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Current Trends of **Nanotechnology** in Basic Sciences, Pharmaceutical and Engineering

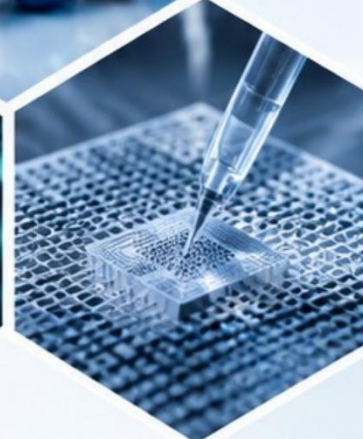
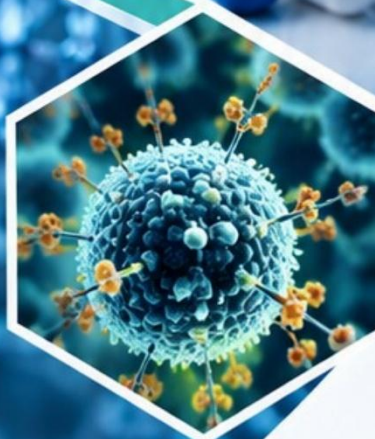
Volume I

Editors

Dr. Bassa Satyannarayana

Dr. Mohd Ayub Ansari

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Pharmaceutical and Engineering Volume I

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PREFACE

Nanotechnology has emerged as a transformative field at the interface of science, engineering, and medicine, enabling researchers to manipulate matter at the nanoscale and develop materials, systems, and applications with unique properties. Current Trends of Nanotechnology in Basic Sciences, Pharmaceutical and Engineering – Volume I brings together contemporary research perspectives highlighting the expanding role of nanotechnology across diverse academic and applied domains.

The volume explores recent developments in nanomaterials, nanostructures, synthesis techniques, characterization methods, and their applications in basic sciences, pharmaceutical research, and engineering. Advances in nanoparticles, nanocomposites, nanocarriers, nanodevices, and functional materials are opening new possibilities for addressing complex scientific and technological challenges. In pharmaceutical sciences, nanotechnology offers promising approaches for drug delivery, targeted therapy, diagnostics, and improved therapeutic performance. In engineering, nanoscale innovations contribute to advanced materials, energy technologies, electronics, environmental applications, and high-performance systems.

The chapters presented in this volume reflect the multidisciplinary nature of nanotechnology and demonstrate how fundamental scientific understanding can be translated into practical innovations. They also highlight the importance of precise characterization, controlled synthesis, interdisciplinary collaboration, and responsible development in advancing nanoscale research. Alongside technological opportunities, considerations related to environmental sustainability, safety, scalability, and ethical applications remain essential for the future growth of the field.

This book is intended for researchers, academicians, teachers, students, scientists, engineers, pharmaceutical professionals, and readers seeking an understanding of contemporary developments in nanotechnology. By presenting diverse perspectives and emerging research directions, the volume aims to encourage knowledge exchange, support further investigation, and promote innovative applications of nanoscale science.

The editors hope that this volume will serve as a valuable academic reference and contribute to continued exploration of nanotechnology. It is envisioned as a platform connecting fundamental research with practical applications and inspiring new ideas for scientific advancement, technological innovation, healthcare improvement, and sustainable development.

- Editors

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Chapter

1

**NANOMATERIALS FOR HEAVY METAL REMEDIATION IN
AQUEOUS SYSTEMS: ADSORPTION MECHANISMS,
MATERIAL DESIGN, REGENERATION AND ENVIRONMENTAL
APPLICATIONS**

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ABSTRACT

Nanomaterials have become important candidates for aqueous heavy-metal remediation because their small dimensions, high specific surface area and tunable surface chemistry can provide a large population of accessible binding sites. This chapter develops the nanomaterial perspective from the supplied research paper on magnetic adsorption, retaining its central emphasis on interfacial adsorption, surface complexation, adsorbent design, regeneration and practical deployment. Particular attention is given to magnetite (Fe₃O₄) and functionalized magnetic nanocomposites, where the nanoscale surface supplies chemically active sites and the magnetic core enables recovery from treated water. The chapter explains how hydroxylated iron-oxide surfaces interact with dissolved metal species through protonation/deprotonation and surface complex formation, while recognizing that electrostatic association, ion exchange and precipitation may occur concurrently. Nanomaterial design is discussed in terms of particle size, aggregation control, functional groups, porous supports, protective coatings and magnetic responsiveness. Operational variables such as pH, contact time, adsorbent dosage, initial concentration, ionic strength, competing ions and natural organic matter are considered because they strongly influence apparent performance. Regeneration, repeated use, secondary waste and nanoparticle release are treated as essential aspects of environmental feasibility rather than afterthoughts. Finally, the chapter outlines practical opportunities and research priorities for moving nanomaterial adsorption from single-solute laboratory experiments toward real-water, multi-ion and continuous-flow applications.

KEYWORDS: Nanomaterials, Magnetic Nanoparticles, Magnetite, Fe₃O₄, Heavy Metals, Adsorption, Surface Complexation, Functionalization, Regeneration, Wastewater Treatment.

INTRODUCTION

Heavy-metal contamination of water is a persistent environmental concern associated with mining, metallurgy, electroplating, battery manufacture, pigment production, fertilizer use and related industrial activities. Metals such as Pb(II), Cd(II), Cu(II), Ni(II), Zn(II) and chromium species cannot simply be biologically degraded; treatment therefore requires their transfer from

the aqueous phase into a recoverable or safely manageable phase. The base paper identifies adsorption as an attractive route because it can operate across a broad concentration range and can be coupled with relatively simple solid–liquid separation. It further emphasizes magnetic materials because adsorption and recovery can be integrated into one treatment cycle. [Source paper, pp. 1–2]. Nanomaterials extend this concept by engineering the adsorbent at dimensions where surface effects become especially important. Their value is not merely a consequence of being small. The important features are the accessibility and chemistry of the surface, the ability to introduce selected functional groups, and—when magnetic nanoparticles are used—the possibility of recovering fine particles with an external magnetic field. The supplied paper specifically identifies iron oxides, particularly Fe_3O_4 and $\gamma\text{-Fe}_2\text{O}_3$, as widely investigated magnetic materials because they can be synthesized relatively economically, possess surface hydroxyl groups and respond to magnetic fields.

This chapter therefore treats nanomaterials as an enabling material platform for adsorption rather than as a separate treatment technology. The discussion follows a mechanism-to-application pathway: material structure $\rightarrow$ interfacial chemistry $\rightarrow$ operating conditions $\rightarrow$ regeneration $\rightarrow$ process feasibility. This preserves the conceptual framework of the base paper while expanding it into a book-chapter treatment of nanomaterial use.

NANOMATERIALS AS ADSORBENTS FOR HEAVY METALS

At the nanoscale, a large fraction of the material can participate in interfacial processes. This can increase the number of accessible sites per unit mass, shorten characteristic diffusion distances and make surface modification highly influential. For heavy-metal removal, however, a high surface area alone is not sufficient. An effective Nano adsorbent must present chemically accessible sites, remain sufficiently dispersed during contact, withstand the water matrix and be recoverable after treatment.

