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Review Article

Comprehensive Review of Nanotechnology: Innovations and Multidisciplinary Applications

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ABSTRACT

Nanotechnology, which involves the control of substances at the nanoscale, has emerged as a valuable discipline that holds the capacity to fundamentally transform numerous scientific sectors, such as materials science, healthcare, environmental remediation, and agriculture. This review article explores the uses and advancements of nanotechnology, emphasizing how it might improve crop yield, advance medical treatments, and provide solutions to environmental problems. This also examines revolutionary applications of nanobiotechnology, including CRISPR/Cas9 genome editing, targeted drug delivery systems, cancer therapy, and regenerative medicine. It highlights the potential of these technologies to enhance diagnostic capabilities and pharmaceutical results. It also looks at how nanotechnology is affecting agriculture, with a focus on improvements in food safety, pest and disease control, and crop yield. Additionally, environmental applications are covered, with an emphasis on the use of nanomaterials for sustainable resource management and pollution remediation. The significance of nanotechnology's contributions to green chemistry, its interdisciplinary character, and the challenges and potential for its incorporation into conventional applications are all emphasized in the review. The article provides an overview of the current status and future directions of nanotechnology by discussing the synthesis of nanoparticles, their commercialization, and the challenges surrounding nano-innovations.

INTRODUCTION

Matter forms the basis of everything. As one cinder block lays the formation of a building, atoms form the basis of matter. Atoms that are arranged in a particular pattern make manufactured products. For instance, a diamond is obtained by putting together coal atoms. Similarly, chips can be manufactured by arranging sand atoms in a specific pattern. The manipulation of matter at the atomic level to produce products with the help of technology is nano-technology. Whereas, the smallest scale at which research or manipulation is being conducted is called the nanoscale, which ranges from 1 to 100 nanometers [1]. Over the past few decades, nanotechnology has contributed to multiple domains of science and technology. The prefix 'nano' comes from a Greek word which means 'dwarf' or something smaller and its value is one thousand millionth of a meter (10–9 m). It is observed under 100 nm of dimensions due to the laws of quantum physics. 'Nano' in nanotechnology is a unit that represents the one-billionth part of one meter. In the early 2000s, this field became a center for public attention; since then, nanotechnology has made breakthrough inventions and contributed to multiple disciplines of science and technology. Today, nanotechnology assists scientists in researching biological processes such as multimodal bioimaging, blood coagulation control, or detecting biology in vivo and in vitro. It also plays a significant role in the revolution of the fourth

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industry. This field has been evolving over the past half while actively participating in various areas such as pharmaceuticals, materials, etc. All inventions are due to nanotechnology's synergistic ability to rearrange material and control physical structures [2]. Semiconductors, coatings, nanowires, and thin films are the top commercialized products of nanotechnology already present in markets. In medicine, micron-sized nanostructured microspheres are readily brought into the cytosol that carries nanosized cargo to the desired position. Nanotechnology is not a recent concept – many examples of nanotechnology can be observed within nature such as the molecules in the human body that have specific nano-dimensions and size, further in the food components. Nanoscale structures have been involved in various technologies for many years, but the modifications of these structures were not possible in those years, it has only been possible in the last quarter century that intentional modification and control of molecules can be performed. This control and modification at the nanoscale set nanotechnology apart from other technologies.

DOMAINS OF NANOTECHNOLOGY

In various scientific disciplines, nanotechnology, a relatively new technology branch, has become a practical and applicable discipline. Due to its effectiveness, it has successfully grasped the attention of scientists and researchers to solve various environmental, health, food, and natural resources management problems [2]. The transformation of various domains of science due to the rapid development and scope of nanotechnology has changed the whole perception of scientists for different states of matter. The field of nanotechnology is very comprehensive and has extensive applications. Therefore, this interdisciplinary science is divided into multiple domains and subdomains for ease and thorough studies. Plant nanotechnology (green nanotechnology), medical or nanobiotechnology, environmental nanotechnology, and food nanotechnology are important domains.

