International Journal of Chemistry Research

Online ISSN- 0976-5689 Vol 10, Issue 1, 2026

Review Article

LECTIN NANOPARTICLES IN FOCUS: FROM FUNDAMENTALS TO FUTURE NANOTECHNOLOGIES-A REVIEW

FAKEHA MOHAMMED REHAN SHAIKH, ASHISH SAMBHAJI UZGARE*

Department of Chemistry, Wilson College (Autonomous), Chowpatty Seaface Road, Mumbai-400007, Maharashtra, India
*Corresponding author: Ashish Sambhaji Uzgare; *Email: ashish.uzgare@wilsoncollege.edu

Received: 19 Aug 2025 Revised and Accepted: 09 Dec 2025

ABSTRACT

Nanotechnology, operating at the scale of 1–100 nanometers, is an interdisciplinary field driving innovations across medicine, agriculture, environmental science, and food technology. By enabling control at the atomic and molecular levels, it facilitates the development of novel materials and devices with enhanced properties. In agriculture, nanomaterials improve nutrient efficiency, pest control, and crop monitoring. In the food industry, they enhance shelf life, safety, and nutritional delivery. In medicine, nanotechnology has advanced applications in diagnostics, targeted drug delivery, and cancer therapies. A notable development is the use of lectin-functionalized nanoparticles, which leverage specific carbohydrate-binding properties for precise drug targeting and disease detection. Despite these benefits, concerns remain regarding environmental impact, nanoparticle toxicity, and insufficient regulation. The production of nanomaterials often involves energy-intensive and chemically hazardous processes, and their long-term effects on health and ecosystems are still unclear. This review highlights the classification, origin, and applications of nanomaterials, with emphasis on the emerging role of lectin-functionalized nanoparticles in targeted therapeutics. It underscores the importance of advancing nanotechnology responsibly, promoting innovation to ensure sustainable development.

Keywords: Lectin, Nanotechnology, Functionalized nanoparticle, Therapeutics

DOI: http://dx.doi.org/10.22159/ijcr.2026v10i1.303 Journal homepage: https://ijcr.info/index.php/journal

INTRODUCTION

Nanoscience focuses on exploring the distinctive properties of materials within the 1–100 nanometer range, while nanotechnology involves applying this knowledge to design or engineer new materials and devices. By enabling control at the atomic and molecular levels, it becomes possible to develop innovative nanomaterials [1]. Nanotechnology has been a recognized area of research since the last century, initially introduced by Nobel laureate Richard P. Feynman in his landmark 1959 lecture titled 'There's Plenty of Room at the Bottom [2]. Nanotechnology involves working with materials at the scale of nanometers, one-billionth of a meter, and includes a variety of technologies with practical uses across many fields [3]. Nanotechnology-enabled products are used across diverse sectors, including transportation, energy, electronics, agriculture, environmental science, and consumer goods. Nanotech products can be classified as nanomaterials (e. g., nanoparticles, nanocomposites, nanotubes), nanotools (e. g., instruments with nanoscale components like scanning probe microscopes), and nanodevices (e. g., nanosensors) [4]. This rapidly advancing field is playing a crucial role in driving innovations in medical science, particularly in areas like nanomedicine. It enables the exploration of biological processes at a scale and precision that were previously unattainable. Applications of nanotechnology in medicine include the creation of nanoparticles for diagnostics and early disease detection (such as cancer), the engineering of artificial cellular components like receptors, and advancements in DNA and protein sequencing through techniques like nanopores and nanosprays. Additionally, it supports the development of novel drug and nutrient delivery systems, as well as emerging approaches in gene therapy and tissue engineering [5, 6]. Among emerging nanomedicine platforms, lectin-functionalized nanoparticles have gained attention for their ability to selectively bind carbohydrate residues on cell surfaces, offering promising potential for targeted drug delivery, cancer diagnostics, and pathogen detection [7]. Lectins are proteins that selectively bind to specific carbohydrates on cell surfaces, exhibiting high molecular specificity. This targeted interaction is essential for key biological processes such as cell recognition, communication, and adhesion, facilitating accurate molecular signaling and physiological functions [8, 9]. Integrating lectins with nanotechnology has advanced targeted therapies by enabling nanoparticles to recognize specific glycan patterns on cells, enhancing precision in drug delivery and diagnostics [7].

This review aims to explore the recent advancements in nanotechnology, with a special emphasis on the emerging role of lectin-functionalized nanoparticles in drug delivery. Inspired by the author's ongoing research on lectins, the paper focuses on their potential as targeted delivery agents and their integration with nanoscale systems to improve the precision and effectiveness of future therapeutic strategies.

Data were gathered from various online scientific literature sources, including databases such as Google Scholar, Research gate, Web of Science, Scopus, and Science Direct. The review covers the details from 2004 to 2025. A total of 81 articles were reviewed.

Method of preparation of nanomaterials

Top-down approach

In top-down approaches, bulk materials are broken down to produce nanostructured materials. From a granular perspective, top-down methods involve manipulating larger particles, atoms, or molecules to form nanostructures through controlled disintegration or patterning. Techniques used include mechanical milling, nanolithography, laser ablation, sputtering, and pulsed electrochemical etching. This approach focuses on constructing nanostructures by breaking down or sculpting materials from larger-scale entities toward the nanoscale [10, 11]. Method of preparation of Top down and Bottom-up Approach Mentioned in fig. 1, 2 and 3 indicate types of top down and Bottom-up Approach.

Bottom-up approach

This approach focuses on fragmenting bulk materials to form targeted nanostructures. Various methods are employed, including sol-gel processes, chemical vapor deposition (CVD), template-assisted synthesis, plasma or flame spraying, and atomic or molecular condensation. Biosynthesis using natural agents such as bacteria, plant extracts, fungi, yeasts, and algae is also a widely used technique [10].

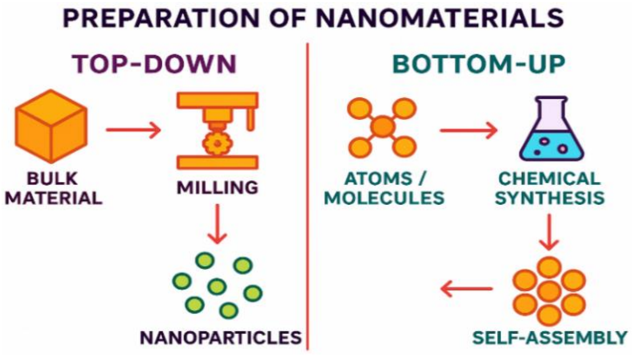

Fig. 1: Method of preparation of nanomaterials

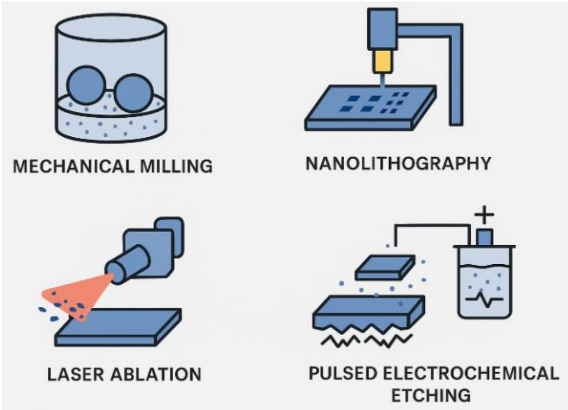

Fig. 2: Types of top-down approach

Mechanical milling

Mechanical milling is a high-energy impact technique that utilizes balls inside containers and is commonly conducted using planetary or shaker mills. It serves as an efficient method for reducing bulk materials to the nanoscale. This process can produce a variety of advanced materials, such as oxide-and carbide-reinforced aluminum alloys, wear-resistant spray coatings, and nanoalloys made from aluminum, nickel, magnesium, and copper. Additionally, a special category of nanoparticles known as ball-milled carbon nanomaterials shows great potential in areas like energy storage, energy conversion, and environmental remediation [12, 13].