Table 1: Major Nanomaterial Platforms

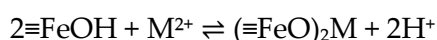
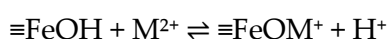
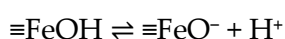
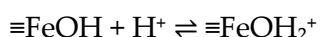
Nanomaterial Platform	Relevant Feature	Principal Consideration
Magnetic iron oxides (Fe_3O_4 , $\gamma\text{-Fe}_2\text{O}_3$)	Surface hydroxyls plus magnetic recovery	Aggregation, coating stability and magnetic-property retention
Functionalized magnetic nanoparticles	Tailored coordination sites	Ligand leaching and selectivity in complex water
Magnetic carbon composites	High-area carbon support with magnetic separation	Pore blockage, synthesis complexity and release
Polymer/biopolymer magnetic composites	Dispersion control and additional binding groups	Mechanical/chemical stability and coating thickness
Porous magnetic nanocomposites	Accessible pores plus magnetic handling	Fouling, mass transfer and magnetic responsiveness

The base paper distinguishes three useful design levels: bare magnetic iron oxide; coated or supported magnetic particles; and chemically functionalized magnetic composites. This classification can be used to understand nanomaterial development. Bare nanoparticles rely

largely on native surface hydroxyl chemistry. Coatings and supports address aggregation and handling while adding surface area or new functional groups. Functionalized composites deliberately introduce ligands such as carboxyl, amino, thiol or phosphonate groups to alter affinity and selectivity.

SURFACE CHEMISTRY AND HEAVY-METAL ADSORPTION MECHANISM

The central mechanistic framework inherited from the base paper is surface complexation. When a hydrated metal ion approaches a hydroxylated iron-oxide surface, its interaction is controlled by the protonation state of surface groups, solution pH, metal speciation and competing dissolved species. Surface sites may be represented as $\equiv\text{FeOH}$. Simplified reactions are:



The first two expressions describe protonation and deprotonation. The latter expressions represent simplified surface complexes involving divalent metal ions. Inner-sphere complexes involve direct coordination between the metal and surface atoms and can be comparatively less sensitive to ionic-strength changes than purely electrostatic outer-sphere associations. Outer-sphere interactions retain a hydration shell and are more strongly screened by dissolved electrolyte. Functionalization introduces a second layer of chemical control. Carboxyl and amino groups can participate in coordination and electrostatic interactions, while sulfur-containing ligands may show stronger affinity for some softer metal ions such as Pb (II) and Cd (II). The presence of these groups can increase capacity or selectivity, but the chapter adopts the caution emphasized in the source paper: a high removal percentage does not by itself prove a particular mechanism. Spectroscopic, surface-chemical and aqueous-speciation evidence is required to distinguish complexation, ion exchange and precipitation.

ROLE OF P^H IN NANOMATERIAL ADSORPTION

pH is both an operational and mechanistic variable. At low pH, abundant protons compete with metal ions and suppress deprotonation of surface hydroxyls, generally reducing metal binding. As pH increases, more negatively charged or coordinatively available sites can appear, promoting adsorption. Excessively high pH, however, can produce metal hydroxide or carbonate precipitation. Consequently, apparent removal should be interpreted against blank precipitation controls and metal-speciation calculations. The source paper explicitly recommends this distinction.

NANOMATERIAL DESIGN: BALANCING SURFACE AREA AND RECOVERABILITY

Nanomaterial engineering involves a fundamental trade-off. Smaller particles can expose more surface, yet strong magnetic dipole interactions and surface forces can drive aggregation. Aggregation reduces accessible surface area and may hinder mass transfer. Stabilizing shells, polymeric coatings, carbonaceous supports and biopolymer matrices can improve dispersion

and handling. At the same time, an excessively thick or dense coating can reduce magnetic responsiveness or block active sites.

Functionalization should therefore be evaluated across the complete treatment cycle. Initial adsorption capacity is only one criterion. Ligand stability, magnetic recovery, structural integrity, capacity retention after regeneration and release of iron or surface ligands are equally important. This design philosophy follows the base paper's conclusion that adsorption chemistry and magnetic recovery should be engineered together.

Table 2: Factors Governing Adsorption Performance

Variable	Effect on Nano Adsorption
pH	Controls surface charge, proton competition and aqueous metal speciation.
Contact time	Reflects external diffusion, intraparticle diffusion and surface reaction processes.
Adsorbent dosage	Increases the number of available sites but may lower uptake per unit mass.
Initial metal concentration	Provides the driving force for mass transfer and determines proximity to site saturation.
Temperature	May affect diffusion and thermodynamics; direction and magnitude must be experimentally established.
Ionic strength and competing ions	Can screen electrostatic interactions or occupy non-specific sites.
Natural organic matter	Can coat surfaces, block pores or complex metals before they reach the adsorbent.

EQUILIBRIUM, KINETICS AND PERFORMANCE EVALUATION

For batch adsorption, equilibrium capacity and removal efficiency can be expressed as:

$$q_e = (C_0 - C_e) V / m$$

$$\text{Removal (\%)} = [(C_0 - C_e)/C_0] \times 100$$

Here C_0 and C_e are the initial and equilibrium aqueous concentrations, V is the solution volume and m is the adsorbent mass. Langmuir and Freundlich models are frequently used as empirical descriptions. A Langmuir fit may be consistent with a finite population of relatively similar sites, whereas Freundlich behavior represents heterogeneous adsorption. Neither model, by itself, establishes a molecular mechanism. Similarly, pseudo-first-order, pseudo-second-order and intraparticle-diffusion models can aid comparison of kinetic behavior but should not be treated as direct proof of a particular rate-limiting chemical step.

For nanomaterials, reporting should extend beyond $q_{\max}$. Particle size distribution, aggregation state, surface functional groups, magnetic properties where relevant, pH, adsorbent dose, ionic strength, competing ions and metal speciation should accompany adsorption data. This is necessary because the base paper stresses that capacities obtained under different experimental conditions are not universal material properties.

REGENERATION, REUSE AND METAL RECOVERY

Regeneration determines whether a Nano adsorbent can function as a reusable treatment material. Acidic regenerates can protonate surface sites and weaken metal–oxygen interactions; chelating agents may provide stronger desorption for selected metals; and saline solutions may be useful where electrostatic or ion-exchange contributions are important. The appropriate regenerant depends on the material and metal-binding chemistry.

A robust regeneration study should report desorption efficiency, adsorption capacity after each cycle, magnetic recovery efficiency, structural stability, surface chemistry and metal concentration in the regenerant. A material that maintains adsorption capacity but releases iron, nanoparticles or ligands into the treated water may not be environmentally preferable. The concentrated regenerant must also be managed. Where economically valuable metals such as Cu or Ni are present, selective recovery may contribute to process circularity; highly toxic metals such as Pb and Cd require stringent containment.

APPLICATIONS IN WATER AND WASTEWATER TREATMENT

Functionalized magnetic nanomaterials are particularly relevant to industrial waters containing Pb, Cd, Cu, Ni and Zn. Electroplating wastewater is a promising target because metal concentrations can be substantial and pH adjustment may be feasible. Mining-affected waters and acid mine drainage are more demanding because low pH, high ionic strength and multiple competing metals can challenge both surface stability and selectivity.

Table 3: Advantages and Limitations of Nanomaterial-Based Adsorption

Advantages	Limitations
High accessible surface area	Aggregation can reduce accessible area
Tailorable surface chemistry	Functional ligands may leach
Potentially rapid adsorption	Mass transfer can be altered by aggregation/coating
Magnetic recovery for magnetic nanomaterials	Coatings may decrease magnetic response
Potential selectivity through functionalization	Complex water matrices can suppress uptake
Regeneration and reuse may be possible	Repeated cycles can cause capacity or magnetization loss
Reduced filtration burden for magnetic particles	Nanoparticle release and end-of-life management remain concerns

For groundwater or surface-water polishing, Nano adsorbents may be considered after pretreatment that reduces suspended solids and organic matter. Magnetic separation is attractive because it can reduce reliance on filtration for very fine particles. Nevertheless, the source paper identifies continuous-flow implementation, engineered magnetic separators and pilot validation as major gaps. Batch performance should therefore not be presented as proof of field readiness.