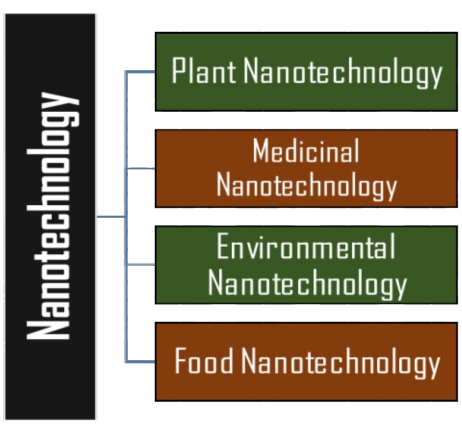

Figure 1: Nanotechnology Domains

PLANT NANOTECHNOLOGY

The synthesis of nanoparticles or nanomaterials (NMs) is considered a versatile tool that promotes the working and application of nanotechnology in various disciplines, especially in botany and plant-related disciplines. Because of drawbacks of chemical or physical methods like poor control of size, the difference in morphology of substances, use of toxin materials, and substandard size distribution, the use of nanoparticles has leverage over the traditional methods[3]. Nanotechnology also has excellent advantages in forest management, high-quality crop production, genetically engineered plants, and plant biotransformation, which are discussed in the following paragraphs.

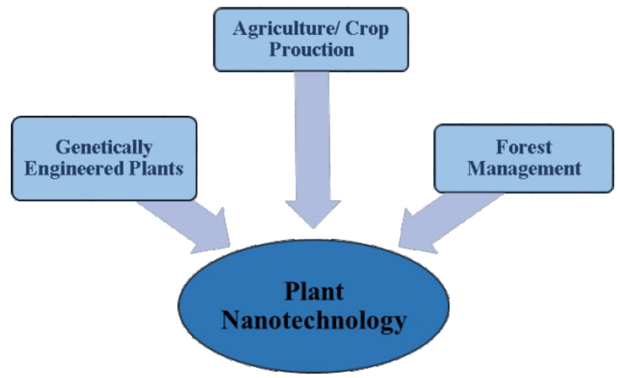

Figure 2: Different Domains of Plant Nanotechnology

Agriculture Nanotechnology & Forest Management

Agriculture nanotechnology should be a concern, particularly for developing countries, as it can effectively manage food supply and decrease the mortality rate in children and underfeeding. The impacts of nanotechnology can also be observed in agroecosystems, climate change, management of forests, and industrial sectors. The awareness of nanotechnology is beneficial for the nanomaterial synthesis for forest management, for the solution of climate change issues, environmental risks like salinity, invasion, fire, drought, attack of pathogens and flood, etc. NMs are used to improve forest production, forest-based paper industry, increase energy efficiency, manage water resources, and other potential domains of forests[4].

Application In High-Quality Crop Production

The use of nanotechnology also enhances crop production by increasing agriculture input efficiency by ensuring minimal use of Agri inputs. It can facilitate site-targeted controlled nutrient delivery. In recent years, green nanoparticles (NPs) have drawn the attention of scientists because of their simple production process of crops compared to other different routes, their eco-friendly nature, and their yield in a relatively short period. Plant species like bacteria, fungi, and algae are used for this

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purpose [5]. For example, *Brassica juncea* (mustard greens), *Medicago sativa* (alfalfa), and *Helianthus annuus* (sunflower) are some live plants used to produce inorganic nanoparticles such as silver, cobalt, zinc, and nickel.

Genetically Engineered Plants

The biochemical changes in plants due to novel technologies and effective techniques are known as the biotransformation of plants. The genetic engineering of plants has strengthened the plant potential against biotic and abiotic stresses that could be the cause of food security and crop health. The recent developments in genetic engineering and the discovery of CRISPR (clustered regularly interspaced short palindromic repeats) or Cas (CRISPR-associated protein) genome editing of crops are a few important to note[6]. Despite the notable progress of genome editing and its revolutionary nature, many critical challenges of the CRISPR-Cas technique have been addressed by nanoparticles (especially green NPs). These problems are sought out by improvements in the cargo delivery process, gene editing efficiency, germline transformation, species independence, etc. The liposomes are commonly used for efficient delivery due to their tunable structure. The liposomes are first prepared (giving them a positive charge) so they can easily encapsulate negatively charged RNA molecules/ gene of interest. Then the mixture is prepared (liposome + RNA molecule). The liposome facilitates the entry of this mixture into the cell. When they reach the cell, liposomes release the RNA molecule (CRISPR component) to let the gene editing process complete[7].

