oil, natural gas, or coal). A fascinating suggestion, which at first glance appears unfeasible, is to manufacture all of the fuels, chemicals, and materials derived from feedstocks that would never deplete or degrade, so environment friendly and renewable feedstock should be carefully chosen. Coal, petro-

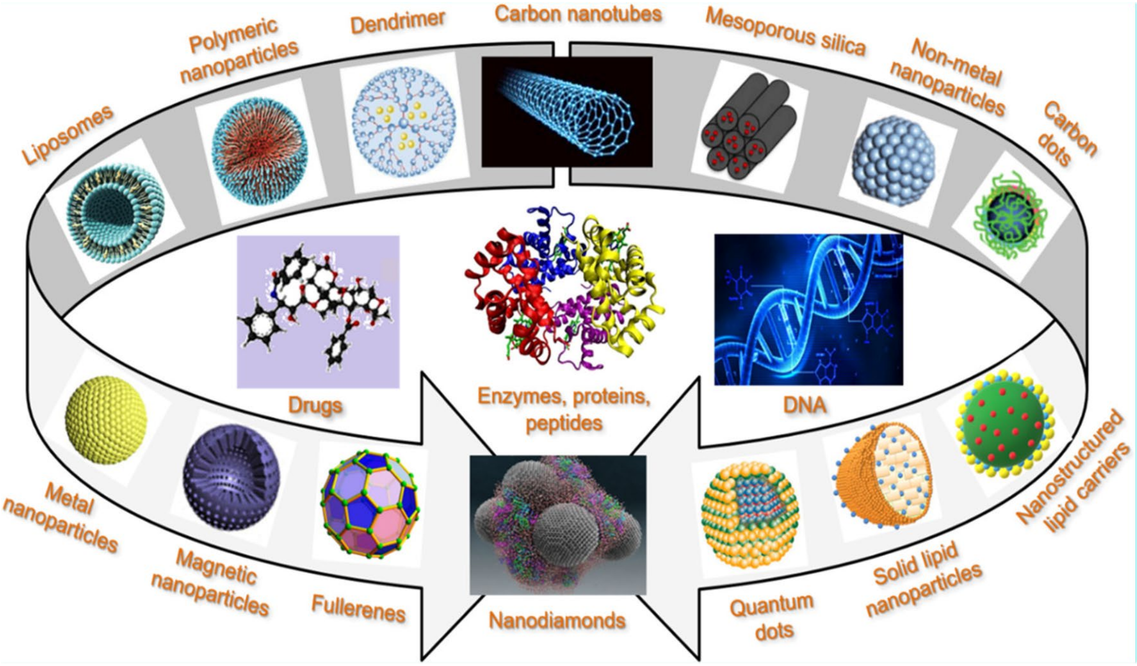


Fig. 1 Illustrates the architectures of various nanovectors and pharmaceutical components that may be efficiently targeted, delivered, and engineered to carry a variety of compounds, including medicines, enzymes, peptides, proteins, DNA, and other molecules. [43][Reproduced with permission from ACS omega 2019, 4 (5), 8804–8815]

leum and natural gas are all extracted from beneath the ground surface to be used as fossil fuels, as well as the extraction of useful minerals for profit. Particularly, with the expected increase in world population and the expansion of energy-intensive businesses across many continents, our fossil fuels for carbon-based chemicals and materials will indeed be depleted as a result of global climate change, in a relatively short period. In the next 50 years, our scientists and policy makers will observe a significant impact on human health and the environment, according to predictions [18, 48].

(v) **Employ catalysts, and not stoichiometric chemical reagents**: By employing catalytic reactions, minimize thermal energy and reduce waste. Catalysts in modest quantities are utilized and can repeatedly perform a given reaction. They are better than stoichiometric reagents, which can work selectively as per given reactants or sometimes do not react at normal conditions. The prime objective of green chemistry is to decrease the production of waste substances and associated side products, or preferably to eliminate them: as is often said; 'preventing is better than curing'. This will require an overall shift from one focusing on chemical yield, to the other that attaches importance to waste minimization. The key concept is of nuclear economy: “synthetic procedures should be developed to optimize the formation of end products by all participating elements employed in the process”. For example, if the, decrease in reduction of ketone to secondary alcohol, using sodium borohydride (SBH) and molecular hydrogen is compared, it is observed that SBH has a nuclear economy of 81%, whereas hydrogen route is 100% atomic, which means that all the product ends up and there is no waste generated. Sustainable nanotechnology with aid of green chemistry will help in producing environment friendly and safer products. Hence sustainable strategies, decision-making support and guidance to facilitate sustainable manufacturing processes is the key to green nanotechnology and minimization of waste [49–52].

(vi) **Avoid chemical derivatives**: In green chemistry, one of the main concepts is the reduction in the usage of derivatives and protective groups in the synthesis of desired molecules. If feasible, avoid unnecessary derivatives, because such operations necessitate the use of extra chemicals and can result in waste. A strategy that has proven to be very helpful in this regard is the application of enzymes. Enzymes have a unique property that they can frequently react on a single site while leaving the rest of the molecule alone and hence reduce the use of protective groups. A classical example green chemistry application and of use of enzymes to avoid protective groups, is the production of semi-synthetic penicillin.

(vii) **Design safer chemicals and products**: Syntheses are designed so that a maximum proportion of the beginning materials is included in the final result without causing toxicity and harm to living beings. Handling toxicity is one of the most challenging factors in the development of safe products and processes while preserving function and efficiency of products. To achieve this objective, we need not only to comprehend the fundamentals of green chemistry, but also of toxicology, sustainability and environmental science [18, 48–53]. Different studies related to pollutants degradation and utilizing green chemistry in synthesizing green nanoparticles have been reported [54–57]. Chemists utilize highly reactive chemicals to produce goods, because they are precious to affect molecular processes. But these chemicals react with unanticipated, ecological and biological targets, which have undesirable health impacts. The qualified molecular chemists sometimes also are not able to handle these hazard issues, due to lack of structural risk knowledge and associated toxicity.