ENVIRONMENTAL SAFETY AND PRACTICAL SUSTAINABILITY

The environmental value of a nanomaterial cannot be judged from removal efficiency alone. The same small size that creates high surface reactivity can also complicate containment. Possible release of nanoparticles, dissolution of the magnetic phase, ligand leaching and transformation during repeated regeneration should therefore be monitored. Life-cycle thinking should include synthesis energy, chemical consumption, transport, regeneration, metal recovery and end-of-life treatment. A practical evaluation should compare laboratory objectives with validation criteria: removal should meet an effluent target in real water; capacity should remain useful at realistic concentrations; selectivity should be demonstrated in multi-ion systems; recovery should remain stable in continuous operation; regeneration should retain performance across repeated cycles; and material release should be minimized.

RESEARCH GAPS AND FUTURE DIRECTIONS

- Mechanism verification: combine XPS, FTIR, EXAFS/XANES, zeta potential and surface titration with aqueous speciation to distinguish complexation, ion exchange and precipitation.
- Real-water validation: test multi-metal waters containing major ions and natural organic matter instead of relying mainly on single-solute synthetic solutions.
- Regeneration-by-design: select ligands and surface structures that provide strong adsorption without making desorption effectively irreversible.
- Magnetic process engineering: develop scalable separators, magnetically assisted fixed beds and continuous-flow contactors with quantified recovery.
- Durability and release testing: monitor iron dissolution, ligand leaching, particle release and changes in magnetic properties during repeated cycles.
- Standardized reporting: provide pH, ionic strength, adsorbent dose, particle size, magnetic properties, contact time, metal speciation and analytical detection limits.
- Life-cycle assessment: evaluate synthesis, regeneration, metal recovery and end-of-life impacts alongside adsorption capacity.

CONCLUSION

Nanomaterials provide a versatile platform for heavy-metal adsorption because their interfacial properties can be engineered at multiple levels. The magnetic adsorption framework presented in the source paper is particularly useful because it links surface chemistry with physical recovery. Magnetite and related iron-oxide nanoparticles provide hydroxylated surfaces for metal interaction, while functionalization can introduce additional coordination sites and improve selectivity. Yet the performance of a Nano adsorbent depends on more than its nominal surface area or maximum laboratory capacity. Aggregation, matrix effects, ligand stability, regeneration, nanoparticle release and process scale-up must be considered together.

The most credible route toward practical application is therefore integrated design: the chemical affinity of the nanomaterial, its physical architecture, its recovery method and its regeneration strategy should be developed as one treatment cycle. Future work should emphasize mechanistically verified adsorption, real-water testing, repeated-cycle durability and

continuous-flow validation. Such an approach can help translate nanomaterial adsorption from a promising laboratory concept into a safer and more reliable component of aqueous heavy-metal remediation.

SOURCE BASIS AND ORIGINALITY NOTE

This chapter was developed from the user's supplied research paper, "Magnetic Adsorption for Heavy Metal Remediation in Aqueous Systems: Surface Complexation Mechanism, Adsorbent Design, Regeneration and Practical Applications." The supplied paper itself frames magnetic adsorption as a single technology, emphasizes surface complexation, and discusses adsorbent design, operating variables, regeneration and practical barriers. The present chapter reorganizes and expands those themes specifically around the broader use of nanomaterials, while retaining the source paper's technical terminology and cautions. The wording of this chapter is newly composed; it is not intended as a copy of the source paper.

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Chapter

2

**AN INTRODUCTORY FUNDAMENTAL ON CONVERGENCE IN
SCIENCE AND TECHNOLOGY**

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ABSTRACT

Convergence in science and technology is the deep integration of various fields—e.g. Life sciences, Physical sciences, Engineering, and Computer science—to solve complex problems that single subjects cannot fix alone. It shifts focus from isolated research to team-based creation. Convergence in technology is the process where separate, unrelated tools or systems combine into a single, unified device or platform. A clear example is the modern smartphone, which replaces standalone cameras, GPS units, music players, and landline phones.

KEYWORDS: Convergence, Science, Technology.

INTRODUCTION

Technological convergence is a process where previously separate and unrelated technologies, systems or digital data formats merge into a single, unified device or system. A clear everyday example is the smartphone, which combines a phone, camera, GPS, music player, and computer into one tool.

Convergence is the act of coming together or merging separate things into one. Because the word has different meanings in different subjects, its types depend on whether you mean media, math, biology or vision.

TECHNOLOGY IN SCIENCE

In science, technology is the practical use of scientific knowledge to create tools, machines, and systems that solve real-world problems. While science focuses on discovering how the natural world works, technology applies those discoveries to build practical solutions that make tasks easier and improve daily life.

KEY AREAS

Merging Fields: Combining Biology, Nanotechnology, Math and Computer science creates new tools.

Modern Products: Items like smart medical sensors, brain-computer links, and AI tools rely on mixed skill sets.

Shared Goals: Teams focus on big needs like clean energy, better health, and global challenges

WHY IT MATTERS

Fast Progress: Blending ideas speeds up new discoveries.

Teamwork: Universities and industries work closer to build real-world items.

New Solutions: It helps fix hard issues in health and the environment.

COMMON CHALLENGES

Complexity: Harder to fix when multi-functional systems break.

Security Risks: More points of entry for cyber threats.

Battery Drain: Running many features on one device uses power fast

CONVERGENCE IN TECHNOLOGY

Convergence in technology is the process where separate, unrelated tools or systems combine into a single, unified device or platform. A clear example is the modern smartphone, which replaces standalone cameras, GPS units, music players, and landline phones

KEY EXAMPLES OF CONVERGENCE

Smartphones: Merge telecommunication, computing, and digital photography. Replace cameras, maps, radios, and calendars

Smart TVs: Combine traditional television screens with internet streaming and computer apps.

Smart watches: Blend wristwatch styles with mobile health tracking and phone tech.

IoT (Internet of Things): Connect home appliances, security, and power grids to Wi-Fi networks for remote control via phone or single network

FEWER SEPARATE GADGETS TO BUY, CARRY OR MAINTAIN-

Efficiency: Faster sharing of data and better use of power or space.

Lower Cost: Reduced need for single-purpose hardware

BENEFITS AND DRAWBACKS

Pros: Save space, lower costs, boost speed, and make daily tasks easier

Cons: High initial costs and a single point of failure if one multi-use device breaks.

MEDIA AND TECHNOLOGY CONVERGENCE

In media studies (identified by scholar Henry Jenkins), convergence is how tools, stories, and companies mix

Technological convergence: Different tools combine into one device, like a smartphone that replaces cameras and maps.

Economic convergence: One big company owns many types of media, like TV, radio, and news websites.

Cultural convergence: Stories flow across different platforms and fans interact with them.

Global convergence: Ideas and media move easily between different countries and cultures.

Organic convergence: People use multiple kinds of media at the exact same time, like texting while watching TV

MATHEMATICS AND STATISTICS

In math, convergence means a sequence or series gets closer and closer to a specific value or limit:

Point wise convergence: Values get closer to a limit at every single point.

Uniform convergence: Values get close to a limit at the same steady rate across a whole region.

Convergence in probability: A random value gets closer to a target value as trials increase.