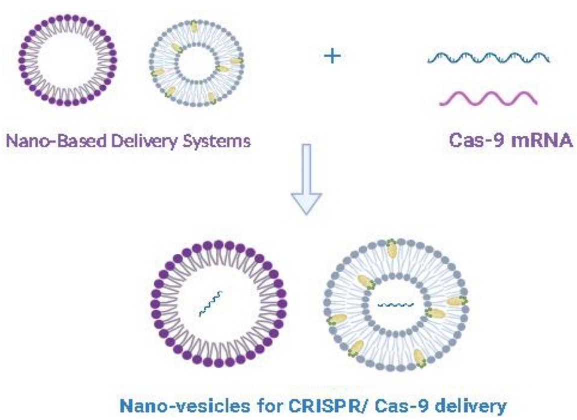

Figure 3: Nanotechnology-Based CRISPR/Cas9 System Delivery for Genome Editing.

MEDICINAL NANOTECHNOLOGY – CLINICAL ASPECTS OF NANOTECHNOLOGY

While nanotechnology embodies other areas of science, the field of modern medicine can significantly benefit from its applications. Its impact can create new developments in the prevention, diagnosis, and treatment of various diseases[8]. The following paragraphs will shed light on the medicinal applications of nanotechnology, the production of biomedicines, virus detection, tracking infection mechanisms, drug delivery systems, the discovery of nano-knife and immunoprophylaxis.

Cancer Therapy

Even with the recent medical developments, researchers could not find a complete cure for cancer. Therefore, it has become a priority for scientists to develop new anticancer treatments. Using nanomaterials is one of the futuristic approaches to enhancing cancer therapy and increasing the efficiency of drugs while reducing the side effects. It is introduced with minimum side effects, such as nano shells that are currently under testing. These nanoparticles are gold-coated and can penetrate deep inside the tumor tissues. Similarly, CRISPR/Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats-associated protein 9), which is also associated with nanotechnology, is used to treat and diagnose cancer. It is effective for cancer therapy[9].

Regenerative Medicine

Scientists have been working on repairing and regenerating damaged cells for a while. Nevertheless, in recent years advancements in nanotechnology have accelerated the possibility of regenerative medicines. Studies have shown more excellent effects of nanomaterials on cells and tissues of bone, the nervous system, skin, and cardiac muscles. Carbon nanotubes (CNTs) have proven to be effective in repairing damaged tissues, particularly those needing electrical impulses. Another innovation is CNTs combined with glass fiber (CNT-PGFs), which is proven effective in prompting the active regeneration of damaged nerves. CNTs also have the feature to transport protein across the cell membrane for a better natural response [10]. Simultaneously, they also have the characteristic to thoroughly react with water solutions, potentially used in treating various diseases. In short, CNTs provide a promising strategy for regenerating nerve cells and biology developments.

Nano-Knifes

For the past few years, nano-knife has been used for treating or removing damaged cells from the body. In this method, tumor cells are exposed to an electrical current with a voltage of up to 3000V, lasting for a micro-unit of a second. It allows the electrical current to penetrate and destroy damaging cells, which leads to the prevention of electrical signals that are responsible for irregular heartbeats. Nano-knife replaces the traditional method in which cells were subjected to small burns or freezes of longer duration and had adverse thermal effects.