Nanolithography

Nanolithography refers to the technique of forming or transferring nanoscale patterns onto a surface or substrate. It focuses on the use and manipulation of nanometer-sized particles, typically around 1 nm, through processes involved in nanofabrication and patterning at the nanoscale [14].

Laser ablation

Laser ablation is a highly efficient and eco-friendly nanofabrication technique known for its low cost, stability, and reliable quality. It is widely used to synthesize nanomaterials with enhanced chemical, optical, magnetic, and electronic properties. Various laser-based methods, such as ablation, vaporization, PLD, and LCVD, enable precise control over the size, shape, and properties of nanoscale materials across different conditions [15].

Sputtering

Sputtering is a technique where high-energy plasma or gas particles strike a solid surface, causing the ejection of microparticles from the material. During this process, energetic gaseous ions collide with the target, physically removing small atom clusters depending on the ions' energy. This method is notable for being more economical than electron-beam lithography and for producing nanomaterials that retain the target's composition with low levels of impurities [13].

Pulsed electrochemical etching

This is one of the most common methods for synthesizing metal nanoparticles. A pulsed current is applied to a metal wire, causing it to evaporate and generate a metal vapor, which then cools in the presence of an ambient gas to form nanoparticles. This approach enables rapid and efficient production of large quantities of nanoparticles [13].

Sol-gel processes

The sol-gel method is a wet chemical technique used to synthesize nanostructures, especially metal oxide nanoparticles. It involves dissolving a metal precursor (like metal alkoxide) in water or alcohol, followed by hydrolysis or alcoholysis to form a gel. The gel is then dried, often by burning alcohol and calcined to obtain nanopowders. This cost-effective method allows precise control over chemical composition at low temperatures and is useful in ceramics fabrication and metal oxide thin film applications [16].

Fig. 3: Types of bottom-up approach

Chemical vapor deposition (CVD)

Chemical Vapor Deposition (CVD) is a technique that deposits a thin film on a substrate through reactions of vapor-phase precursors. Ideal precursors are volatile, pure, stable, safe, affordable, and leave no residue. Variants of CVD include vapor phase epitaxy, metal-organic CVD, atomic layer epitaxy, and plasma-enhanced CVD. CVD is known for producing high-quality, uniform, and durable nanomaterials, including two-dimensional nanoparticles [13].

Template-assisted synthesis

Template-assisted electrodeposition is an effective technique for synthesizing metallic nanomaterials with controlled size, shape, and structure. It involves using either active or restrictive templates as the cathode in an electrochemical setup. The template type significantly influences the physical and chemical properties of the resulting nanomaterials. Fabrication can be achieved through chemical reactions or physical methods like surface coating or channel replication. Templates are removed using techniques such as calcination or chemical dissolution. Depending on the template used, the method is categorized into hard and soft template approaches, enabling precise control over nanomaterial morphology [17, 18].

Plasma spraying

Conventional plasma spraying is a well-developed technique used to synthesize nanoparticles and coatings of materials like alumina, zirconia, and yttria-stabilized zirconia by processing atomized liquid precursor droplets. In this method, a high-temperature plasma jet melts and sprays the feed material into the flame. It is primarily used to apply protective or performance-enhancing coatings. The plasma flame, serving as the working medium, is characterized by extremely high temperatures, high enthalpy, fast heating and cooling rates, high velocity, and a reactive environment [19].

Biosynthesis

Biomimetic synthesis involves chemical processes that imitate the natural methods used by living organisms to produce materials. This approach utilizes biological components such as proteins, enzymes, cells, viruses, pollen, or biomass to create nanoparticles. It is generally classified into two types: functional biomimetic synthesis, which mimics specific properties or features of natural materials and systems, and process biomimetic synthesis, which replicates natural pathways to form various nanostructures. This method has enabled the *in vitro* assembly of complex nanostructures like dendrimer-like forms, pyramids, cubes, 2D nanoparticle arrays, and 3D gold nanoparticle tubes [13].

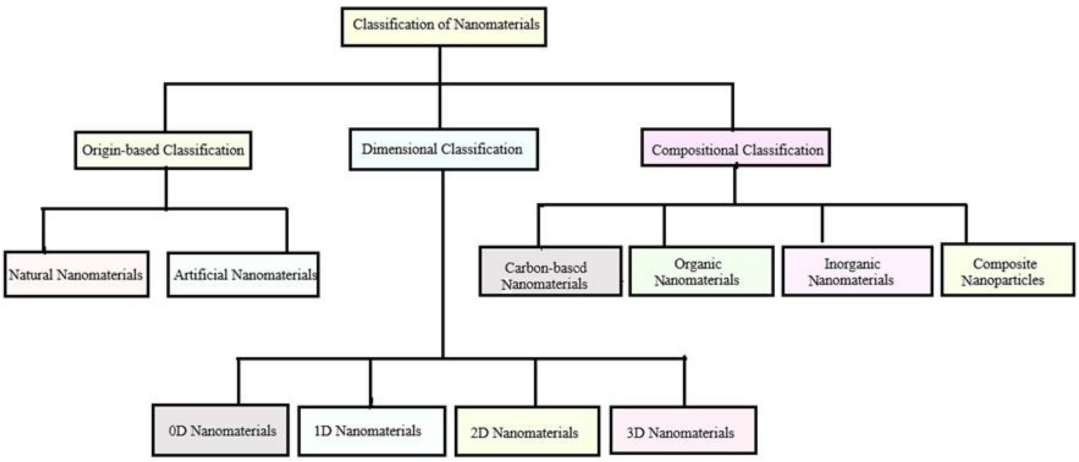

Fig. 4: Schematic diagram: classification of nanomaterials

Classification of nanomaterials

Nanomaterials are fundamental to nanotechnology and are defined as substances with at least one dimension measuring less than 100 nanometers [20]. Classification of nanomaterials mentioned in fig. 4.

Origin-based classification of nanomaterials: natural and artificial

Nanomaterials can be classified based on their origin into two categories: natural and synthetic (artificial) nanoparticles [21, 22]. Some example of Natural and Artificial nanomaterials mentioned in fig. 5 and 6.

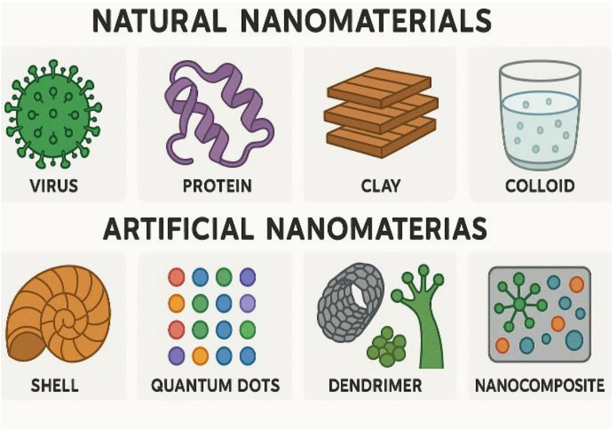

Fig. 5: Some example of natural and artificial nanomaterials

Natural nanomaterials are found widely in nature in various forms. These include biological structures like viruses, proteins, and mineral-based materials such as clay. Natural colloids like milk, blood, fog, and gelatin also exhibit nanoscale features. Other examples include mineralized tissues (e. g., shells, corals, bones), and surfaces like insect wings, lotus leaves, gecko feet, spider silk, as well as environmental sources like volcanic ash and ocean spray [21, 22].

Artificial nanomaterials are synthetically produced through controlled physical, chemical, or mechanical processes to achieve desired nanoscale properties. Common examples include quantum dots and carbon nanotubes, which are widely used in electronics, medicine, and materials science. These nanomaterials are typically categorized into metal-based, dendrimer-based, and composite materials based on their structural characteristics and functional applications [21, 22].