Convergence in distribution: The overall pattern or shape of data gets closer to a target probability curve.

BIOLOGY AND EVOLUTION

In biology, it describes how living things change or share traits:

Convergent evolution: Unrelated species develop similar traits because they live in similar environments, like birds and bats both having wings.

ANATOMY AND VISION

In **Eye convergence:** Both eyes turn inward at the same time to focus on an object that is close to your face vision, it is the movement of your eyes

THE KEY TRENDS IN ICT CONVERGENCE

Convergence in Information and Communication Technology (ICT) is the merging of different, distinct technologies, devices or media types into a single unified system to perform common tasks more efficiently. It allows users to access overlapping services—such as using a smartphone to run computer programs, sync via cloud storage, and connect over mobile broadband—anytime and anywhere.

MAJOR IMPACT AREAS

Cloud Integration: Real-time file syncing and software access across multiple gadgets without heavy reliance on local device memory.

Fintech & Digital Commerce: Unifying telecommunications with financial institutions for mobile banking and cashless payment systems.

Unified Communications: Combining email, instant messaging, voice calls, and video conferencing into single corporate workspaces.

HOW SCIENCE AND TECHNOLOGY WORK TOGETHER

Science builds knowledge: Scientists use experiments and observations to learn new facts about the universe.

Technology builds tools: Engineers and inventors use those facts to design useful products like computers, medicines, and vehicles.

Technology helps science grow: Advanced tools like microscopes, telescopes, and supercomputers let scientists study space, cells, and climate data much faster.

EXAMPLES IN THE REAL WORLD

Electricity: Science discovered the rules of electric charges, and technology used them to build light bulbs and phones.

Medicine: Science discovered bacteria and viruses, and technology created vaccines and digital X-ray machines to treat patients.

Space Exploration: Science figured out gravity and orbit math, and technology-built rockets and satellites to explore space.

THE TYPES OF TECHNOLOGY IN SCIENCE

Science builds knowledge of the natural world, while technology applies that knowledge to solve problems. Together, they divide into core fields covering the physical universe, living things, human society, and practical engineering

MAIN BRANCHES OF SCIENCE

Physical Science: Study of non-living matter, energy, and the universe (Physics, Chemistry, Astronomy).

Life Science (Biology): Study of living things, from tiny cells to complex animals and plants (Genetics, Medicine, Botany).

Earth Science: Study of the Earth, air, water, and space (Geology, Oceanography, Meteorology).

Social Science: Study of human society, relationships, and behavior (Psychology, Sociology, Economics).

Formal Science: Study of logic, math, and abstract systems (Mathematics, Statistics, Computer Science theory)

THE THREE MAIN TYPES OF TECHNOLOGY

The three main types of technology, classified by their nature and function, are –

Mechanical technology (machines and physical movement),

Electronic technology (circuits and electricity), and

Information technology (computers and data management).

MECHANICAL TECHNOLOGY

- Uses physical parts to do work.
- Relies on motion and force.
- Includes simple tools like wheels, levers, and gears.
- Powers engines and heavy machinery.

ELECTRONIC TECHNOLOGY

- Uses electric circuits to run.
- Requires power from an outlet or battery.
- Controls flow of electrical current.
- Includes appliances, TVs, and light fixtures.

INFORMATION TECHNOLOGY

- Manages and processes data.
- Uses software and digital networks.
- Connects people through digital communication.
- Includes computers, smartphones, and the internet

OTHER TYPES OF TECHNOLOGY

Biotechnology: Using living cells and organisms to create medical, agricultural, or industrial products.

Engineering and Applied Technology: Designing and building physical structures, machines, and electronics (Mechanical, Electrical, and Civil).

Medical and Health Technology: Tools, devices, and treatments used to diagnose and cure diseases (MRIs, pharmaceuticals, radiology).

Environmental and Agricultural Technology: Systems for farming, green energy, and protecting natural resources

THE THREE CS OF TECHNOLOGICAL CONVERGENCE

The 3Cs of technological convergence are **computing**, **communication**, and **content**. They represent how previously separate digital tools, networks, and media formats merge into unified, single systems and smart devices like modern smartphones.

The Three Components

COMPUTING

- The hardware and software power
- Data processing on devices
- Running applications locally or in the cloud

COMMUNICATION

- The networks and infrastructure
- Connecting computers and mobile systems
- Transferring data via internet and wireless signals

CONTENT

- The digital information or media
- Text, audio, images, and video
- Delivered digitally across multiple platforms

THE TWO TYPES OF CONVERGENCE

In mathematics, convergence often refers to two main types of infinite series or two primary types of function sequences

a. Infinite Series

Absolute Convergence: The sum of the absolute values of the terms converges.

Conditional Convergence: The original series converges, but the sum of the absolute values diverges

b. Sequences of Functions

Point wise Convergence: Each individual point in the domain converges to a limit value independently.

Uniform Convergence: All points in the domain converge toward the limit at the same overall rate.

THE THREE TYPES OF CONVERGENCE

In geology, the three types of convergent plate boundaries are-

- a. Oceanic-continental convergence,
- b. Oceanic-oceanic convergence, and
- c. Continental-continental convergence.

These boundaries form when Earth's tectonic plates crash into each other.

a. Oceanic-Continental Convergence

- An oceanic plate slides under a lighter continental plate.
- Forms deep ocean trenches and volcanic mountain chains on land.
- Example: The Andes Mountains

b. Oceanic-Oceanic Convergence

- Two oceanic plates collide, and the older, colder, denser plate goes under the other.
- Creates deep trenches and volcanic island arcs.

c. Continental-Continental Convergence

- Two continental plates push together with equal density, meaning neither sinks.
- The crust buckles, folds, and pushes upward to form massive mountain ranges.
- Example: The Himalayas.
- Example: The Mariana Trench

THE OPPOSITE OF CONVERGENCE

The primary opposite of convergence is divergence, which means moving apart or separating from a common point. It depends on the context, other antonyms include dispersion, scattering, or separation.

Contexts and Meanings

General & Math/Science: Divergence (or divergent evolution in biology) describes lines, ideas, or species spreading apart rather than coming together.

Physical Movement: Scattering, spreading, or dispersing.

Social or Group Dynamics: Splitting up, breaking up, or disbanding.

CHARACTERISTICS OF TECHNOLOGY

The technology is the practical use of scientific knowledge to solve human problems, build tools, and expand what people can do. It ranges from simple items like stone tools and wheels to complex systems like computers and artificial intelligence

CORE TRAITS OF TECHNOLOGY

Purposeful: Built with a clear goal to fix a problem or fulfill a human need.

Always Changing: Constantly improves, updates, and evolves into newer versions.

Human-Centered: Created by people, driven by human actions, and meant to serve human purposes.

Expanding Capability: Acts as an extension of the human body and mind, helping us see, move, and compute better.

Pervasive: Found everywhere in daily life, shaping how we work, communicate, and live.

Dual-Impact: Brings both helpful benefits and unintended risks or social challenges.

Interconnected: Relies on a mix of different tools, systems, and networks working together.

MAJOR FIVE DIFFERENCES BETWEEN SCIENCE AND TECHNOLOGY

Science is the systematic study of the natural world to discover new knowledge and explain how things work. Technology is the practical application of that knowledge to invent tools, systems, and solutions that solve human problems and meet specific needs

Core Purpose

Science: Aims to understand and explain natural phenomena. Its motto is knowing.

Technology: Aims to manipulate or control nature to build useful products. Its motto is doing.

Methods

Science: Relies on the scientific method, which involves forming hypotheses, testing ideas, and conducting experiments.