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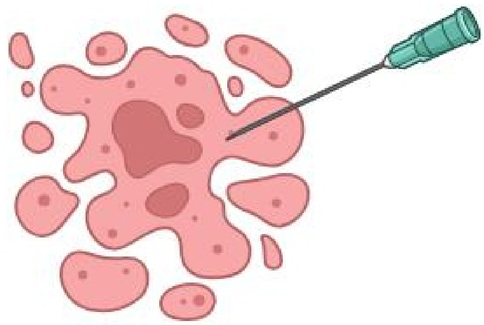

Figure 4: Nano-Knife Tissue Ablation System –Now FDA Approved to Start Clinical Trials through Nanoknife. Source: Geodynamics

The nano-knife technique has also allowed the treatment of neoplasms (abnormal cells) at locations where ablation was nearly impossible[11]. The subjugated tissues' material remains intact, increasing the possibility of much better regeneration. So far, the nano-knife technique has been used to treat cells of kidneys, lungs, and liver, while some organs are under trial.

Immunoprophylaxis

Vaccines have always been a matter of priority for scientists because they treat diseases before their anticipation and can potentially eradicate certain illnesses. Nanomaterials, however, possess smart delivery systems that could greatly benefit immunology[9]. Because of their nano nature, they can quickly enter into the antigen-presenting cells to regulate immune systems. Like nanomedicines, it would not be wrong to call nano-vaccines possessing nanomaterials. Nanomaterials with nanoparticles, such as poly-D and copolymers can transport antigens to dendritic cells more efficiently. Studies have shown that dendritic cells are the integral constituent of the immune system; therefore, they need efficient delivery of antigens. Nanoparticles offer room for the vaccine antigen to be quickly delivered to the cells and provoke an immune response.

Application in Diagnosis

Nanotech advances disease diagnosis, imaging, early detection, and prognosis. Biomedical imaging and tissue-specific diagnosis are enhanced due to the biophysical properties of nanoparticles that enable contrast enhancement to perform this procedure. Moreover, there is a unique possibility of nanoparticles to multiplex results from the change of optical, electrical, and magnetic properties due to changes in size, shape, and composition variation. Medical resonance imaging (MRI), computed tomography (CT scan), optimal imaging agents, and up conversion luminescent imaging are some examples of nanotechnology. The concept of nanotechnology has revolutionized oncology like diagnosis and treatment of gastrointestinal cancer and various other medical fields [10]. The association of nanoparticles and chemotherapeutic medicinal agents improves the stability of anti-tumor agents, improves their solubility, protects against drug degradation, and reduces toxicity. The use of nanoparticles also enhances the drug level in infected cells and tissues and decreases it in healthy cells and tissues. Nanotechnology is also used in the detection of extracellular cells via cancer biomarkers. They act as measurable biological molecules that indicate the existence of cancer in the body. They are found in blood and other fluids of the body like urine and saliva etc. Nano sensors are also proven to be compatible for in-vivo and in-situ examination because of their extremely low size[12].

Table 1. Clinical Aspects of Nanotechnology

1	**Cancer Therapy**	Anticancer treatment with minimum side effects Nano shells
2	**Regenerative Medicines**	CNT-PGFs for repairing damaged cells Transport essential proteins
3	**Nano-Knife**	Use electric current of 3000V Repairing cell damage Prevent irregular heartbeats
4	**Immunoprophylaxis**	Regulation of the immune system Transport antigens to dendritic cells
5	**In Diagnosis**	Powerful and innovative analytical biosensors advances in disease diagnosis, imaging, early detection, and prognosis

ENVIRONMENTAL NANOTECHNOLOGY

In this modern era, every developed country or state is concerned about the environment and undoubtedly, environmental pollution has become the greatest threat that the world faces today. For the remediation of contaminants, new technologies have been explored constantly and nanotechnology is one of them. Particulate and heavy metals, pesticides, insecticides, oil spills, sewage, toxic gasses, fertilizers, herbicides, organic compounds and industrial effluents are some major contaminants which are desired to be removed from the environment. Because of the low reactivity, high volatility and complexity of different mixtures, degradation and remediation of environmental threats can be challenging [13]. In past decades, nanomaterials have gained intentions for new remediation technologies development. They are considered to be used because of their unique physical properties, better effectiveness, high surface-to-volume ratio and enhanced reactivity as compared to other bulkier counterparts. They have a special chemistry that has the potential to target specific molecules which are pollutants and have to be removed for efficient remediation. The materials that are used should be biodegradable so they can be easily handled and there is less production of waste after the whole procedure. Green chemistry, recyclability, facile synthesis, target specific, regeneration (potential for recovery after use),

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biodegradability, and non-toxicity are some of the reasons that nanomaterials are used widely for environmental remediations and control. Here is the general overview of some nanomaterials used for efficient cleaning of the environment.