(viii) **Employ harmless solvents and safe reaction procedures**: Solvents, reagents and other auxiliary chemicals affect the greenness of the process or reactions and energy consumption required. If toxic chemicals need to be utilized, they should be used with proper care and ensuring safety of the overall process. Whereever possible, it should be made a practice not to utilize the auxiliary toxic substances (for example solvents, separating agents, etc.) and harmful reagents. Sometimes, there would be no reactions if the solvents and/or mass separation agents are not present [44]. Mass and energy transfer are dependent on solvents and separation agents utilized, and many reactions will not proceed without their presence. Hence there is great importance and utility of chemical reagents and solvents utilized for particular processes or reactions.

(ix) **Increase energy efficiency**: Use as little energy as feasible to carry out chemical reactions at room temperature and pressure. Environmental and economic consequences of increasing energy demand should be recognized. In the twenty-first century, energy is the most significant concern [44]. Most part of the current energy sources are from fossils fuels. And during conversion and transmission, the majority of the energy provided to the point of consumption is lost, as compared to what was available at the beginning i.e. present in fuel. It is also evident that a large percentage of fossil fuel energy is utilized by transportation services, while space heating and cooling ranks as the second most important use of fossil fuel energy. There is a great need and opportunity to improve this energy use by the technocrats into useful life cycle of fossil fuel based energy into useful applications and with minimal wastage.

(x) **Design chemicals and products to degrade after use**: Design chemical products to break down into safe compounds in order to not to get accumulated in the environment after usage. Chemicals should be designed to degrade into innocuous degradation products rather than to persist in the environment after they have completed their job, to avoid polluting the ecosystem. Green chemists aim to optimize a chemical's commercial utility, while reducing its associated risk and hazard. The hazard associated with a chemical is an intrinsic feature arising from a chemical’s stereochemistry. However, to limit the danger or the likelihood of an injury, principle ten governs the design of entities that will degrade after their commercial use of a chemical is completed. The risk associated with a chemical or compound depends both upon the inherent hazard capability of the molecule its exposure to another chemical. Degradation via bio-route, hydrolysis or photolysis/photo-catalysis can reduce significant exposure to chemicals and minimize the risk [44]. The life cycle of a material is depicted in Fig. 2.

(xi) **Real-time analysis to abate pollution**: To avoid or curb the generation of by-products, during the syntheses, real-time control and monitoring are implemented in-process. To enable in-depth monitoring and monitoring in real time before harmful compounds are formed, analytical procedures must be further developed. Laboratory analysis from the undergraduate studies is well known to most chemists. Process analysis chemistry is a sub-discipline of chemistry that can be used in a chemical plant and can be performed in-line or online. For example, it is possible to identify temperature, pressure and/or pH variations in the process before a reaction goes out of control, to detect catalyst poisoning, or to detect any other harmful event before any big accident occurs.

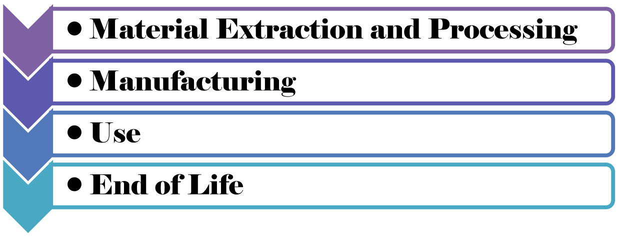


Fig. 2 Synthesis and life cycle of materials

(xii) **Minimize scope of hazards and accidents**: The choice of chemical compounds used in different processes should reduce the risk of accidents, including explosions, fires, and environmental releases (solid, liquid, or gas). In order to reduce the likelihood of chemical accidents, the choice of ingredients (chemical entities) and form of a material utilized in a chemical process must be carefully decided. With regards to an acceptable level of risk, safety could be described as a measure to control the recognized dangers. The green chemistry principle 12 (safety principle) is the logical result of many of the other principles. Laboratory safety must practice green chemistry since it is “primarily oriented at decreasing or eliminating the use or manufacturing of hazardous compounds”. Although there are certain exceptions, the majority of the Green Chemical Principles result in a safer environment. [47, 52].

Sustainable nanotechnology

The framework for efficient design and sustainable production is based on Green Chemistry fundamentals. It is utilized for the designing processes, products and methods required to manufacture molecules and materials to enable safety against health and the environmental hazards, which is essential for survival [50–53]. The framework has been built to serve as a proactive component to the multiple reactive strategy currently in use today, employed over the years to fix damaged items and inefficient activities. However, following the introduction of new chemical substances into trade (and the environment), monitoring and mitigation measures are utilized to overcome the wastage of resources. Green chemistry has thus been developed as a preventive strategy which has been employed since the introduction of new chemicals. While many systems based on engineering design and management principles aim to eliminate waste or to boost energy efficiency, all of these aims, and many more are being achieved utilizing green chemistry. Green chemistry takes the entire life cycle into account and applies its principles to help optimizing the design framework as depicted in Fig. 3. This is important because a benign target molecule or chemical, which is possible to produce a life-saving drug, can also result in a damaging and polluting manner at the end of life-cycle of that drug, which is otherwise beneficial to the society.

On the other side, approaches are available to develop a method of manufacture or synthetic technique that is environmentally friendly and economical and results in a product which can be utilized safely till end of its life cycle.