Dimensional classification of nanomaterials: 0D to 3D structures

Zero-dimensional (0-D) nanomaterials are characterized by having all three dimensions within the nanoscale range. Common examples include quantum dots, fullerenes, and nanoparticles [23].

One-dimensional (1D) nanomaterials have two dimensions in the nanoscale and one extended dimension (>10 nm). Examples include nanorods, nanotubes, and nanowires, which may be metallic, ceramic, or polymeric. They can be crystalline or amorphous, pure or composite, and exist independently or within other materials [24].

Two-dimensional (2D) nanomaterials have one dimension within the nanoscale range, while the other two extend beyond it. Common examples include nanosheets, nanofilms, and nanolayers [22, 23].

Three-dimensional (3D) nanomaterials, also known as bulk nanomaterials, are not limited to the nanoscale in any dimension. This category includes bulk powders, nanoparticle dispersions, and structured arrays of nanowires or nanotubes [23].

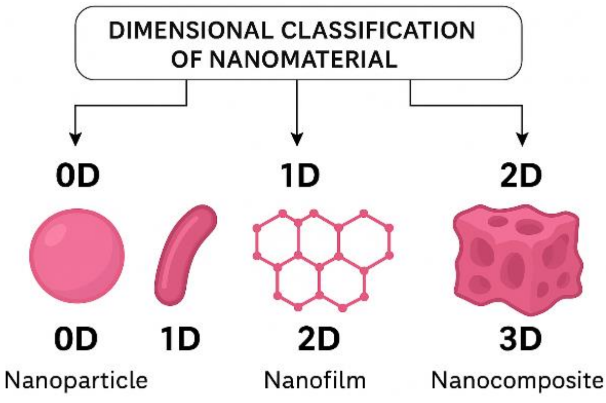

Fig. 6: Some example of dimensional nanomaterials

Structural and compositional types of nanomaterials

Nanomaterials can be classified as follows: Structural and compositional types of nanomaterials indicates in fig. 7.

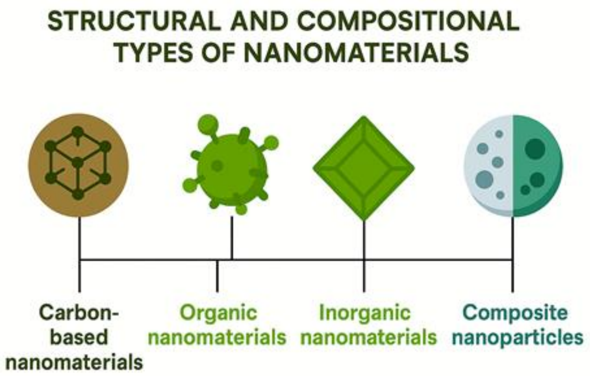

Fig. 7: Structural and compositional types of nanomaterials

Carbon-based nanomaterials

Carbon-based nanomaterials such as fullerenes, carbon nanotubes, graphene derivatives, nanodiamonds, and carbon quantum dots are valued for their unique structures and excellent mechanical, electrical, and optical properties. Their biocompatibility and ease of functionalization make them promising for biomedical uses, especially in imaging and drug delivery. Their broad one-photon absorption and intrinsic two-photon fluorescence in the near-infrared II region enable deep-tissue imaging, making them strong candidates for tumor diagnosis and therapeutic applications [24].

Organic nanomaterials

Organic nanoparticles, composed of materials like proteins, lipids, or polymers, are typically biodegradable, non-toxic, and often used in biomedical applications. Examples include dendrimers, liposomes, and micelles, which may have hollow cores and are sensitive to heat and light. Their composition, stability, and surface features influence their use in targeted drug delivery and cancer therapy [23, 25].

Inorganic nanomaterials

Inorganic nanoparticles, which lack carbon content, are known for their hydrophilicity, non-toxicity, and biocompatibility with biological systems. They also exhibit greater stability compared to their organic counterparts [26].

Composite nanoparticles

Composite nanoparticles are nanomaterials composed of two or more nanoscale components, combined to exhibit unique physical and chemical properties not found in the individual constituents [27]. Nanocomposites are generally categorized into four main types [28]. The first type is ceramic-matrix nanocomposites, which combine metals with compounds such as nitrides, borides, or silicides [28]. The second category is metal-matrix nanocomposites, which often feature carbon nanotubes embedded within a metal matrix [27, 28]. The third type, polymer-matrix nanocomposites, uses polymers as the primary matrix material [28]. Finally, magnetic nanocomposites possess magnetic properties due to the incorporation of magnetic components [28]. Nanotechnology Meets Lectinology*:* The Role of Lectins in Nano-Applications.

Lectinology focuses on the study of lectins, a group of proteins or glycoproteins that interact specifically and reversibly with carbohydrates [29]. Lectins are a varied class of proteins involved in critical biological functions like cell signaling, adhesion, and recognition. They have gained significant attention in glycoscience, as well as in biotechnological and pharmaceutical applications [30]. Lectins are well-suited as cytoadhesive ligands, enabling targeted binding to epithelial surfaces via specific receptor-mediated interactions, which support the attachment of polymeric drug delivery systems. Lectin-conjugated fluorescent nanoparticles have been employed to detect differences in glycosylation between normal and cancerous cells. In recent years, lectin-based nanoparticles have attracted growing interest for their applications in pharmaceuticals and innovative biomedical fields [31]. Fig. 8 shows a lectin-functionalized nanoparticle.