Technology: Relies on the design process, which involves planning, building, testing, and optimizing practical items

Primary Outcomes

Science: Produces theories, laws, models, and published knowledge.

Technology: Produces tangible artifacts, machines, gadgets, and digital systems.

Focus of Value

Science: Focuses on discovery and truth. Knowledge itself is viewed as inherently pure and useful.

Technology: Focuses on invention and utility. Specific technologies can sometimes have both helpful and harmful applications

Intellectual Property

Science: Discoveries of natural laws or principles cannot be patented.

Technology: New physical inventions, software designs, and specialized processes can be patented.

IMPORTANCE OF SCIENCE AND TECHNOLOGY

Science and technology shape every part of our day and our world by improving health care, speeding up communication, and making daily tasks easier. They drive economic growth, solve big problems, and help us understand how the universe works. They give us clean water, electricity, smart phones, and life-saving medicines. These tools save time, keep us safe, and help us learn and work faster.

HEALTH AND MEDICINE

New drugs: New medicines and vaccines fight dangerous diseases.

Medical tools: Advanced machines like X-rays and MRI scanners help doctors see inside the body to heal us.

Better sanitation and care increase human life expectancy

DAILY LIFE AND WORK

- Smart tools, phones, and computers save time and effort.
- Fast travel options make moving from place to place easy.
- Home appliances handle chores quickly so we have free time

EDUCATION AND GROWTH

- Digital books and smart classrooms make learning simple.
- Online platforms and digital libraries make learning materials open to everyone.
- New farming science grows more food to feed the world

- Scientific research gives us a clearer and truer picture of how the natural world works.

COMMUNICATION AND WORK

- **Instant connection:** Phones and the internet let us talk to people across the world in seconds.
- **Easy tasks:** Computers and smart software help us finish office work and school projects quickly.
- Digital tools help businesses reach global markets and support remote work
- Communities share news and coordinate emergency responses quickly

HOME AND COMFORT

Daily tools: Items like refrigerators, stoves, and washing machines save hours of hard work.

Power and light: Electricity turns on our lights and runs fans or air conditioning

Travel and Food

Fast transport: Cars, trains, and planes help us travel long distances in less time.

Better farming: Science helps farmers grow more food using good seeds and smart watering methods

HIGH EFFICIENCY AND PRODUCTIVITY

- Computers and automation complete repetitive tasks fast, saving time and labor.
- Modern farming technology and better irrigation increase food production.
- Transportation networks move people and goods safely and quickly

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Chapter

3

BIOLOGICAL APPLICATIONS OF NANOMATERIALS

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ABSTRACT

Nanomaterials have emerged as important tools in modern biology, biotechnology, medicine, and healthcare because their physicochemical properties can differ substantially from those of bulk materials. Their nanoscale dimensions, large surface-area-to-volume ratios, tunable surface chemistry, optical properties, magnetic behavior, and ability to interact with biomolecules make them suitable for a wide range of biological applications. Nanomaterials are increasingly being investigated for targeted drug delivery, cancer therapy, molecular imaging, biosensing, diagnostics, antimicrobial treatment, tissue engineering, regenerative medicine, gene delivery, vaccine development, and theranostics. Depending on their composition and architecture, nanomaterials can be designed to transport therapeutic molecules, enhance diagnostic signals, protect biological cargo, interact selectively with diseased cells, or provide structural cues for tissue regeneration. This paper reviews the major biological applications of nanomaterials and discusses the relationship between nanoscale properties and biological function. Particular attention is given to metallic nanoparticles, polymeric nanoparticles, liposomes, dendrimers, carbon-based nanomaterials, silica nanoparticles, magnetic nanoparticles, quantum dots, and nanocomposite biomaterials. The paper also examines important challenges, including nanoparticle toxicity, immune-system interactions, protein-corona formation, biodistribution, biodegradability, manufacturing reproducibility, and regulatory requirements. Although nanomaterials offer substantial opportunities for improving diagnosis and treatment, successful biological translation requires careful control of their physicochemical characteristics and rigorous evaluation of safety and efficacy. Future developments are expected to emphasize multifunctional, biodegradable, stimuli-responsive, personalized, and environmentally sustainable nanomaterials.

KEYWORDS: Nanomaterials, Nanotechnology, Nanomedicine, Drug Delivery, Biosensors, Cancer Therapy, Tissue Engineering, Regenerative Medicine, Nanoparticles, Biomedical Applications

INTRODUCTION

Nanotechnology is the science and engineering of materials and systems at dimensions where size-dependent properties become important. The nanoscale is commonly associated with

dimensions of approximately 1–100 nanometers, although regulatory and scientific definitions can vary depending on the material and its properties. At this scale, materials may display optical, electrical, magnetic, catalytic, mechanical, and biological characteristics that differ from their bulk counterparts. The United States Food and Drug Administration (FDA) notes that engineered nanoscale materials can possess unique properties that may influence their safety, effectiveness, and performance. Food and Drug Administration.

The biological sciences have benefited considerably from advances in nanotechnology. Biological systems themselves contain numerous structures at the nanoscale, including proteins, nucleic acids, lipid membranes, molecular motors, and cellular organelles. Consequently, engineered nanomaterials can interact with biological structures at dimensions comparable to their natural components. This compatibility has encouraged researchers to develop nanoscale systems capable of transporting drugs, recognizing biomarkers, imaging cells, modifying biological pathways, and supporting tissue regeneration.

Nanomaterials are particularly attractive for drug delivery because they can encapsulate or bind therapeutic molecules and alter their pharmacokinetic behavior. Nanocarriers may improve solubility, protect unstable drugs, increase circulation time, facilitate cellular uptake, and provide controlled or stimuli-responsive release. Recent research has also expanded toward nucleic-acid therapeutics, including messenger RNA (mRNA), small interfering RNA (siRNA), DNA, and other oligonucleotides. The success of lipid nanoparticles in nucleic-acid delivery has significantly increased interest in nanomedicine. Nanomaterials are also important in biological sensing. Gold nanoparticles, carbon nanotubes, graphene, quantum dots, magnetic nanoparticles, nanowires, and other nanostructures can improve the sensitivity and detection limits of biosensors. Their large surface area permits attachment of biological recognition molecules, while their electrical, optical, and catalytic properties can amplify detection signals. Applications include detection of cancer biomarkers, infectious organisms, glucose, cardiac markers, nucleic acids, and other clinically important analytes. At the same time, nanomaterials introduce new biological and environmental considerations. The same properties that make nanoparticles useful can also produce unexpected biological effects. Size, shape, surface charge, chemical composition, aggregation, solubility, and surface functionalization may influence cellular uptake, immune responses, biodistribution, and toxicity. In biological fluids, nanoparticles rapidly interact with proteins and other biomolecules, forming a dynamic protein corona that can alter their biological identity and behavior. Therefore, the development of biologically useful nanomaterials requires a balance between functionality and safety. This paper provides an overview of the major biological applications of nanomaterials, their mechanisms of action, advantages, limitations, and future prospects.

CLASSIFICATION OF NANOMATERIALS

Nanomaterials can be classified according to their composition, dimensionality, morphology, or origin. Common categories include inorganic, organic, carbon-based, and hybrid nanomaterials.

Metallic Nanoparticles

Metallic nanoparticles include gold (Au), silver (Ag), copper (Cu), iron, platinum, and other metals. Gold nanoparticles are widely investigated because of their optical properties, relatively convenient surface functionalization, and ability to interact with biomolecules. Silver nanoparticles have attracted considerable attention because of their antimicrobial activity.