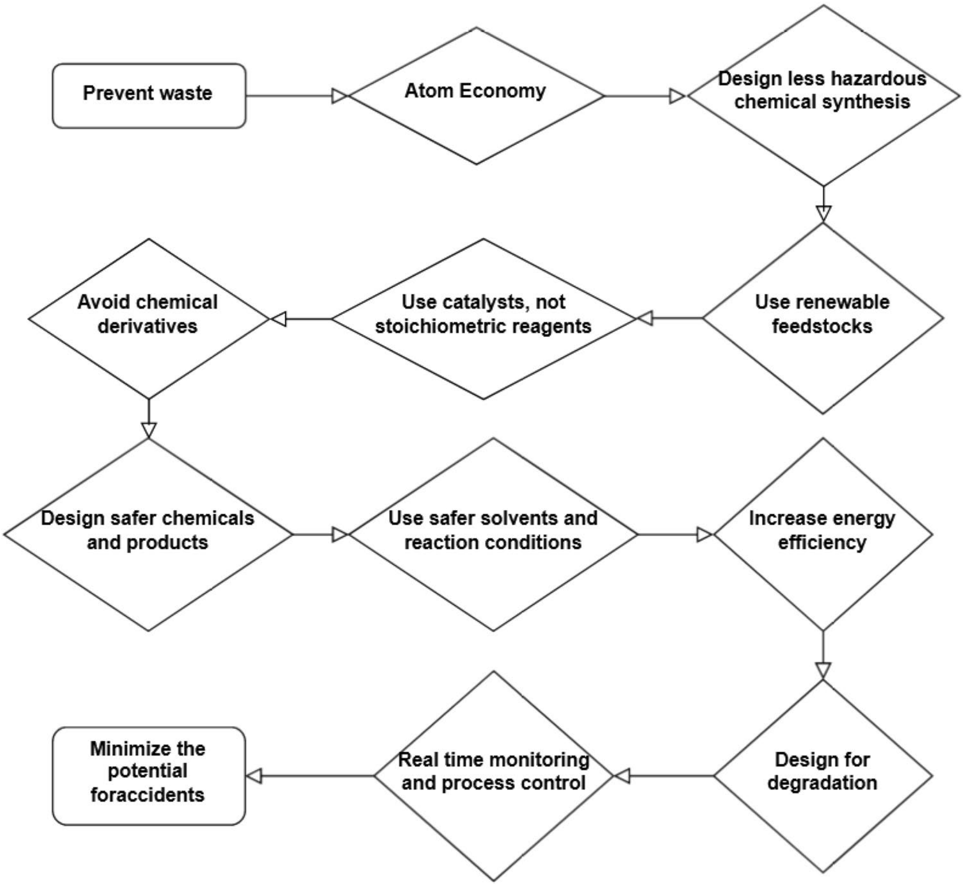


Fig. 3 The stages of the life cycle related to each of the Twelve Principles of Green Chemistry

Assuming only a single phase of the life cycle, for instance, severe unanticipated effects have previously occurred. Sustainable technologies utilizing green and natural materials and characterization techniques and tools can help producing new materials and catalysts which have distinct advantages over tradition materials, which have resulted in useful scientific literature in the recent past [58–63]. Given our existing technical capabilities, the development of the Green Chemistry Principles, as with every multiparameter system, may lead to a compromise between principles. However, because there is no proof that one of these potential compromise agreements is intrinsically better than the other—Principles must always be diametrically opposed—it is simply a design difficulty that enables synergies to be maximized and the principles to be aligned with the best solutions. Feedstock origins (Principle 7), which are one of the 12 principles, are based on renewability rather than depletion of initial resources, to commence the approach to life cycles, where possible [64]. While the term "renewable" is often used to identify bio-based feedstocks rather than fossil-based carbon, generally, only a subset of engineered nanomaterial (ENM) classes is relevant (i.e. newly synthesized or rapidly cycling). Many ENMs must be investigated in order to assess whether the elements originate from harmful minerals or are safe. In various cases, environmental, geopolitical and economic variables can influence feedstock supplies. For instance, medicines are thought to be of extremely small volume and value and are yet significantly concerned for human and ecological health, as well as their release and persistence in the environment. Various ideas link directly to the production cycle (Principles 1–3, 8, 11). First of all, it is desired that each atom entering the production process will end up as product instead of trash. Several measures have been designed to estimate how close a process nears to this aim, such as the atomic economy and the environmental factor (E-factor). Recent studies have showed that some of these conditions are not well met by ENM synthesis, which can cause considerably more waste than in the synthesis of medicines and chemicals otherwise, hence the material and the energy consumption processes are evaluated very critically [65–67]. However, exposure of ENMs at organelle level e.g. cells and tissues, shows that the effects are widely different on various organisms and species and therefore the need of the hour is to evolve standard procedures to study the impact of ENMs on humans and other species [68]. The use of nanoparticles of TiO_2 in a photocatalytic reactor using computational fluid dynamics, modelling and its effects on kinetics have been reported in the literature, describing the scale up-studies and mesh effects [69]. Similarly, studies on photocatalytic detoxification of amaranth dye on immobilized TiO_2 and correlation between biochemical and chemical oxygen demand have been reported [70, 71]

Synthesis of green nanoparticles, scope, applications, and limitations

Green nanotechnology is a term used to describe nanoparticles (nanomaterials) synthesized from natural pathways such as microbes, fungus or plant-based extracts using different biotechnological approaches. The resulting nanoparticles are free from hazardous substances and are environmentally beneficial. Nanoparticles can be generated in a greener way by utilizing plant parts for the bio-reduction of metal ions [72]. Green synthesis has been used to make a variety of nanoparticles. Table 1 enlists details of some nanoparticles that have been synthesized by the green approach, including silver [73], gold [74], palladium [75], iron [76], and zinc oxide [77]. The green synthesis of silver nanoparticles is depicted in Fig. 4 below.