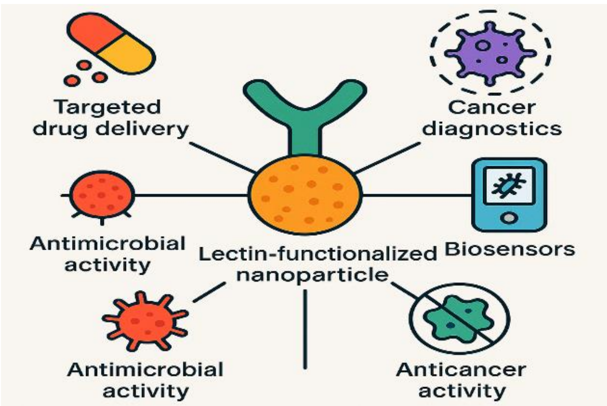

Fig. 8: Lectin functionalized nanoparticle

Subramaniyan and Veerappanhighlighted lectins' potential as targeted carriers for metal nanoparticles (MNPs) due to their carbohydrate-binding specificity. Despite concerns about MNP toxicity, lectin-MNP conjugates offer improved therapeutic efficiency with reduced side effects [32]. Yasin *et al.* Formulated lectin-loaded chitosan-TPP nanoparticles, which showed enhanced anticancer activity against HepG2 cells by increasing apoptotic gene expression and reducing proliferation markers, indicating their potential as a promising anticancer agent [33]. Punjabi *et al.* developed a point-of-care biosensor using lectin-functionalized chitosan nanoparticles entrapped with crystal violet to detect bacterial infections. The<200 nm nanoparticles formed visible aggregates in the presence of bacteria, enabling rapid detection within 10 min without sample preparation. The device showed 100% sensitivity and specificity with a detection limit of 10^5 cfu/ml and remained stable for over 90 days, offering a promising tool for quick, low-cost infection screening [34]. Sharma *et al.* developed wheat germ agglutinin (WGA)-functionalized poly(lactide-co-glycolide) (PLG) nanoparticles for oral/aerosol delivery of antitubercular drugs. These nanoparticles enhanced drug bioavailability and sustained plasma levels, reducing dosing frequency. Just three doses of lectin-coated PLG nanoparticles matched the efficacy of 45 doses of free drugs [35]. Wang *et al.* developed a method to conjugate lectins to gold nanoparticles (GNPs) using a bifunctional PEG linker, preserving lectin activity. Additional PEG-thiol improved stability and minimized nonspecific binding. The resulting lectin-GNPs showed strong, specific binding to various cell lines, demonstrating potential as optical probes for analyzing cell surface glycans [36]. Terävä *et al.* developed lectin-coated europium nanoparticle assays to detect glycovariants of CA15-3 for improved breast cancer diagnostics. The CA15-3^Lectin assays, especially with WGA, showed higher sensitivity than conventional tests. This approach offers better detection of metastatic breast cancer [37]. Kumar *et al.* synthesized silver nanoparticles using jacalin lectin from jackfruit seeds and characterized them using UV-Vis, XRD, DLS, and SEM. The jacalin-AgNPs effectively inhibited HeLa cancer cell proliferation while sparing normal PBMCs, highlighting their potential as selective anticancer agents [38]. Lakshmi *et al.* demonstrated that a hybrid of platinum nanoparticles and *Metapenaeusdobsoni* lectin (Pt-lec) possesses strong antimicrobial and immune-boosting activity in infected Nile tilapia. The Pt-lec conjugate reduced bacterial load by disrupting membranes and triggering ROS, while also enhancing immune gene expression. This biohybrid shows potential as a sustainable therapeutic in aquaculture [39]. Gidwani *et al.* introduced a nanoparticle–lectin immunoassay designed to better distinguish malignant from benign origins of serum CA125. By targeting cancer-specific glycosylation patterns using lectin-coated nanoparticles, the assay achieved improved specificity. This approach enhances the diagnostic reliability of CA125 for ovarian cancer detection [40]. Sánchez-Pomales *et al.* developed a rapid, lectin-based gold nanoparticle assay for analyzing glycosylation patterns of glycoproteins like RNase B and Rituxan® using dynamic light scattering and plasmon resonance. This method offers a fast, simple alternative for glycoanalysis with potential in therapeutic protein quality control [41]. Budhadev *et al.* used glycan-coated gold nanoparticles to study multivalent lectin interactions, revealing distinct binding modes of DC-SIGN and DC-SIGNR. They developed a fluorescence method to measure affinity and proposed a model to predict binding outcomes. Their nanoparticles effectively blocked DC-SIGN-mediated Ebola virus entry [42]. Ferreira *et al.* synthesized lectin-functionalized magnetic nanoparticles to selectively recover glycoproteins from body fluids. Sugar-protection during conjugation preserved lectin activity, significantly enhancing glycoprotein binding. The platform enabled high-affinity, low-nonspecific glycoprotein capture, proving valuable for glycoproteomics [43].

Combining lectins with nanotechnology has improved targeted therapies by allowing nanoparticles to identify distinct glycan structures on cells, thereby increasing the accuracy of drug delivery and diagnostic applications [7].

Applicationof nanotechnology in various fields

Nanotechnology is an innovative and promising field that has found applications across various sectors, including medicine, agriculture, and the food industry [44]. Fig. 9. Indicates application of nanotechnology in various field.

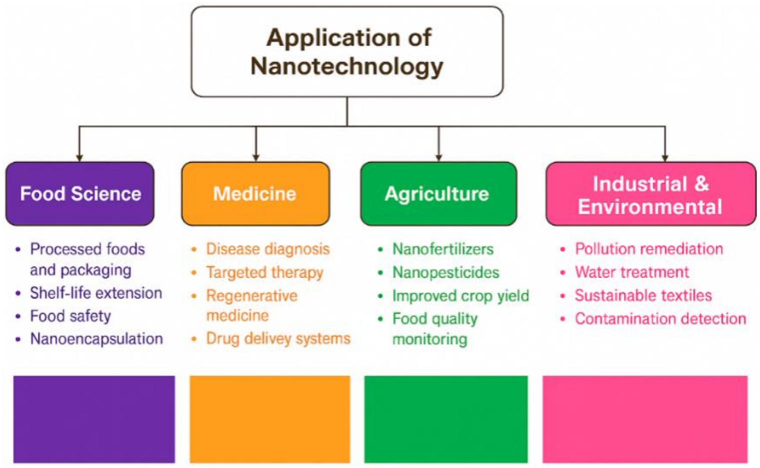

Fig. 9: Application of nanotechnology in various field

From nano to nourishment: technological advances in food science

Recent advancements in nanotechnology have brought transformative changes to various scientific and industrial fields, with a notable impact on the food industry. The growing focus on nanoparticles has enabled their application in several areas of food science and microbiology, including the optimization of food processing, improvement of packaging systems, creation of functional foods, enhancement of food safety, identification of foodborne pathogens, and extension of food product shelf life [45]. Nanotechnology extends the shelf life of various types of food products and helps reduce food waste caused by microbial contamination [46]. Nanoencapsulation masks odors and tastes, controls certain ingredient release and interaction with food, targets delivery, and protects compounds from moisture and heat [47]. Nanotechnology plays a key role in food preservation, additives, and packaging through antimicrobial agents such as Cu/CuO, Ag, TiO_2, ZnO, and graphene. It offers superior strength, heat resistance, and biodegradability over conventional packaging, while nanosensors enable early detection of spoilage due to enhanced antibacterial activity [48]. Moreover, prior to the development and use of antimicrobial nanoparticles from sustainable sources, it is essential to conduct *in vitro* and *in vivo* studies to evaluate their interactions with living organisms [49].

Healing at the nanoscale: applications of nanotechnology in medicine

The use of nanotechnology in medicine, known as nanomedicine, includes applications such as nanodiagnostics, targeted nanotherapy, and regenerative treatments. Nano-diagnostics involves creating nanoscale and imaging tools to identify diseases, detect cellular abnormalities, and monitor malfunctioning cells. Nanotherapy delivers drugs through nanosystems for more precise and efficient treatment with fewer side effects. Regenerative medicine uses nanomaterials to restore or rebuild damaged tissues and organs [50]. Nanotechnology has great potential to transform healthcare, providing groundbreaking advancements in diagnostics, targeted drug delivery, cancer treatment, and the fight against infectious diseases [51]. Abaszadeh *et al.* highlighted growing role ofnanotechnology across surgical fields, aiding in tissue regeneration, wound healing, and enhancing implants used in surgery. The study covers advanced applications like nanorobots, nano-scaffolds, and surgical diagnostics, while also addressing ethical and safety concerns and emphasizing its potential to improve surgical outcomes [52]. Karahmet *et al.* reviewed the progress of nanotechnology in medicine, focusing on nano-delivery systems for cancer and viral infection treatments. These systems enable precise delivery of sensitive molecules like RNA, with high efficiency and reduced side effects, improving patient outcomes and adherence. The study analyzes *in vitro* and *in vivo* research, emphasizing applications in oncology and virology, and highlights the ongoing potential and challenges of tnanomedicine [53]. Yadav highlights impact of nanotechnologyin pharmaceutical sciences. Tools like carbon nanotubes, liposomes, and quantum dots offer targeted, less toxic alternatives to conventional treatments. These nanodevices are applied in diagnosing and treating diseases such as cancer, Alzheimer’s, Parkinson’s, and tuberculosis, significantly advancing healthcare and medical technologies [54]. Rabiei and Samavati highlighted nanotechnology’s role in overcoming limitations of conventional drug therapies, such as poor absorption, side effects, and resistance. Nanodelivery systems enable targeted, controlled release improving treatment for diseases like diabetes, skin disorders, and conditions affecting nerves, bones, and cartilage while enhancing efficacy and patient outcomes [55]. Haleem *et al.* highlight nanotechnology's role in diagnostics, targeted drug delivery, and wearable health devices, enhancing safety and precision in treatments. The study offers a concise overview of nanomedicine's applications and future research potential [56]. Yavuz *et al.* explored nanotechnology's role in improving diagnostics and targeted therapies, particularly for cancer, dermatological, and infectious diseases, highlighting its ability to enhance drug delivery and medical imaging with minimal side effects [57].