Inorganic Nanomaterials

Different inorganic nanomaterials like metal or metal oxides are preferred for remediation because of their high absorption capacity and fast kinetics. They are highly flexible in aqueous solutions in both in or ex-situ conditions. For instance, silver NPs or ions act as water disinfectants. They are commonly known as antibacterial, antifungal and antiviral agents that can detoxify certain harmful microorganisms like E. coli and Pseudomonas aeruginosa when their diameter of 10 nm is used. They also prevent the viruses from binding into the host cell thus protecting from viral infections [14]. Another most investigated nanomaterial from environmental protection is titanium oxide (TiO_2). They have the property of activation by the stimulus of light. So considered effective for the removal of organic contaminants from various mediums. They produced highly reactive hydroxyl oxidants that are disinfectant to bacterial, fungal and viral attacks. Titanium oxide has photocatalytic ability in which these can doped with other transition metals or metal oxides to enhance performance.

Table 2. Hoshyar and Coworkers Experimentally Determined the Efficiency and Sonication Time of Inorganic Nanomaterials for Metal Remediation

Sr No.	Inorganic Type	Metal to be Removed	Efficiency	Sonication Time
1.	Iron Nanomaterials	Copper	59%	30min
2.	Iron Nanomaterials	Nickel	38%	20min

Iron-based nanomaterials remove heavy metals and chlorinated solvents from water. It exhibits a core-shell structure that consists of zerovalent iron i.e., FeO. These core shells facilitate the remediation of heavy metals that have higher value of standard reduction potentials.

Carbon-Based Nano-Materials

The structural properties and mutable hybridization state make carbon-based nanomaterials different from other metal or nonmetal-based materials. Fullerenes (C60), graphene and carbon nanotubes whether single-wall or multi-walled are some examples of different hybridization states of carbon. The absorption properties of porous carbon nanomaterials make them useful for organic or inorganic contaminants remediation from large aqueous mediums. The mechanisms of working of carbon-based nanoparticles depend on the photons generated by UV radiations. The photons produce valence band holes and conduction holes (e^-) that lead to the formation of hydroxyl radicals useful for the removal of chlorinated organic compounds [15]. The activity and conductivity rate of TiO_2 increases when mixed with graphene as compared to bare TiO_2 nanoparticles. Moreover, graphene composites of ZnO and CdS have great photocatalytic rates toward water contaminants. It is reported that within 20 minutes, a 5% addition ratio of graphene can promote a 100 pc $Cr6^+$ reduction in water.

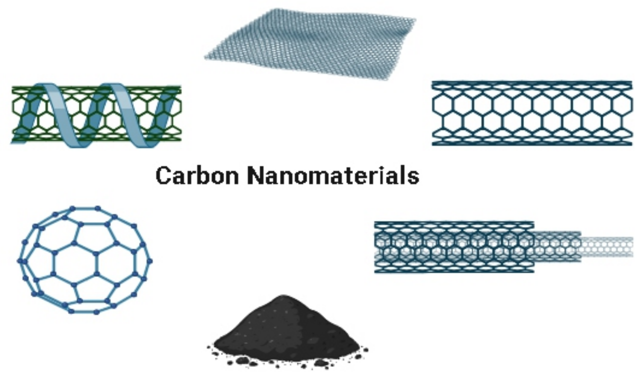

Figure 5: Different Types of Carbon Nanomaterial

Polymer-Based Nanomaterials

Polymer-based nanomaterials are employed to enhance performance and desirable properties like strength, activity rate etc. They are also used to overcome and minimize some of the nanoparticle imitations. For example, amphiphilic polyurethane nanoparticles (APU NPs) have been employed for the remediation of aromatic hydrocarbons from the soil. They not only promote the mobility of soil but hydrophobic interior confers greater affinity for organic contaminants. They remove phenanthrene from the soil to the extent of 80% recovery [16]. Similarly, amidoamine or PAMAM (dendrimers) are utilized in wastewater management, especially for the remediation of metal ions. They are like chelating agents that bind with ions like Cu, Ag, Au, Fe, Ni etc. and facilitate water purification. They are also antibacterial or antifungal agents used to target specific VOCs.