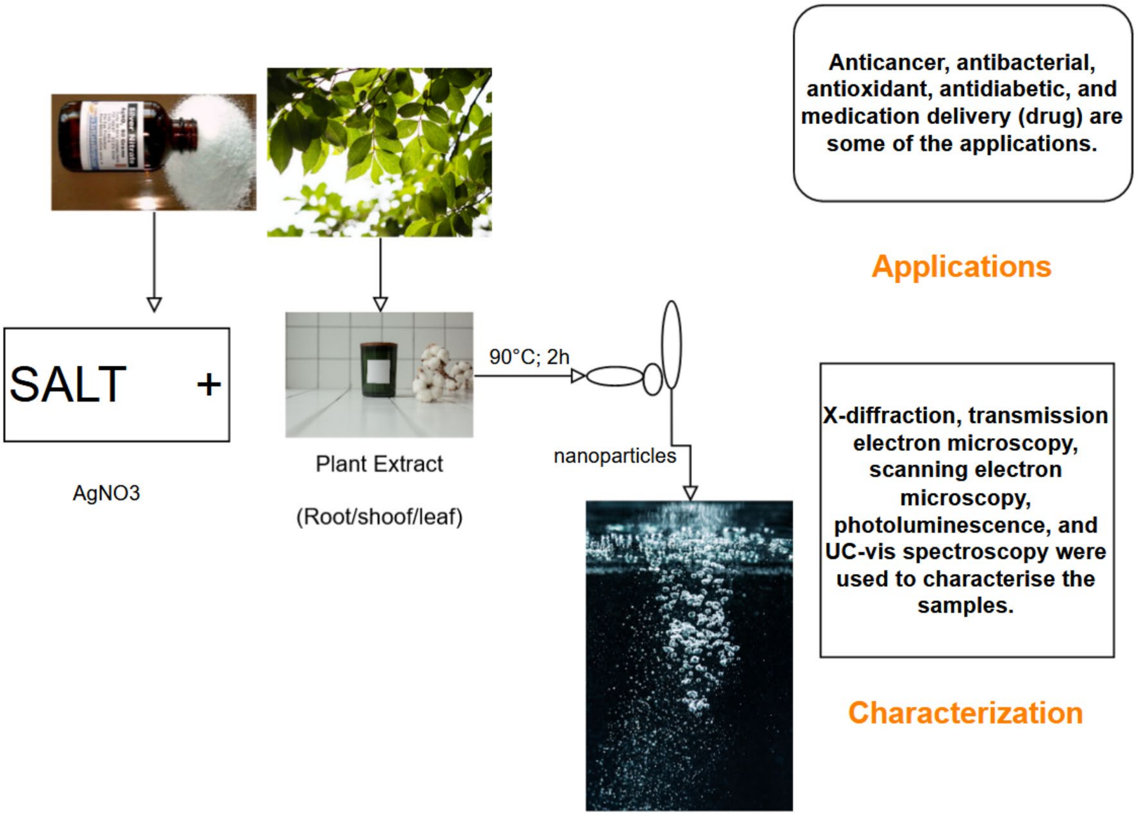
To create nanoscale conditions, such as nanoscale channels nano-arrays, for polymers made from nucleotides, like DNA, nanotechnology can be very helpful. It can also be employed in the development of computerized nano-based sensors and electrodes, analytical and diagnostic devices and other applications where DNA is a target or serves as a 'conveyor belt' for connected particles. Using nanotechnological approaches, different synthetic polymers, e.g. molecular motors with 'smart' polymers, can be created to manage biological processes [78]. There are numerous applications of nanotechnology as discussed in the literature; however, there are some limitations to green synthesis of nanoparticles also. Also generation and stabilization of nanoparticles generated by biological sources are controlled by a variety of process conditions e.g. pH, process temperature, pressure and reaction time [72]. There are certain limitations for synthesizing nano-entities like nano-particles from bio based routes e.g. micro-organisms include maintenance of large cultures for synthesis, pathogen activity and slowness of synthesis process [79].

Recommendations for the better implementation of green nanotechnology

Green infrastructure and economically efficient eco-engineering are the key to massive scientific restoration and endurance. It aims to reduce environmental issues by

Table 1 Nanoparticles synthesized employing microbes and plants components

Nanomaterial produced	Biotic individual or sources	Size of the particle	References
Silver (Ag)	Reetha and Shikakai leaves extract, Pongamia pinnata, A. indica leaf extract Algae Chenopodium murale leaf extract Rhodococcus NCIM 2891 Aspergillus fumigatus (Fungus) Fusarium oxysporium (Fungus) MKY3 (Yeast)	~30 nm (Small, 5–15 nm) and (large, 22–25 nm) 15–35 nm 2–15 nm 30–50 nm 10 nm 5–25 nm 5–15 nm 2–5 nm	[81], [82], [83], [84], [85], [86], [87], [88], [89]
Gold (Au)	Colletotrichum sp. (Fungus) Avena sativa (Plant) Fusarium oxysporium (Fungus) Pseudomonas aeruginosa (Bacterium) P. jadinii (Yeast) *Cladosporium cladosporioides* fungus isolated from seaweed Hibiscus leaf extract	20–40 nm 5–20 nm (at pH 3 and 4), 25–85 nm (at pH 2) 20–40 nm 15–30 nm Few to 100 nm Within 100 nm 16–30 nm	[90], [91], [92], [93], [94], [95], [96]
Iron (Fe)	Eucalyptus leaf extract Eucalyptus leaves	95 ± 5 nm 70 ± 20 nm	[97], [98]
Palladium (Pd)	Desulfovibrio desulfuricans (Bacterium)	–	[99]
Zinc Oxide (ZnO)	*Rosa canina* Leaf extract of Azadirachta *indica* *Ocimum basilicum* L Seaweeds *Limonia acidissima* L. leaf *L. nobilis* L. leaves	Less than 50 nm 9.6–25.5 nm 50 nm 36 nm 12–53 nm 21–25 nm	[100], [101], [102], [103], [104] [77]


Anticancer, antibacterial, antioxidant, antidiabetic, and medication delivery (drug) are some of the applications.

X-diffraction, transmission electron microscopy, scanning electron microscopy, photoluminescence, and UC-vis spectroscopy were used to characterise the samples.

Fig. 4 Green production of silver nanoparticles

energy efficiency improvements, lowering pollution or greenhouse gases, and limiting fossil fuel-based feedstock consumption. Green chemistry aims to promote green synthesis, sustainable production and at the same time, minimizing waste production. There are still many limitations in transition towards green synthesis of materials, but the potential opportunities of utilizing nanoscience and nano-engineering is propelling the scientific endeavours in green nanotechnology and sustainable chemistry to a great extent [80].