Nanotechnology for agricultural productivity and sustainability

Nanotechnology's potential in agriculture is to boost crop productivity and reduce agrochemical use. While nanofertilizers and nanopesticides enhance plant growth, their long-term effects on beneficial plant-associated microorganisms remain unclear, warranting further research for sustainable agricultural practices [58]. Balusamy *et al.* highlighted the potential of nanoparticles in sustainable agriculture, particularly for nutrient delivery and crop growth enhancement. They emphasize that small-sized metal nanoparticles applied via seed priming or foliar spray at low concentrations can improve plant performance with minimal toxicity. However, concerns remain over regulatory gaps and unknown long-term ecological impacts [59]. Fraceto *et al.* explored how nanotechnology can support sustainable agriculture by enhancing productivity, minimizing environmental impact, and improving food safety. They havefocussed on innovations like controlled-release systems for fertilizers and pesticides, and nanosensors for monitoring crop health and food quality [60]. Umesha *et al.* emphasize the growing role of nanotechnology in agriculture, noting its ability to boost crop yields, enhance seed germination, and reduce agrochemical use. They highlight its promise as a sustainable and efficient alternative to conventional farming methods [61]. Abobattadescribes nanotechnology as a promising solution for improving agricultural productivity and sustainability. He stresses on precise delivery of nutrients and pesticides, reduced agrochemical use, and addresses key challenges like resource overuse and environmental impact. Nano-fertilizers, developed through top-down or bottom-up methods, enhance nutrient efficiency and reduce pollution [62]. Daniel *et al.* explore how nanotechnology and proteomic tools can address challenges in agriculture caused by population growth and climate change. While nanoparticles offer promising benefits due to their unique properties, their agricultural use is still limited by safety concerns and unclear plant interactions. This study highlights a shift from basic studies to advanced research using proteomics to better understand how nanoparticles influence plant growth and gene expression. This knowledge could support the development of biomarkers and innovative strategies for crop improvement and sustainable farming [63]. Bratovcic *et al.* discuss nanotechnology as a solution to challenges in modern agriculture, such as limited resources, declining soil health, and rising food demand. His work addresses the use of nanofertilizers, nanosensors, and nanoherbicides to enhance crop yields, nutrient delivery, and pest control. Emphasis is placed on the potential of nanoparticles for precise, controlled release of agrochemicals, offering a more efficient and sustainable approach to food production [64]. Zhao *et al.* highlight nano-biotechnology’s potential to advance sustainable agriculture by using certain nanoparticles to directly enhance plant growth and stress tolerance. Their effectiveness depends on type, application method, and concentration. The study urges the development of tailored, agriculture-specific nanoparticles to maximize benefits [65].

Green nano: transforming industry and environment through nanotechnology

Nanotechnology offers powerful tools for tackling environmental issues, especially in air, water, and wastewater treatment. Methods such as nano-adsorbents, filtration, photocatalysts, and sensors help remove and detect pollutants efficiently. Its ability to control contamination and support purification processes makes it a promising green technology for sustainable development [66]. Taran *et al.* discuss nanotechnology’s potential in addressing environmental issues like pollution and waste through its high reactivity and efficiency in detecting, preventing, and removing contaminants. While effective, nanoparticles may pose health and environmental risks due to their small size andpersistence, necessitating thorough risk assessments, regulatory oversight, and the development of safe-by-design nanomaterials to ensure responsible use. The study reviews applications in waste management, air and water treatment, and highlights the importance of safety considerations [67]. Pathakoti *et al.* emphasize that nanotechnology offers sustainable solutions to key environmental issues, including pollution reduction, water purification, and environmental monitoring. The review underscores the role of engineered nanomaterials in advancing eco-friendly technologies and explores future opportunities for their application in natural systems [68]. Guerra *et al.* examine the role of nanomaterials in environmental remediation, emphasizing their effectiveness due to a high surface area and enhanced reactivity. The review categorizes nanomaterials into inorganic, carbon-based, and polymeric types, highlighting their application in removing pollutants from soil, water, and air through techniques such as adsorption, photocatalysis, and filtration. It also outlines their use in treating contaminants like heavy metals, dyes, organic pollutants, and herbicides, providing recent examples to demonstrate their practical value in environmental cleanup efforts [69]. Laxmi *et al.* highlight nanotechnology's growing role in addressing environmental challenges arising from industrialization and pollution. With its ability to manipulate materials at the molecular level, nanotechnology enhances environmental sensing and remediation through high surface-to-mass ratio nanomaterials. Recent advancements, applications, and future prospects in using nanotechnology for environmental sustainability highlight its transformative potential in areas such as water purification, air and soil remediation, and clean energy production, while also addressing associated challenges like toxicity, environmental impact, regulatory gaps, and scalability issues [70]. Santos *et al.* highlight nanotechnology as a transformative field with applications in electronics, healthcare, energy, and more. Despite its industrial potential, challenges like limited awareness and safety concerns hinder wider adoption. The study emphasizes the need for collaboration between academia and industry to advance practical and safe nanotech applications [71]. Subhan *et al.* highlight the wide industrial applications of molecular nanomaterials and stresses the importance of scalable synthesis, industry-academia collaboration, and safety regulations. While nanomaterials offer significant benefits across sectors, their toxicological impacts and regulatory challenges must be addressed for sustainable use [72]. Prasad *et al.* explored the transformative impact of nanotechnology on the textile industry. The study highlights how incorporating nanomaterials has enhanced fabric properties, including antibacterial effects, water repellency, selfcleaning, and wrinkle resistance. It discusses the use of nanotechnology across various textile processes such as dyeing, printing, coating, finishing, and surface modification. The review also emphasizes the role of nanostructures like nanofibers, nanocomposites, and nanocoatings in creating smart textiles and protective garments. Additionally, it addresses the challenges, potential applications, and biological implications, calling for further research and innovation in this field [73]. Nakkeeranexplicates that rapid industrialization has caused severe pollution of air, water, and soil, threatening ecosystems and human health. Traditional cleanup methods may be insufficient for future needs. Nanotechnology, by manipulating materials at the nanoscale, offers a powerful new approach for environmental remediation. While promising, it also poses potential risks like new toxins. Natural nanoscale particles affect pollutant behavior, highlighting nanotechnology's importance in addressing environmental challenges [74]. Stark *et al.* explore how nanoparticles have transitioned from research concepts to practical industrial applications, replacing conventional materials with more sustainable solutions. The review outlines the characteristics that make nanoparticles valuable in chemical product development and details their established and emerging uses across industries. Table 1. Indicates Advantages and Limitations of Nanotechnology in Various Fields [75].

Table 1: Advantages and limitations of nanotechnology in various sectors

Sector	Advantages	Limitations	References
Medicine	MRI contrast enhancement using superparamagnetic nanoparticles.	Toxicity concerns and biocompatibility issues. Ethical concerns in human testing, High R and D costs and lengthy regulatory approvals.	[76]
Agriculture	Controlled release nano-formulations, Targeted pest control, Early detection of plant diseases.	Environmental persistence of nanoparticles, Lack of large-scale field validation, Costly production and delivery methods.	[77]
Food Science	Nano-encapsulation increases bioavailability of nutrients (e. g., vitamins, omega-3s). Enables targeted and controlled release, ensuring nutrients are absorbed where needed in the body.	Potential migration of nanoparticles into food , Lack of consumer awareness, Insufficient regulatory standards for nano-ingredients.	[44]
Industrial and Environmental	Nanocoatings for corrosion resistance, Nanocatalysts in energy production, Photocatalytic water purification	Occupational exposure risks (inhalation, dermal), Long-term ecological effects of released nanoparticles, Difficulty in nanoparticle recovery and disposal	[78]

Next-generation nanotechnology: potential and hazards

Nanotechnology is frequently described as a transformative innovation with the potential to revolutionize various fields. Often labeled the "technology of tomorrow," it offers promising solutions for challenges in health, industry, agriculture, and environmental sustainability. While the advantages are widely celebrated, it's important to approach this field with caution, as it is still in its early stages of development and not without concerns. Supporters of nanotechnology suggest that it could play a vital role in combating environmental issues like climate change and pollution. However, these benefits may be offset by the environmental costs of producing nanomaterials, which often involve high energy usage, large volumes of water, and toxic chemicals. In the food industry, nanotechnology can enhance shelf life and safety, but the extension of shelf life may encourage global distribution, increasing carbon emissions through long-distance transport. Moreover, the use of nanomaterials in agriculture, such as nanopesticides, raises health-related questions. There is still limited knowledge about how these particles behave inside the human body, how they are absorbed, and whether they pose any long-term risks. Until more comprehensive safety data is available, the widespread use of nanotechnology in food and agriculture should be approached carefully and ethically [79-81].