FOOD NANOTECHNOLOGY

The applications of nanotechnology are growing tremendously in numerous sectors including food systems due to their unique properties of self-assembled and high-order structures. Small three-dimensional structures of nanomaterials are used for the preparation of custard-like food by boiling cornstarch, which ranges from tens and multiples of tens nanometers in size. Similarly, milk proteins like globules and casein also contain nanoparticles present in dairy products.

Nanotechnology in Food Packaging

In the process of food packaging, atmospheric gasses, water vapors and other compounds are impermeable but complete immigration of these substances is also not good in fresh vegetables and fruit packaging that undergo the

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respiration process. For the prevention of decarbonization and flow of oxygen in carbonated beverage packaging, nanocomposite materials and polymers have been used in recent years [17]. Nanomaterials are a thousand times thinner than book pages of about 100,000 nm thickness and approximately a hundred times thinner than about 10,000 nm human hair thickness. They are magnificent for the research programs especially those that are associated with food science.

Nanotechnology in Food Safety & Functionality

Nanoparticles play a very important role in the protection of food that is decaying, mainly because of various unwanted chemical reactions between the food matrices and external surroundings. Researchers suggest that there are some metal and metal oxide nanomaterials which can cause nano-toxicity, which leads to the formation of ROS and inadequate redox state in cells. Moreover, polymeric nanoparticles are responsible for encapsulation and release of bioactive compounds (such as vitamins) in acidic environments (like Stomach) [18]. The antioxidants mainly control the browning process however; some nanoparticles may also be used as anti-browning agents such as Nano-ZnO. Nanotechnology can also increase the functionality of food in two ways: either by removing chemicals and toxicants or by increasing nano-sized supplements in food items. For example, green tea has Nano-selenium contents in it which is responsible for the effective uptake of selenium in the body which is very beneficial for health. Nano-sized SiO2 is frequently used in food products and declared as a food additive by the EU [18]. Recent developments in nanotechnology have revolutionized the food enterprise with its numerous packages in meal processing, protection, and security, in addition to its strides in improving nutraceutical value, extending shelf-life, and decreasing packaging waste. Nanomaterials, consisting of metal nanoparticles, quantum dots, carbon nanotubes and different energetic nanomaterials may be used to increase biosensors for the quantification of microbes and different checks for food safety applications [19].

CHALLENGES AND RECOMMENDATIONS

It can easily be estimated the nanotechnological roles in the modern world in almost all fields, especially in medicine, zoology, botany, management, and computers. The world has witnessed remarkable technological progress, and certainly, there must be space for more work. Improvements can be made to increase accessibility for people and the world super-fast. Instead of downscaling micro techniques into the nanometer range, the opposite development gives a more optimistic view [20]. For example, perovskite quantum dots, the area of photovoltaics, seems more promising, but this area needs more research as it has instability. Pauling and his coworkers gave us hope for constructing complex molecular machinery and functional systems by artificially producing ultimate modules. Strategies that apply to controlled molecular self-assembly and supramolecular chemistry are the main areas for gaining the concept of molecular machines [21]. These ideas would be very beneficial for future innovations and inventions. Lastly, it emphasizes that some vagueness in the bottom-up nanotechnological manufacturing concept is inevitable, and the standard is not yet achieved.

CONCLUSIONS

Nanotechnology covers a wide range of sciences and industries – earth sciences directly concerned with environmental and climate effects, organic chemistry, molecular biology and engineering, and semiconductor and energy storage physics. On the cutting edge, researchers have developed self-assembling devices and manipulated matter down to the atomic scale. Nanomedicine, nanoelectronics, biotech, nano energy production, advanced nanomaterials, and consumer products are on the horizon.

Authors Contribution

Conceptualization: WR, AM
Writing-review and editing: MA, WR

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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