Some critical recommendation for the near future can be summarized as follows:

a- The first step in green chemistry is to examine applications and implications of green synthesis and methods. This comprehensive approach to technological development should stimulate interdisciplinary research that can promote successful communication with the society. This opportunity must be taken to engage all stakeholders, since the public anticipation and acceptance are ultimately the success of every new technology.
b- To develop novel synthesis processes or equipment, enhancing large-scale production of nanomaterials is required for all practical applications and commercial manufacturing.
c- Guidelines to produce synthetic nanomaterials should be framed to motivate industries adopt green nanotechnology based manufacturing. Also, blending of green nanomaterials with the synthetic ones should be tested to check on the effectiveness of the materials.
d- Tremendous amount of mystery around green nanoparticles necessitates thorough investigation. This is only conceivable if university-level and peer research is included and promoted. Toxicologists' inputs would also be helpful to bridge the gap between green production and associated impacts more effectively.

Conclusions

Green nanotechnology aims for various green solutions that utilize the physicochemical characteristic of materials and employ green-synthesis, energy-efficient and environmentally sustainable applications with predictable outcomes and exciting impacts on a wide variety of economies. These solutions may lead to minimizing the strain on traditional raw materials in the energy sector and increasing the energy availability for future, efficiency and reliability of the energy production system. The application of different green chemistry methods and principles helps us to create better products, although improvements are always possible. It is natural and appealing to most scientists and scholars, but sometimes it perplexes policymakers, corporate executives and consumers, who often want clear solutions. It is crucial for scientists and engineers to approach the public, to aware them about green synthesis and nanotechnology, prevent weak legislation and tackle greenwashing campaigns. The applications and the ramifications of new technologies must be explained to the public. The crucial parameters influencing the synthesis of nanomaterials employing greener approaches must be explained and care must be taken to showcase the best products and technologies having actual waste minimization potential and environmental safeguarding rather than widespread greenwashing. Sustainable research in the field of nanotechnology should be envisioned, incorporating toxicological studies, societal impacts and industrial manufacturing.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Verma A, Gautam SP, Bansal KK, Prabhakar N, Rosenholm JM (2019) Green nanotechnology: advancement in phytoformulation research. Medicines 6(1):39
2. Dragutan V, Demonceau A, Dragutan I, Finkelshtein ES (Eds.) (2009). Green metathesis chemistry: great challenges in synthesis, catalysis and nanotechnology. Springer Science & Business Media. https://1lib.in/book/1209725/bcd94e
3. Rafique M, Tahir MB, Rafique MS, Hamza M (2020) History and fundamentals of nanoscience and nanotechnology. In: Nanotechnology and photocatalysis for environmental applications (pp. 1–25). Elsevier.
4. Marchiol L (2018) Nanotechnology in agriculture: new opportunities and perspectives. New Vision Plant Sci 9(4):161
5. Bakar KA, Sam MFM, Tahir MNH, Rajiani I, Muslan N (2011) Green technology compliance in Malaysia for sustainable business development. J Glob Manag 2(1):55–65
6. Schmidt K (2007) Green nanotechnology: it's easier than you think. https://www.wilsoncenter.org/publication/pen-8-green-nanotechnology-its-easier-you-think-report
7. Hunt AJ, Anderson CW, Bruce N, García AM, Graedel TE, Hodson M, Meech JA, Nassar NT, Parker HL, Rylott EL, Sotiriou K (2014) Phytoextraction as a tool for green chemistry. Green Process Synth 3(1):3–22
8. Preeti NJ (2016) Green chemistry for nanotechnology: opportunities and future challenges. Combichem Bioresource Center, National Chemical Laboratory, Pune, India, vol 5(1), e-ISSN:2319-9849
9. Wu Y, Wang H, Tu W, Liu Y, Tan YZ, Yuan X, Chew JW (2018) Quasi-polymeric construction of stable perovskite-type LaFeO3/g-C3N4 heterostructured photocatalyst for improved Z-scheme photocatalytic activity via solid pn heterojunction interfacial effect. J Hazard Mater 347:412–422
10. Tahir MB, Nabi G, Iqbal T, Sagir M, Rafique M (2018) Role of MoSe2 on nanostructures WO3-CNT performance for photocatalytic hydrogen evolution. Ceram Int 44(6):6686–6690
11. Tahir MB, Nabi G, Hassan A, Iqbal T, Kiran H, Majid A (2018) Morphology tailored synthesis of C-WO 3 nanostructures and its photocatalytic application. J Inorg Organomet Polym Mater 28(3):738–745
12. Tahir MB, Nabi G, Khalid NR, Rafique M (2018) Role of europium on WO3 performance under visible-light for photocatalytic activity. Ceram Int 44(5):5705–5709
13. Mulvihill MJ, Beach ES, Zimmerman JB, Anastas PT (2011) Green chemistry and green engineering: a framework for sustainable technology development. Annu Rev Environ Resour 36:271–293
14. Marquis BJ, Love SA, Braun KL, Haynes CL (2009) Analytical methods to assess nanoparticle toxicity. Analyst 134(3):425–439
15. Tahir MB, Sagir M (2019) Carbon nanodots and rare metals (RM= La, Gd, Er) doped tungsten oxide nanostructures for photocatalytic dyes degradation and hydrogen production. Sep Purif Technol 209:94–102
16. Tahir MB, Nabi G, Khalid NR (2018) Enhanced photocatalytic performance of visible-light active graphene-WO3 nanostructures for hydrogen production. Mater Sci Semicond Process 84:36–41
17. Hutchison JE (2016) The road to sustainable nanotechnology: challenges, progress and opportunities. ACS Sustainable Chem Eng 4(11):5907–5914. https://doi.org/10.1021/acssuschemeng.6b02121
18. Khan SH (2020). Green nanotechnology for the environment and sustainable development. In: Green materials for wastewater treatment. Springer, Cham, pp. 13–46
19. Iavicoli I, Leso V, Ricciardi W, Hodson LL, Hoover MD (2014) Opportunities and challenges of nanotechnology in the green economy. Environ Health 13(1):1–11
20. Lowry GV, Avellan A, Gilbertson LM (2019) Opportunities and challenges for nanotechnology in the agri-tech revolution. Nat Nanotechnol 14(6):517–522
21. Maksimović M, Omanović-Mikličanin E (2017) Towards green nanotechnology: maximizing benefits and minimizing harm. In: CMBEBIH 2017. Springer, Singapore, pp. 164–170
22. Schulte PA, McKernan LT, Heidel DS, Okun AH, Dotson GS, Lentz TJ, Geraci CL, Heckel PE, Branche CM (2013) Occupational safety and health, green chemistry, and sustainability: a review of areas of convergence. Environ Health 12(1):1–9
23. Tang SL, Smith RL, Poliakoff M (2005) Principles of green chemistry: productively. Green Chem 7(11):761–762
24. Anastas PT, Warner JC (1998) Principles of green chemistry. Green Chem: Theory Prac 7:29–56
25. Tahir MB (2018) Construction of MoS_2/CND-WO_3 ternary composite for photocatalytic hydrogen evolution. J Inorg Organomet Polym Mater 28(5):2160–2168
26. Albrecht MA, Evans CW, Raston CL (2006) Green chemistry and the health implications of nanoparticles. Green Chem 8(5):417–432
27. Aithal PS, Aithal S (2015) Ideal technology concept & its realization opportunity using nanotechnology. Int J Appl Innov Eng Manag (IJAIEM) 4(2):153–164
28. Dutta D, Das BM (2020) Scope of Gre28en nanotechnology towards amalgamation of green chemistry for cleaner environment: a review on synthesis and applications of green nanoparticles. Environ Nanotechnol Monitor Manag 15:100418
29. Beach ES, Cui Z, Anastas PT (2009) Green chemistry: a design framework for sustainability. Energy Environ Sci 2(10):1038–1049