CONCLUSION

Based on the above-reported findings by various investigators, it is evident that nanotechnology holds immense potential to revolutionize diverse fields through its ability to manipulate materials at the nanoscale. From precision medicine and targeted drug delivery using lectin-functionalized nanoparticles to advancements in agriculture, food science, and environmental applications, the impact of nanomaterials is both profound and far-reaching. Lectin-based nanotechnologies, in particular, demonstrate remarkable specificity in disease detection and therapeutic targeting, offering new avenues for improved clinical outcomes. However, as this rapidly evolving field continues to expand, it is crucial to understand the associated challenges that need to be addressed, including toxicity, ecological risks, and regulatory gaps. The high energy demands and chemical inputs required for nanomaterial synthesis, along with uncertainties surrounding their long-term biological interactions, highlight the need for cautious and ethical deployment. Future research must focus on developing safer and more sustainable nanotechnologies while reinforcing regulatory oversight to mitigate potential risks. Balancing progress with precaution is essential to ensure that nanotechnology truly serves as a catalyst for positive change in the future.

ACKNOWLEDEGEMENT

The authors have acknowledged the contributions of other researchers listed in the references section about their research publications while preparing this review paper.

FUNDING

Nil

AUTHORS CONTRIBUTIONS

Manuscript written by Fakeha Shaikh under the guidance of Ashish Uzgare.

CONFLICT OF INTERESTS

Authors declare no conflict of interest.

REFERENCES

1. Sim SS, Wong NK. Nanotechnology and its use in imaging and drug delivery. Biomed Rep. 2021;14(5):42. doi: 10.3892/br.2021.1418, PMID 33728048.

2. Khan I, Saeed K, Khan I. Nanoparticles: properties applications and toxicities. Arab J Chem. 2019;12(7):908-31. doi: 10.1016/j.arabjc.2017.05.011.
3. Nasrollahzadeh M, Sajadi SM, Sajjadi M, Issaabadi Z. An introduction to nanotechnology. Interface Sci Technol. 2019;28:1-27. doi: 10.1016/B978-0-12-813586-0.00001-8.
4. Rambaran T, Schirhagl R. Nanotechnology from lab to industry a look at current trends. Nanoscale Adv. 2022;4(18):3664-75. doi: 10.1039/D2NA00439A, PMID 36133326.
5. Srinivas PR, Philbert M, Vu TQ, Huang Q, Kokini JL, Saltos E. Nanotechnology research: applications in nutritional sciences. J Nutr. 2010;140(1):119-24. doi: 10.3945/jn.109.115048, PMID 19939997.
6. Riehemann K, Schneider SW, Luger TA, Godin B, Ferrari M, Fuchs H. Nanomedicine challenge and perspectives. Angew Chem Int Ed Engl. 2009;48(5):872-97. doi: 10.1002/anie.200802585, PMID 19142939.
7. Kovalenko VL, Komedchikova EN, Sogomonyan AS, Tereshina ED, Kolesnikova OA, Mirkasymov AB. Lectin modified magnetic nano-PLGA for photodynamic therapy *in vivo*. Pharmaceutics. 2022;15(1):92. doi: 10.3390/pharmaceutics15010092, PMID 36678721.
8. Shaikh Fakeha MR, Uzgare AS. Partial purification and characterization of a lectin like protein from Terminalia catappa seeds. Res J Chem Environ. 2025;29(7):117-23. doi: 10.25303/297rjce1170123.
9. Shaikh FM, Uzgare AS. Study of lectin-like protein from Terminalia catappa (TC) seeds for its physicochemical and antimicrobial properties. In: Proceedings of the 28th International Electronic Conference on Synthetic Organic Chemistry (ECSOC-28), Basel, Switzerland. Chem Proc. 2024;16(1):75. doi: 10.3390/ecsoc-28-20179.
10. Singh A, Parashar T, Khan A, Jakhmola V. Synthesis and method of nanoparticles and their applications an exhaustive review. IJDDT. 2024;14(2):1071-6. doi: 10.25258/ijddt.14.2.71.
11. Baig N, Kammakakam I, Falath W. Nanomaterials: a review of synthesis methods properties recent progress and challenges. Mater Adv. 2021;2(6):1821-71. doi: 10.1039/D0MA00807A.
12. Prasad Yadav T, Manohar Yadav R, Pratap Singh D. Mechanical milling: a top down approach for the synthesis of nanomaterials and nanocomposites. Nanosci Nanotechnol. 2012;2(3):22-48. doi: 10.5923/j.nn.20120203.01.
13. Altammar KA. A review on nanoparticles: characteristics synthesis applications and challenges. Front Microbiol. 2023;14:1155622. doi: 10.3389/fmicb.2023.1155622, PMID 37180257.
14. Sebastian EM, Jain SK, Purohit R, Dhakad SK, Rana RS. Nanolithography and its current advancements. Mater Today Proc. 2020;26(2):2351-6. doi: 10.1016/j.matpr.2020.02.505.
15. Larosi MB, Garcia JD, Rodriguez AR. Laser synthesis of nanomaterials. Nanomaterials (Basel). 2022;12(17):2903. doi: 10.3390/nano12172903, PMID 36079941.
16. Bokov D, Turki Jalil A, Chupradit S, Suksatan W, Javed Ansari M, Shewael IH. Nanomaterial by sol-gel method: synthesis and application. Adv Mater Sci Eng. 2021;2021(1):5102014. doi: 10.1155/2021/5102014.
17. Bera D, Kuiry SC, Seal S. Synthesis of nanostructured materials using template-assisted electrodeposition. JOM. 2004;56(1):49-53. doi: 10.1007/s11837-004-0273-5.
18. Gangwar N, Gangwar C, Sarkar J. A review on template-assisted approaches & self-assembly of nanomaterials at liquid/liquid interface. Heliyon. 2024;10(17):e36810. doi: 10.1016/j.heliyon.2024.e36810, PMID 39263084.
19. Karthikeyan J, Berndt CC, Tikkanen J, Reddy S, Herman H. Plasma spray synthesis of nanomaterial powders and deposits. Mater Sci Eng A. 1997;238(2):275-86. doi: 10.1016/S0921-5093(96)10568-2.
20. Kolahalam LA, Kasi Viswanath IV, Diwakar BS, Govindh B, Reddy V, Murthy YL. Review on nanomaterials: synthesis and applications. Mater Today Proc. 2019;18:2182-90. doi: 10.1016/j.matpr.2019.07.371.
21. Khan S, Hossain MK. Nanoparticle-based polymer composites. Vol. 1. London: Woodhead Publishing; 2022. p. 15.
22. Mekuye B, Abera B. Nanomaterials: an overview of synthesis classification characterization and applications. Nano Select. 2023;4(8):486-501. doi: 10.1002/nano.202300038.
23. Joudeh N, Linke D. Nanoparticle classification physicochemical properties characterization and applications: a comprehensive review for biologists. J Nanobiotechnol. 2022;20(1):262. doi: 10.1186/s12951-022-01477-8.
24. Patel KD, Singh RK, Kim HW. Carbon-based nanomaterials as an emerging platform for theranostics. Mater Horiz. 2019;6(3):434-69. doi: 10.1039/C8MH00966J.
25. Gujrati M, Malamas A, Shin T, Jin E, Sun Y, Lu ZR. Multifunctional cationic lipid-based nanoparticles facilitate endosomal escape and reduction-triggered cytosolic siRNA release. Mol Pharm. 2014;11(8):2734-44. doi: 10.1021/mp400787s, PMID 25020033.
26. Alshammari BH, Lashin MM, Mahmood MA, Al Mubaddel FS, Ilyas N, Rahman N. Organic and inorganic nanomaterials: fabrication properties and applications. RSC Adv. 2023;13(20):13735-85. doi: 10.1039/D3RA01421E, PMID 37152571.
27. Luo G, Du L, Wang Y, Wang K. Composite nanoparticles. In: Li D, editor. Encyclopedia of microfluidics and nanofluidics. Boston: Springer US; 2014. p. 1-9. doi: 10.1007/978-3-642-27758-0_243-3.
28. Singh A, Suki M, Sharma R, Ingle P. Applications of nanotechnology: a review. Int J Adv Res Chem Sci. 2020;7(2):16-32. doi: 10.20431/2349-0403.0702004.
29. Osterne VJ, Nascimento KS, Cavada BS, Van Damme EJ. The future of plant lectinology: advanced technologies and computational tools. BBA Adv. 2025;7:100145. doi: 10.1016/j.bbadva.2025.100145, PMID 39958819.
30. Mohammed Rehan SF, Uzgare AS. A review of scalable and efficient techniques for the purification of lectins. Anal Bioanal Chem Res. 2025;12(3):259-68. doi: 10.22036/abcr.2025.494266.2249.
31. Rekha Mol KR, Mohamed Hatha AA. Use of lectin-functionalized and lectin-targeted nanoparticles for multiple therapeutic applications. In: Applications of multifunctional nanomaterials. Amsterdam: Elsevier; 2023. p. 543-66. doi: 10.1016/B978-0-12-820557-0.00023-0.
32. Bala Subramaniyan S, Veerappan A. Lectins as the prominent potential to deliver bioactive metal nanoparticles by recognizing cell surface glycans. Heliyon. 2024;10(8):e29394. doi: 10.1016/j.heliyon.2024.e29394.
33. Yasin U, Bilal M, Bashir H, Amirzada MI, Sumrin A, Asad MH. Preparation and nanoencapsulation of lectin from *Lepidium sativum* on chitosan-tripolyphosphate nanoparticle and their cytotoxicity against hepatocellular carcinoma cells ($HepG_2$). BioMed Res Int. 2020;2020:7251346. doi: 10.1155/2020/7251346, PMID 33145357.
34. Punjabi K, Adhikary RR, Patnaik A, Bendale P, Saxena S, Banerjee R. Lectin-functionalized chitosan nanoparticle-based biosensor for point-of-care detection of bacterial infections. Bioconjug Chem. 2022;33(8):1552-63. doi: 10.1021/acs.bioconjchem.2c00299, PMID 35920551.
35. Sharma A, Sharma S, Khuller GK. Lectin-functionalized poly (lactide-co-glycolide) nanoparticles as oral/aerosolized antitubercular drug carriers for treatment of tuberculosis. J Antimicrob Chemother. 2004;54(4):761-6. doi: 10.1093/jac/dkh411, PMID 15329364.
36. Wang J, Liu D, Wang Z. Synthesis and cell-surface binding of lectin-gold nanoparticle conjugates. Anal Methods. 2011;3(8):1745-51. doi: 10.1039/c1ay05151b.
37. Terava J, Tiainen L, Lamminmaki U, Kellokumpu Lehtinen PL, Pettersson K, Gidwani K. Lectin nanoparticle assays for detecting breast cancer-associated glycovariants of cancer antigen 15-3 (CA15-3) in human plasma. PLOS One. 2019;14(7):e0219480. doi: 10.1371/journal.pone.0219480, PMID 31344060.