Metal nanoparticles can be synthesized with different shapes and sizes, including spheres, rods, shells, cubes, and triangular structures. Changes in particle size and morphology can modify optical and biological properties.

Metal Oxide Nanoparticles

Metal oxide nanomaterials include titanium dioxide, zinc oxide, iron oxide, cerium oxide, and others. Iron oxide nanoparticles are especially important for magnetic applications, including magnetic resonance imaging, magnetic separation, and magnetically guided delivery.

Polymeric Nanoparticles

Polymeric nanoparticles may be prepared from biodegradable polymers such as poly (lactic-co-glycolic acid) (PLGA), polylactic acid (PLA), chitosan, and other natural or synthetic polymers. Their composition can be modified to control drug loading, degradation, release rate, and cellular interactions.

Liposomes and Lipid Nanoparticles

Liposomes are spherical vesicles consisting primarily of lipid bilayers. They can carry hydrophilic compounds within their aqueous core and hydrophobic compounds within the lipid membrane. Lipid nanoparticles have become particularly important for nucleic-acid delivery because their formulation can facilitate cellular uptake and intracellular release.

Carbon-Based Nanomaterials

Carbon nanotubes, graphene, graphene oxide, carbon dots, and fullerene-based materials possess distinctive electrical, mechanical, optical, and chemical properties. Their biological applications include biosensing, imaging, drug delivery, photothermal therapy, and tissue-engineering scaffolds.

Silica and Mesoporous Silica Nanoparticles

Mesoporous silica nanoparticles possess porous structures that can accommodate therapeutic molecules. Their pore size and surface chemistry can be modified, making them useful for controlled drug delivery and imaging.

Quantum Dots

Quantum dots are semiconductor nanocrystals exhibiting size-dependent optical properties. They can produce intense and tunable fluorescence, making them useful for biological labeling, imaging, and biosensing. However, the potential toxicity of some heavy-metal-containing quantum dots remains an important consideration.

NANOMATERIALS IN DRUG DELIVERY

Drug delivery is one of the most extensively investigated biological applications of nanomaterials. Conventional drug administration can suffer from poor solubility, rapid degradation, nonspecific distribution, short circulation time, and systemic toxicity. Nanocarriers

can potentially overcome some of these limitations by modifying the distribution and release of therapeutic compounds.

Nanocarriers may transport drugs through the bloodstream and release them at desired biological locations. Their surfaces can also be functionalized with antibodies, peptides, proteins, carbohydrates, or other ligands to promote interaction with specific cell types.

Research on nanomedicine has increasingly moved from conventional small-molecule drug delivery toward delivery of biological macromolecules such as nucleic acids. Lipid nanoparticles have demonstrated particular importance for mRNA delivery and have stimulated broader research into nanoparticles for genomic medicine.

Controlled Drug Release

Nanomaterials can be engineered to release drugs gradually rather than delivering the entire dose immediately. Controlled release may improve therapeutic effectiveness and reduce toxicity. Release can occur through diffusion, polymer degradation, dissolution, or changes in environmental conditions.

Stimuli-Responsive Delivery

Advanced nanocarriers can respond to specific stimuli. These may include: pH, temperature, light, magnetic fields, enzymes, reactive oxygen species, redox conditions. For example, nanoparticles designed to respond to the acidic environment of certain tumors may release therapeutic cargo preferentially within the tumor microenvironment.

Targeted Drug Delivery

Targeting can be passive or active. Passive targeting may exploit physiological differences between diseased and healthy tissues. Active targeting uses molecules on the nanoparticle surface to recognize receptors or other biological features. Targeted systems have been extensively studied for cancer therapy, where selective accumulation or cellular uptake could increase drug concentration in tumors while reducing exposure of healthy tissues. Nevertheless, biological barriers and variability among patients mean that targeting performance observed experimentally does not always translate directly into clinical benefit.

NANOMATERIALS IN CANCER DIAGNOSIS AND THERAPY

Cancer is one of the major areas in which nanotechnology has been investigated. Conventional cancer treatment can be limited by nonspecific toxicity, drug resistance, poor tumor penetration, and inadequate delivery to tumor cells. Nanomaterials can combine diagnostic and therapeutic functions in a single platform, an approach commonly called **theranostics**.

Cancer Imaging

Gold nanoparticles, magnetic nanoparticles, quantum dots, silica nanoparticles, and other nanostructures have been studied as imaging agents. Their unique optical or magnetic characteristics can produce detectable signals. Magnetic nanoparticles, particularly iron oxide-based systems, can interact with magnetic fields and have been investigated for magnetic resonance imaging and magnetic manipulation. Quantum dots can provide strong and tunable fluorescence and have been studied for cellular and molecular imaging.

Photothermal Therapy

Certain nanoparticles can absorb electromagnetic radiation and convert it into heat. Gold nanostructures are especially interesting for photothermal therapy because their optical properties can be engineered to interact with specific wavelengths.

When nanoparticles accumulate near tumor cells, external irradiation can generate localized heating. The resulting temperature increase can damage cancer cells.

Photodynamic Therapy

Nanomaterials can also be designed to transport photosensitizing agents. After activation by light, these systems can generate reactive oxygen species that damage cellular components.

Combination Therapy

Nanoparticles may carry multiple therapeutic agents, for example a chemotherapeutic drug together with a nucleic-acid therapeutic. Such systems may provide opportunities for combination therapy and controlled sequential release.

However, tumor heterogeneity, biological barriers, nanoparticle clearance, and variations in tumor vascularization remain significant challenges.

NANOMATERIALS IN BIOSENSORS AND BIOLOGICAL DIAGNOSTICS

Biosensors convert biological interactions into measurable signals. Nanomaterials can improve biosensor performance through increased surface area, enhanced electrical conductivity, catalytic activity, optical effects, and improved immobilization of recognition molecules.

Recent reviews describe applications of nanomaterial-based biosensors in oncology, infectious disease, diabetes, cardiovascular disease, and other areas of healthcare. Nanomaterials may also facilitate integration with microfluidic, wearable, and point-of-care technologies.

Gold Nanoparticle-Based Biosensors

Gold nanoparticles have favorable surface chemistry and optical properties. Biomolecules such as antibodies, DNA probes, enzymes, and aptamers can be attached to their surfaces.

Changes in nanoparticle aggregation can produce visible color changes, making some gold nanoparticle assays suitable for relatively simple detection systems.

Graphene and Carbon Nanotube Biosensors

Graphene and carbon nanotubes possess useful electrical properties and high surface areas. Their surfaces can be modified to recognize specific biological molecules.

Such sensors have been investigated for detection of glucose, proteins, nucleic acids, pathogens, and cancer-associated biomarkers.

Quantum-Dot Biosensors

Quantum dots can provide fluorescent signals with tunable optical characteristics. They can be coupled with biological recognition elements for sensitive detection.

Magnetic Nanoparticle Biosensors

Magnetic nanoparticles can bind target molecules and subsequently be separated using magnetic fields. This provides opportunities for sample preparation, enrichment, and detection.