30 Aithal S, Aithal PS (2021) Green and eco-friendly nanotechnology-concepts and industrial prospects. Int J Manag Technol Soc Sci (IJMTS) 6(1):1–31

31 Soni GD (2015) Advantages of green technology. Social Issues and environmental problems. Int J Res Granthaalayah 3(9):1–5

32. Sanghi R, Singh V (eds) (2012) Green chemistry for environmental remediation. Wiley. https://onlinelibrary.wiley.com/doi/book/10.1002/9781118287705

33. Pandey G (2018) Nanotechnology for achieving green-economy through sustainable energy. Rasayan J Chem 11(3):942–950

34. Karn B, Wong SS (2013) Ten years of green nanotechnology. In: Sustainable nanotechnology and the environment: advances and achievements (pp. 1–10). American Chemical Society.

35. Khalid NR, Liaqat M, Tahir MB, Nabi G, Iqbal T, Niaz NA (2018) The role of graphene and europium on TiO2 performance for photocatalytic hydrogen evolution. Ceram Int 44(1):546–549

36. Khalid NR, Majid A, Tahir MB, Niaz NA, Khalid S (2017) Carbonaceous-TiO2 nanomaterials for photocatalytic degradation of pollutants: a review. Ceram Int 43(17):14552–14571

37. Khalid NR, Ahmed E, Niaz NA, Ghulam Nabi M, Ahmad MB, Tahir MR, Rizwan M, Khan Y (2017) Highly visible light responsive metal loaded N/TiO2 nanoparticles for photocatalytic conversion of CO2 into methane. Ceram Int 43(9):6771–6777

38. Anastas PT, Warner JC (1998) Green chemistry. Frontiers, 640. https://global.oup.com/academic/product/green-chemistry-9780198506980?cc=ca&lang=en&

39. Anastas PT, Kirchhoff MM (2002) Origins, current status, and future challenges of green chemistry. Acc Chem Res 35(9):686–694. https://doi.org/10.1021/ar010065m

40. Clark JH, Macquarrie DJ (Eds.) (2008). Handbook of green chemistry and technology. Wiley.

41. Poliakoff M, Fitzpatrick JM, Farren TR, Anastas PT (2002) Green chemistry: science and politics of change. Science 297(5582):807–810

42. Anastas PT (1999) Green chemistry and the role of analytical methodology development. Crit Rev Anal Chem 29(3):167–175

43 Kanwar R, Rathee J, Salunke DB, Mehta SK (2019) Green nanotechnology-driven drug delivery assemblies. ACS Omega 4(5):8804–8815

44. Sheldon RA (2012) Fundamentals of green chemistry: efficiency in reaction design. Chem Soc Rev 41(4):1437–1451

45. Lancaster M (2020) Green chemistry: an introductory text. Royal society of chemistry. https://pubs.rsc.org/en/content/ebook/978-1-78262-294-9

46. Clark JH (2002) Solid acids for green chemistry. Acc Chem Res 35(9):791–797

47. Dhingra R, Naidu S, Upreti G, Sawhney R (2010) Sustainable nanotechnology: through green methods and life-cycle thinking. Sustainability 2(10):3323–3338

48 Sadik O, Karn B, Keller A (2014) Sustainable nanotechnology. ACS Sustain Chem Eng 2(7):1543–1544

49. Falsini S, Bardi U, Abou-Hassan A, Ristori S (2018) Sustainable strategies for large-scale nanotechnology manufacturing in the biomedical field. Green Chem 20(17):3897–3907

50. Malsch I, Subramanian V, Semenzin E, Hristozov D, Marcomini A (2015) Supporting decision-making for sustainable nanotechnology. Environ Syst Decis 35(1):54–75

51. Gilbertson LM, Zimmerman JB, Plata DL, Hutchison JE, Anastas PT (2015) Designing nanomaterials to maximize performance and minimize undesirable implications guided by the principles of green chemistry. Chem Soc Rev 44(16):5758–5777

52. Eason T, Meyer DE, Curran MA, Upadhyayula VK (2011) Guidance to facilitate decisions for sustainable nanotechnology. US Environmental Protection Agency, Washington, DC

53. Krishnaswamy K, Orsat V (2017). Sustainable delivery systems through green nanotechnology. In: Nano-and microscale drug delivery systems. Elsevier, pp. 17–32

54. Verma P, Kumar J (2014) Degradation and microbiological validation of Meropenem antibiotic in aqueous solution using UV, UV/H_2O_2, UV/TiO_2 and UV/TiO_2/H_2O_2 processes. Int J Eng Res Appl 4(7):58–65

55. Mishra D, Arora R, Lahiri S, Amritphale SS, Chandra N (2014) Synthesis and characterization of iron oxide nanoparticles by solvothermal method. Prot Met Phys Chem Surf 50(5):628–631

56. Parial D, Patra HK, Dasgupta AK, Pal R (2012) Screening of different algae for green synthesis of gold nanoparticles. Eur J Phycol 47(1):22–29

57. Kumar J, Bansal A (2010). Photocatalytic degradation of amaranth dye in aqueous solution using sol-gel coated cotton fabric. In: Proceedings of the world congress on engineering and computer science (Vol. 2, pp. 20–22).