38. Kumar BA, Ahmed N, Jamal S. Biosynthesis and characterization of silver nanoparticles (AgNPs) with jacalin a lectin from jackfruit seeds and its antiproliferative effects on HeLa cancer cells. Lett Appl NanoBioSci. 2024;13(3):106. doi: 10.33263/lIANBS133.106.
39. Lakshmi S, Rubeena AS, Subramaniyan SB, Raman T, Vaseeharan B, Arockiaraj J. Hybrid of *Metapenaeus dobsoni* lectin and platinum nanoparticles exert antimicrobial and immunostimulatory effects to reduce bacterial bioburden in infected Nile tilapia. Sci Rep. 2023;13(1):525. doi: 10.1038/s41598-022-26719-5, PMID 36631627.
40. Gidwani K, Huhtinen K, Kekki H, Van Vliet S, Hynninen J, Koivuviita N. A nanoparticle-lectin immunoassay improves discrimination of serum CA125 from malignant and benign sources. Clin Chem. 2016;62(10):1390-400. doi: 10.1373/clinchem.2016.257691, PMID 27540033.
41. Sanchez Pomales G, Morris TA, Falabella JB, Tarlov MJ, Zangmeister RA. A lectin-based gold nanoparticle assay for probing glycosylation of glycoproteins. Biotechnol Bioeng. 2012;109(9):2240-9. doi: 10.1002/bit.24513, PMID 22488121.
42. Budhadev D, Poole E, Nehlmeier I, Liu Y, Hooper J, Kalverda E. Glycan-gold nanoparticles as multifunctional probes for multivalent lectin-carbohydrate binding: implications for blocking virus infection and nanoparticle assembly. J Am Chem Soc. 2020;142(42):18022-34. doi: 10.1021/jacs.0c06793, PMID 32935985.
43. Ferreira JA, Daniel Da Silva AL, Alves RM, Duarte D, Vieira IA, Santos LL. Synthesis and optimization of lectin functionalized nanoprobes for the selective recovery of glycoproteins from human body fluids. Anal Chem. 2011;83(18):7035-43. doi: 10.1021/ac200916j, PMID 21809823.
44. Mohammad ZH, Ahmad F, Ibrahim SA, Zaidi S. Application of nanotechnology in different aspects of the food industry. Discov Food. 2022;2(1):1-21. doi: 10.1007/s44187-022-00013-9.
45. Singh T, Shukla S, Kumar P, Wahla V, Bajpai VK. Application of nanotechnology in food science: perception and overview. Front Microbiol. 2017;8:1501. doi: 10.3389/fmicb.2017.01501, PMID 28824605.
46. Pradhan N, Singh S, Ojha N, Shrivastava A, Barla A, Rai V. Facets of nanotechnology as seen in food processing packaging and preservation industry. BioMed Res Int. 2015;2015:365672. doi: 10.1155/2015/365672, PMID 26613082.
47. Ubbink J, Kruger J. Physical approaches for the delivery of active ingredients in foods. Trends Food Sci Technol. 2006;17(5):244-54. doi: 10.1016/j.tifs.2006.01.007.
48. Biswas R, Alam M, Sarkar A, Haque MI, Hasan MM, Hoque M. Application of nanotechnology in food: processing preservation packaging and safety assessment. Heliyon. 2022;8(11):e11795. doi: 10.1016/j.heliyon.2022.e11795, PMID 36444247.
49. Das S, Jagan L, Isiah R, Rajesh B, Backianathan S, Subhashini J. Nanotechnology in oncology: characterization and *in vitro* release kinetics of cisplatin-loaded albumin nanoparticles: implications in anticancer drug delivery. Indian J Pharmacol. 2011;43(4):409-13. doi: 10.4103/0253-7613.83111, PMID 21844995.
50. Ejidike IP, Ogunleye O, Bamigboye MO, Ejidike OM, Ata A, Eze MO. Role of nanotechnology in medicine: opportunities and challenges. In: Shah MP, Bharadvaja N, Kumar L, editors. Biogenic nanomaterials for environmental sustainability: principles, practices and opportunities. Cham: Springer International Publishing; 2024. p. 353-75. doi: 10.1007/978-3-031-45956-6_14.
51. Ma X, Tian Y, Yang R, Wang H, Allahou LW, Chang J. Nanotechnology in healthcare and its safety and environmental risks. J Nanobiotechnology. 2024;22(1):715. doi: 10.1186/s12951-024-02901-x, PMID 39548502.
52. Abaszadeh F, Ashoub MH, Khajouie G, Amiri M. Nanotechnology development in surgical applications: recent trends and developments. Eur J Med Res. 2023;28(1):537. doi: 10.1186/s40001-023-01429-4, PMID 38001554.
53. Karahmet Sher E, Alebic M, Markovic Boras M, Boskailo E, Karahmet Farhat E, Karahmet A. Nanotechnology in medicine revolutionizing drug delivery for cancer and viral infection treatments. Int J Pharm. 2024;660:124345. doi: 10.1016/j.ijpharm.2024.124345, PMID 38885775.
54. Yadav N. Application of nanotechnology in health sciences. Plant Arch. 2017;17(1):539-45.
55. Rabiei M, Sabereh Samavati S. The application of nanotechnology in the pharmaceutical treatment of common diseases. In: Umamaheswari A, Lakshmana Prabu S, editors. Dosage forms emerging trends and prospective drug-delivery systems. IntechOpen; 2024. doi: 10.5772/intechopen.1005467.
56. Haleem A, Javaid M, Singh RP, Rab SR, Suman R. Applications of nanotechnology in medical field: a brief review. Glob Health. 2023;7(2):70-7. doi: 10.1016/j.glohj.2023.02.008.
57. Yavuz G, Yilmaz E, Halvaci E, Catal C, Turk I, Maran F. Nanotechnology in medical applications: recent developments in devices and materials. J Sci Rep C. 2023;5:1–32. doi: 10.55736/jsr-c.2023.005.
58. Mgadi K, Ndaba B, Roopnarain A, Rama H, Adeleke R. Nanoparticle applications in agriculture: overview and response of plant-associated microorganisms. Front Microbiol. 2024;15:1354440. doi: 10.3389/fmicb.2024.1354440, PMID 38511012.
59. Balusamy SR, Joshi AS, Perumalsamy H, Mijakovic I, Singh P. Advancing sustainable agriculture: a critical review of smart and eco-friendly nanomaterial applications. J Nanobiotechnology. 2023;21(1):372. doi: 10.1186/s12951-023-02135-3, PMID 37821961.
60. Fraceto LF, Grillo R, De Medeiros GA, Scognamiglio V, Rea G, Bartolucci C. Nanotechnology in agriculture: which innovation potential does it have? Front Environ Sci. 2016;4:20. doi: 10.3389/fenvs.2016.00020.
61. Umesha MK, Seshagiri S, Kumar H, Shivashankara NG, Surynan S. Agricultural application of nanotechnology in plant growth and protection: a review. Lett Appl NanoBioSci. 2024;13(2):82. doi: 10.33263/lIANBS132.082.
62. Abobatta WF. Nanotechnology application in agriculture. Acta Sci Agric. 2018;2(6):99–102.
63. Daniel AI, Husselmann L, Shittu OK, Gokul A, Keyster M, Klein A. Application of nanotechnology and proteomic tools in crop development towards sustainable agriculture. J Crop Sci Biotechnol. 2024;27(3):359-79. doi: 10.1007/s12892-024-00235-6.
64. Bratovcic A, Hikal WM, Mehdizadeh M, Al Ahl HA, Omidi A, Adetunji CO. Application of nanotechnology in agroecosystems: nanoparticles for improving agricultural production. Rev Agric Sci. 2023;11:291-309. doi: 10.7831/ras.11.0_291.
65. Zhao L, Lu L, Wang A, Zhang H, Huang M, Wu H. Nano-biotechnology in agriculture: use of nanomaterials to promote plant growth and stress tolerance. J Agric Food Chem. 2020;68(7):1935-47. doi: 10.1021/acs.jafc.9b06615, PMID 32003987.
66. Aghababai Beni A, Jabbari H. Nanomaterials for environmental applications. Results Eng. 2022;15:100467. doi: 10.1016/j.rineng.2022.100467.
67. Taran M, Safaei M, Karimi N, Almasi A. Benefits and application of nanotechnology in environmental science: an overview. Biointerface Res Appl Chem. 2020;11(1):7860-70. doi: 10.33263/BRIAC111.78607870.
68. Pathakoti K, Manubolu M, Hwang HM. Nanotechnology applications for environmental industry. In: Handbook of nanomaterials for industrial applications. Elsevier; 2018. p. 894-907. doi: 10.1016/B978-0-12-813351-4.00050-X.
69. Guerra FD, Attia MF, Whitehead DC, Alexis F. Nanotechnology for environmental remediation: materials and applications. Molecules. 2018;23(7):1760. doi: 10.3390/molecules23071760, PMID 30021974.
70. Laxmi V, Singhvi N, Ahmad N, Sinha S, Negi T, Gupta V. Emerging field of nanotechnology in environment. Indian J Microbiol. 2023;63(3):244-52. doi: 10.1007/s12088-023-01092-7, PMID 37781004.
71. Santos C, Gabriel B, Blanchy M, Neto V. Industrial applications of nanoparticles a prospective overview. Mater Today Proc. 2014. p. 2-14. doi: 10.13140/2.1.5100.6726.
72. Subhan MA, Choudhury KP, Neogi N. Advances with molecular nanomaterials in industrial manufacturing applications. Nanomanufacturing. 2021;1(2):75-97. doi: 10.3390/nanomanufacturing1020008.
73. Prasad SR, Kumbhar VB, Prasad NR. Applications of nanotechnology in textile: a review. ES Food Agrofor. 2023;15:1-19. doi: 10.30919/esfaf1019.