Table 1: Examples of Nanomaterials and Biological Applications

Nanomaterial	Major Properties	Biological Applications
Gold nanoparticles	Optical activity, surface functionalization	Biosensing, imaging, drug delivery, photothermal therapy
Silver nanoparticles	Antimicrobial activity	Antimicrobial coatings, wound-related applications
Iron oxide nanoparticles	Magnetic behavior	Imaging, magnetic separation, drug delivery
Lipid nanoparticles	Encapsulation and cellular delivery	mRNA and nucleic-acid delivery
PLGA nanoparticles	Biodegradability, controlled degradation	Drug delivery
Carbon nanotubes	Electrical/mechanical properties	Biosensors, drug delivery, tissue engineering
Graphene/graphene oxide	Large surface area, electrical properties	Biosensors, scaffolds, drug delivery
Quantum dots	Tunable fluorescence	Bioimaging and biosensing
Mesoporous silica	High pore volume and tunable surface	Drug delivery and imaging
Dendrimers	Highly branched architecture	Drug and gene delivery

ANTIMICROBIAL APPLICATIONS

The increasing prevalence of antimicrobial resistance has encouraged research into alternative antimicrobial technologies. Nanoparticles may exhibit antimicrobial effects through multiple mechanisms, including membrane disruption, oxidative stress, interaction with intracellular components, and interference with microbial metabolism. Silver, gold, copper, titanium-containing, and other nanoparticles have been investigated for antimicrobial applications. Nanoparticles can also be incorporated into coatings for medical devices and implants.

Mechanisms of Antimicrobial Activity

Potential mechanisms include: Attachment of nanoparticles to microbial cell surfaces. Disruption of membrane integrity., Generation of reactive oxygen species., Release of biologically active metal ions., interaction with proteins and nucleic acids., Interference with cellular metabolism., Reduction of microbial adhesion and biofilm formation.

The simultaneous operation of multiple mechanisms is one reason nanoparticles are being investigated against microorganisms that may exhibit resistance to conventional antibiotics.

Nevertheless, antimicrobial activity must be balanced against potential toxicity toward human cells. A nanoparticle that damages microbial membranes may also interact with mammalian cell membranes. Therefore, selectivity and dose optimization are essential.

NANOMATERIALS IN TISSUE ENGINEERING AND REGENERATIVE MEDICINE

Tissue engineering aims to repair, replace, or regenerate damaged tissues by combining cells, biomaterials, biochemical signals, and appropriate physical environments.

Nanomaterials can provide nanoscale structural and biochemical cues that influence cell attachment, proliferation, differentiation, and extracellular-matrix organization. Reviews of nanomaterial-based scaffolds have examined graphene, carbon nanotubes, nanocellulose, and other materials for tissue-engineering applications.

Bone Regeneration

Bone is a hierarchical structure containing nanoscale mineral and organic components. Nanostructured hydroxyapatite, calcium phosphate nanoparticles, graphene-based materials, and nanocomposite scaffolds have been studied for bone regeneration.

Nano structuring can increase surface area and influence protein adsorption and cellular behavior. Nanomaterials can also be incorporated into polymeric scaffolds to improve mechanical or biological properties.

Dental Applications

Nanocomposite materials are used and investigated in dentistry because nanoscale fillers can alter mechanical strength, surface properties, wear resistance, and biological interactions.

Nanoparticles have also been studied for antimicrobial dental materials and surface coatings.

Neural Tissue Engineering

Nanostructured materials can provide physical and electrical cues relevant to neuronal growth. Conductive materials such as graphene and carbon-based nanomaterials have therefore attracted interest for neural interfaces and tissue engineering.

Wound Healing

Nanomaterials may contribute to wound healing through controlled delivery of drugs, growth factors, genes, or antimicrobial agents. Nano fibrous scaffolds can mimic some aspects of the extracellular matrix and provide surfaces for cell attachment.

Cell behavior can be influenced by nanoscale geometry, surface chemistry, charge, and ligand presentation. Such cell-instructive biomaterials represent an important direction in regenerative medicine.

NANOMATERIALS FOR GENE AND NUCLEIC-ACID DELIVERY

Gene therapy requires efficient and safe delivery of nucleic acids into target cells. Naked DNA and RNA are susceptible to degradation and may have difficulty crossing cellular membranes.

Nanomaterials can protect nucleic acids and facilitate cellular uptake. Polymeric nanoparticles, lipid nanoparticles, dendrimers, gold nanoparticles, and other nanocarriers have been investigated for this purpose.

DNA Delivery

DNA can be encapsulated or electrostatically associated with positively charged nanomaterials. Following cellular uptake, the carrier may protect DNA from enzymatic degradation and facilitate intracellular trafficking.

siRNA Delivery

Small interfering RNA can selectively reduce expression of target genes. However, siRNA is unstable in biological fluids and requires efficient intracellular delivery. Nanocarriers can improve its stability and cellular uptake.

mRNA Delivery

mRNA therapeutics have received substantial attention because they can provide transient production of therapeutic proteins without requiring genomic integration. Lipid nanoparticles are among the most important delivery platforms for mRNA.

The development of lipid nanoparticles for nucleic-acid delivery has expanded interest in applications such as vaccines, protein replacement, cancer immunotherapy, and gene editing.

CRISPR and Gene Editing

Nanoparticle systems are being explored for delivery of CRISPR-associated components. The goal is to provide controlled delivery of gene-editing molecules while reducing unwanted systemic exposure.

However, gene delivery remains challenging because nanoparticles must overcome extracellular barriers, cellular uptake limitations, endosomal trapping, and potential immune responses.

NANOMATERIALS IN IMAGING AND THERANOSTICS

Medical imaging is essential for disease diagnosis, treatment planning, and monitoring. Nanomaterials can serve as contrast agents or molecular probes.

A major advantage of nanotechnology is the possibility of combining imaging with treatment. A nanoparticle can theoretically contain a therapeutic compound while simultaneously carrying an imaging component.

Magnetic Nanoparticles

Magnetic nanoparticles can alter magnetic resonance signals and have been investigated as contrast-enhancing agents. They may also be manipulated externally using magnetic fields.

Fluorescent Nanomaterials

Quantum dots and carbon dots can generate fluorescence useful for biological imaging. Their optical properties can be tuned by changing size, composition, or surface chemistry.

Plasmonic Nanoparticles

Gold and other plasmonic nanoparticles interact strongly with light. These interactions have been exploited for optical sensing, imaging, photothermal therapy, and molecular detection.

Theranostic Systems

A theranostic Nano platform attempts to integrate diagnosis and treatment. Such systems could potentially allow clinicians to identify a disease-associated target, deliver treatment, monitor therapeutic response, and adjust treatment based on biological information.

Despite the promise of theranostics, complex multifunctional nanoparticles can be difficult to manufacture reproducibly and characterize adequately.

NANOMATERIALS IN VACCINE DEVELOPMENT

Nanotechnology has become increasingly important in vaccine research because nanoparticles can act as antigen carriers, adjuvant platforms, or delivery vehicles.

Nanoparticles may improve antigen stability, facilitate uptake by antigen-presenting cells, and promote immune responses. Their size and surface characteristics can be engineered to influence interactions with immune cells. Lipid nanoparticles have been particularly important for nucleic-acid vaccine delivery. Their ability to package and protect mRNA while facilitating intracellular delivery has contributed to the development of mRNA-based vaccine technologies. Future research may focus on nanoparticles capable of delivering multiple antigens, targeting specific immune-cell populations, and producing controlled immune responses.

NANOMATERIALS IN PERSONALIZED AND PRECISION MEDICINE

Precision medicine seeks to tailor diagnosis and treatment according to the biological characteristics of individual patients.

Nanomaterials can support precision medicine by combining targeting, imaging, drug delivery, and molecular sensing. For example, a nanoparticle may be functionalized to recognize a molecular marker expressed by a particular tumor type.

Nano biosensors may also facilitate rapid detection of biomarkers. Wearable and point-of-care nanosensors could potentially provide continuous monitoring of physiological variables.