58. Sudhakar K, Soni RA (2017). Carbon sequestration through solar bioreactors: industrial strategies. In: Carbon utilization. Springer, Singapore, pp. 143–155

59. Soni RA, Rana RS, Godara S (2021). Characterization Tools and Techniques for Nanomaterials and Nanocomposites. In Nanomaterials and Nanocomposites. CRC Press, pp. 61–83

60. Upadhyay AK, Singh DP (eds) (2020) Algae and sustainable technologies: bioenergy. CRC Press, Nanotechnology and green chemistry

61 Pradeep T, Allen DT, Licence P, Subramaniam B (2020) Expectations for manuscripts with nanoscience and nanotechnology elements in ACS sustainable chemistry & engineering. ACS Sustain Chem Eng 21:7751–7752

62. Tahir MB, Nabi G, Rafique M, Khalid NR (2017) Nanostructured-based WO_3 photocatalysts: recent development, activity enhancement, perspectives and applications for wastewater treatment. Int J Environ Sci Technol 14(11):2519–2542

63. Palit S (2020) Frontiers of applications of nanotechnology in biological sciences and green chemistry. In: Green chemistry and sustainable technology, 1st edn. Apple Academic Press, p. 25

64. Sadik O, Yazgan I, Kariuki V (2014). Sustainable nanotechnology: preparing nanomaterials from benign and naturally occurring reagents. In: Chemical processes for a sustainable future, chapter 9. Royal Society of Chemistry. https://www.researchgate.net/publication/283291797_Sustainable_Nanotechnology_Preparing_Nanomaterials_from_Benign_and_Naturally_Occurring_Reagents

65. Hull MS, Quadros ME, Born R, Provo J, Lohani VK, Mahajan RL (2014). Sustainable nanotechnology: a regional perspective. In: Nanotechnology environmental health and safety. William Andrew Publishing, pp. 395–424

66. Mohanta D, Ahmaruzzaman M (2020). Addressing nanotoxicity: green nanotechnology for a sustainable future. The ELSI Handbook of Nanotechnology: Risk, Safety, ELSI and Commercialization, pp. 103–112.

67. Palit S (2019). Green nanotechnology, green nanomaterials, and green chemistry: a far-reaching review and a vision for the future. In: Advances in nanotechnology and the environmental sciences: applications, innovations, and visions for the future, Apple Academic Press, Taylor and Francis Gro, USA. https://www.researchgate.net/publication/336665606_Green_Nanotechnology_Green_Nanomaterials_and_Green_Chemistry_A_Far-Reaching_Review_and_a_Vision_for_the_Future

68. Pagano L, Maestri E, Caldara M, White JC, Marmiroli N, Marmiroli M (2018) Engineered nanomaterial activity at the organelle level: impacts on the chloroplasts and mitochondria. ACS Sustain Chem Eng 6(10):12562–12579