74. Nakkeeran S. Nanotechnology in environmental application. Int J Biotech Trends Technol. 2011;1(3):16-23.
75. Stark WJ, Stoessel PR, Wohlleben W, Hafner A. Industrial applications of nanoparticles. Chem Soc Rev. 2015;44(16):5793-805. doi: 10.1039/C4CS00362D, PMID 25669838.
76. Bhattacharya K, Mukherjee SP, Gallud A, Burkert SC, Bistarelli S, Bellucci S. Biological interactions of carbon-based nanomaterials: from coronation to degradation. Nanomedicine. 2015;12(2):333-51. doi: 10.1016/j.nano.2015.11.011, PMID 26707820.
77. Chen H, Yada R. Nanotechnologies in agriculture: new tools for sustainable development. Trends Food Sci Technol. 2011;22(11):585-94. doi: 10.1016/j.tifs.2011.09.004.
78. Roco MC, Bainbridge WS. Societal implications of nanoscience and nanotechnology: maximizing human benefit. J Nanopart Res. 2005;7(1):1-13. doi: 10.1007/s11051-004-2336-5.
79. Gupta RK, Gawad FA, Ali EA, Karunanithi S, Yugiani P, Srivastav PP. Nanotechnology: current applications and future scope in food packaging systems. Meas Food. 2024;13:100131. doi: 10.1016/j.meafoo.2023.100131.
80. Wen Y. A review of applications and future prospects of nanotechnology. ACE. 2024;56(1):135-40. doi: 10.54254/2755-2721/56/20240640.
81. Singh N. Nanotechnology and its potential in the future. J Nanosci Nanoeng Appl. 2022;12(1):45-52.