69. Kumar J, Bansal A (2015) CFD simulations of immobilized-titanium dioxide based annular photocatalytic reactor: model

development and experimental validation. Indian J Chem Technol 22:95–104

70. Kumar J, Bansal A Photocatalytic degradation of amaranth dye over immobilized nano-crystals of TiO_2, (2010) International conference on energy and environment, Cambridge, pp. 129–133.
71. Kumar J, Jana AK, Bansal A, Garg R (2005) Development of correlation between BOD and COD for refinery waste. Indian J Environ Prot 25(5):405
72. Pal G (2019). Green synthesis, characterization and applications of nanoparticles || Green synthesis of nanoparticles: a greener approach for a cleaner future. https://doi.org/10.1016/B978-0-08-102579-6.00001-0
73. Khalil MM, Ismail EH, El-Baghdady KZ, Mohamed D (2014) Green synthesis of silver nanoparticles using olive leaf extract and its antibacterial activity. Arabian J Chem 7(6):1131–1139
74. Elia P, Zach R, Hazan S, Kolusheva S, Porat ZE, Zeiri Y (2014) Green synthesis of gold nanoparticles using plant extracts as reducing agents. Int J Nanomedicine 9:4007
75. Yang X, Li Q, Wang H, Huang J, Lin L, Wang W, Sun D, Su Y, Opiyo JB, Hong L, Wang Y (2010) Green synthesis of palladium nanoparticles using broth of Cinnamomum camphora leaf. J Nanopart Res 12(5):1589–1598
76. Huang L, Weng X, Chen Z, Megharaj M, Naidu R (2014) Green synthesis of iron nanoparticles by various tea extracts: comparative study of the reactivity. Spectrochim Acta A Mol Biomol Spectrosc 130:295–301
77. Fakhari S, Jamzad M, Fard HK (2019) Green synthesis of zinc oxide nanoparticles: a comparison. Green Chem Lett Rev 12(1):19–24
78. Mohanpuria P, Rana NK, Yadav SK (2008) Biosynthesis of nanoparticles: technological concepts and future applications. J Nanopart Res 10:507–517. https://doi.org/10.1007/s11051-007-9275-x
79. Korbekandi H, Iravani S, Abbasi S (2009) Production of nanoparticles using organisms. Crit Rev Biotechnol 29(4):279–306
80. Suvardhan K, Shakeel A (2018) Green metal nanoparticles (synthesis, characterization and their applications). In: Recent ddvances in green nanotechnology and the visionfor the future. https://doi.org/10.1002/9781119418900
81. Sur UK, Ankamwar B, Karmakar S, Halder A, Das P (2018) Green synthesis of Silver nanoparticles using the plant extract of Shikakai and Reetha. Mater Today Proc 5(1):2321–2329
82. Rajeshkumar S (2016) Synthesis of silver nanoparticles using fresh bark of Pongamia pinnata and characterization of its antibacterial activity against gram positive and gram negative pathogens. Resource-Efficient Technol 2(1):30–35
83. Bansod SD, Bawaskar MS, Gade AK, Rai MK (2015) Development of shampoo, soap and ointment formulated by green synthesised silver nanoparticles functionalised with antimicrobial plants oils in veterinary dermatology: treatment and prevention strategies. IET Nanobiotechnol 9(4):165–171
84. Aziz N, Faraz M, Pandey R, Shakir M, Fatma T, Varma A, Barman I, Prasad R (2015) Facile algae-derived route to biogenic silver nanoparticles: synthesis, antibacterial, and photocatalytic properties. Langmuir 31(42):11605–11612
85. Abdel-Aziz MS, Shaheen MS, El-Nekeety AA, Abdel-Wahhab MA (2014) Antioxidant and antibacterial activity of silver nanoparticles biosynthesized using Chenopodium murale leaf extract. J Saudi Chem Soc 18(4):356–363
86. Otari SV, Patil RM, Nadaf NH, Ghosh SJ, Pawar SH (2012) Green biosynthesis of silver nanoparticles from an actinobacteria Rhodococcus sp. Mater Lett 72:92–94
87. Bhainsa KC, D'Souza SF (2006) Extracellular biosynthesis of silver nanoparticles using the fungus Aspergillus fumigatus. Colloids Surf B: Biointerf 47:160–164
88. Ahmad A, Senapati S, Khan MI, Kumar R, Sastry M (2003) Extracellular biosynthesis of monodisperse gold nanoparticles by a novel extremophilic actinomycete, Thermomonospora sp. Langmuir 19:3550–3553
89. Kowshik M, Ashtaputre S, Kharrazi S, Vogel W, Urban J, Kulkarni SK, Paknikar KM (2003) Extracellular synthesis of silver nanoparticles by a silver-tolerant yeast strain MKY3. Nanotechnology 14:95. https://doi.org/10.1088/0957-4484/14/1/321
90. Shankar SS, Ahmad A, Pasrichaa R, Sastry M (2003) Bioreduction of chloroaurate ions by geranium leaves and its endophytic fungus yields gold nanoparticles of different shapes. J Mater Chem 13:1822–1826
91. Armendariz V, Herrera I, Peralta-Videa JR, Jose-Yacaman M, Troiani H, Santiago P, Gardea-Torresdey JL (2004) Size controlled gold nanoparticle formation by Avena sativa biomass: use of plants in nanobiotechnology. J Nanoparticle Res 6:377–382
92. Mukherjee P, Senapati S, Mandal D, Ahmad A, Khan MI, Kumar R, Sastry M (2002) Extracellular synthesis of gold nanoparticles by the fungus Fusarium oxysporum. Chem Bio Chem 3:461–463
93. Husseiny MI, El-Aziz MA, Badr Y, Mahmoud MA (2007) Biosynthesis of gold nanoparticles using Pseudomonas aeruginosa. Spectrochim Acta A: Mol Biomol Spectrosc 67:1003–1006
94. Gericke M, Pinches A (2006) Microbial production of gold nanoparticles. Gold Bull 39:22–28
95. Joshi CG, Danagoudar A, Poyya J, Kudva AK, Dhananjaya BL (2017) Biogenic synthesis of gold nanoparticles by marine endophytic fungus-Cladosporium cladosporioides isolated from seaweed and evaluation of their antioxidant and antimicrobial properties. Process Biochem 63:137–144
96. Yasmin A, Ramesh K, Rajeshkumar S (2014) Optimization and stabilization of gold nanoparticles by using herbal plant extract with microwave heating. Nano Convergence 1(1):12
97. Liu Y, Jin X, Chen Z (2018) The formation of iron nanoparticles by Eucalyptus leaf extract and used to remove Cr (VI). Sci Total Environ 627:470–479
98. Jin X, Liu Y, Tan J, Owens G, Chen Z (2018) Removal of Cr (VI) from aqueous solutions via reduction and absorption by green synthesized iron nanoparticles. J Clean Prod 176:929–936
99. Yong P, Rowsen NA, Farr JPG, Harris IR, Macaskie LE (2002) Bioreduction and biocrystallization of palladium by Desulfovibrio desulfuricans NCIMB 8307. Biotechnol Bioeng 80:369–379
100. Jafarirad S, Mehrabi M, Divband B, Kosari-Nasab M (2016) Biofabrication of zinc oxide nanoparticles using fruit extract of Rosa canina and their toxic potential against bacteria: a mechanistic approach. Mater Sci Eng C 59:296–302
101. Bhuyan T, Mishra K, Khanuja M, Prasad R, Varma A (2015) Biosynthesis of zinc oxide nanoparticles from Azadirachta indica for antibacterial and photocatalytic applications. Mater Sci Semicond Process 32:55–61
102. Salam HA, Sivaraj R, Venckatesh R (2014) Green synthesis and characterization of zinc oxide nanoparticles from Ocimum basilicum L. var. purpurascens Benth.-Lamiaceae leaf extract. Mater Lett 131:16–18
103. Nagarajan S, Kuppusamy KA (2013) Extracellular synthesis of zinc oxide nanoparticle using seaweeds of gulf of Mannar. India J Nanobiotechnol 11(1):39
104. Patil BN, Taranath TC (2016) Limonia acidissima L. leaf mediated synthesis of zinc oxide nanoparticles: a potent tool against Mycobacterium tuberculosis. Int J Mycobact 5(2):197–204