The integration of nanomaterials with artificial intelligence, microfluidics, wearable devices, and advanced molecular diagnostics is an emerging area of research. Recent biosensing literature specifically identifies microfluidic integration, artificial intelligence, and wearable technologies as important directions for nanomaterial-enabled healthcare

BIOLOGICAL INTERACTIONS AND PROTEIN CORONA

When nanoparticles enter biological fluids, proteins and other biomolecules rapidly adsorb onto their surfaces. This layer is commonly called the **protein corona**. The protein corona can change the effective biological identity of nanoparticles. Instead of interacting with cells according only to their engineered surface, nanoparticles may interact according to the proteins and biomolecules associated with them. Factors influencing protein-corona formation include: Nanoparticle size, Surface charge, Surface chemistry, hydrophobicity, shape, protein concentration, biological environment, Exposure time. Protein-corona formation can influence nanoparticle aggregation, cellular uptake, biodistribution, immune recognition, and toxicity. Understanding these processes is therefore critical for rational nanomedicine design. Current research continues to emphasize the need for mechanistic understanding of these nano-bio interfaces.

TOXICITY AND BIOSAFETY OF NANOMATERIALS

Although nanomaterials have considerable biomedical potential, safety is one of the most important challenges in their development. Nano toxicity can depend on several characteristics rather than simply the total administered dose. Particle size, surface area, shape, chemical composition, surface charge, dissolution behavior, aggregation, and functionalization can all influence biological responses.

Potential mechanisms of toxicity include: Oxidative stress, Inflammation, Mitochondrial dysfunction, Membrane damage, DNA damage, altered cellular signaling, Immune-system activation, Organ accumulation. The biological fate of nanoparticles is also influenced by their route of administration. Nanoparticles administered intravenously may interact with blood proteins and immune cells, while inhaled nanoparticles encounter the respiratory system and particles administered orally encounter the gastrointestinal tract. The WHO has highlighted concerns regarding unexpected interactions between nanomaterials and biological systems and emphasizes the need for continued research into potential health effects.

Table 2: Major Safety Considerations

Factor	Possible Biological Consequence
Particle size	Alters cellular uptake and biodistribution
Surface charge	Influences membrane interaction and protein adsorption
Shape	May influence uptake and circulation
Composition	Determines degradation and chemical activity
Surface coating	Can modify immune recognition
Aggregation	Changes effective particle size
Dose	Influences severity of biological responses
Exposure route	Determines initial biological barriers
Degradation products	May contribute to toxicity or clearance
Protein corona	Changes biological identity

CHALLENGES IN CLINICAL TRANSLATION

Despite extensive laboratory research, only a fraction of experimental nanomaterials reach routine clinical use. Several factors contribute to this gap.

Reproducibility

Small changes in synthesis conditions can produce differences in particle size, surface chemistry, morphology, and biological performance. Large-scale manufacturing must maintain consistent critical quality attributes.

Characterization

Nanoparticles require extensive physicochemical characterization. Important parameters include particle size distribution, morphology, surface charge, chemical composition, aggregation state, drug loading, release characteristics, and stability. FDA notes that nanomaterial-containing drug products may require careful assessment of properties such as particle size, size distribution, morphology, aggregation, and changes during storage.

Biological Complexity

Results obtained in cell cultures may not accurately predict behavior in living organisms. Differences in protein corona formation, immune interactions, blood circulation, tissue penetration, and clearance can substantially influence performance.

Long-Term Safety

For some nanomaterials, long-term biological effects remain incompletely understood. The possibility of accumulation in organs or persistence of poorly degradable materials requires careful investigation.

Regulatory Requirements

Regulatory agencies evaluate nanomaterial-containing products according to their intended use and specific characteristics. FDA emphasizes a product-focused, science-based approach rather than assuming that all nanotechnology products are either inherently safe or inherently harmful. For nanomaterial-containing drug products, FDA guidance addresses development considerations related to characterization, controls, testing, and quality.

FUTURE PERSPECTIVES

The future of biological nanotechnology is likely to move toward increasingly sophisticated and biologically responsive systems.

One important direction is the development of biodegradable nanomaterials. Biodegradable materials could reduce concerns associated with long-term accumulation.

Another direction is stimuli-responsive nanomedicine, in which therapeutic release occurs in response to disease-associated signals such as enzymes, pH, temperature, or redox conditions.

Personalized nanomedicine may also become increasingly important. Nanoparticles could be designed according to individual molecular biomarkers, disease characteristics, and patient-specific treatment requirements.

The combination of nanotechnology with artificial intelligence may accelerate nanoparticle design by helping researchers predict interactions between physicochemical properties and biological outcomes. Machine learning could also assist in analyzing large datasets involving nanoparticle composition, toxicity, biodistribution, and therapeutic efficacy.

Multifunctional nanomaterials represent another major research direction. Instead of performing a single task, future nanoparticles may combine diagnosis, targeting, therapy, imaging, and controlled release in a single platform.

Finally, sustainable nanotechnology will become increasingly important. Researchers are investigating greener synthesis methods, renewable materials, lower-energy manufacturing, and approaches that reduce environmental impact.

DISCUSSION

Nanomaterials have transformed the way researchers approach the interface between materials science and biology. Their nanoscale dimensions permit interactions with biological structures at molecular and cellular levels. This characteristic creates opportunities that are difficult to achieve with conventional materials.

Drug delivery remains one of the most promising applications because nanoparticles can modify the distribution, stability, solubility, and release of therapeutic agents. At the same time, biosensing demonstrates how the electrical, optical, magnetic, and catalytic characteristics of nanomaterials can improve biological measurements.

The use of nanomaterials in tissue engineering demonstrates another important principle: biological responses can be controlled not only through biochemical signals but also through physical and structural cues. Nanoscale surface characteristics can influence cell attachment, differentiation, and organization.

However, the biological behavior of nanoparticles cannot be predicted solely from their intended design. Once nanoparticles enter biological environments, they undergo transformations involving protein adsorption, aggregation, degradation, immune recognition, and cellular uptake. The protein corona is a particularly important example of how the biological environment can modify nanoparticle behavior.

Consequently, future research should move beyond simply designing nanoparticles with desirable properties in isolation. Instead, nanoparticle development should consider the complete life cycle of a material: synthesis, administration, biological transformation, cellular interaction, biodistribution, degradation, clearance, and potential environmental release.

Clinical translation also requires cooperation between materials scientists, biologists, physicians, pharmacologists, toxicologists, engineers, and regulatory scientists. Such interdisciplinary collaboration is necessary because nanomedicine combines multiple scientific disciplines.

CONCLUSION

Nanomaterials represent a rapidly developing platform for biological and biomedical applications. Their unique physicochemical properties provide opportunities for targeted drug delivery, cancer treatment, biosensing, medical imaging, antimicrobial therapy, gene delivery, vaccine development, tissue engineering, regenerative medicine, and personalized healthcare.

The greatest advantage of nanomaterials is their tunability. Size, shape, composition, surface chemistry, charge, and architecture can be modified to obtain specific biological functions. This versatility allows nanomaterials to serve as carriers, sensors, imaging agents, therapeutic agents, scaffolds, or multifunctional theranostic platforms.

Nevertheless, significant challenges remain. Nanoparticle toxicity, immune interactions, protein-corona formation, biodistribution, long-term fate, manufacturing reproducibility, and regulatory evaluation must be carefully addressed. Nanomaterials should therefore not be considered universally safe or dangerous; their biological effects depend strongly on their individual properties and intended applications. This product-specific approach is also reflected in current regulatory thinking. Future research is expected to focus on biodegradable, stimuli-responsive, multifunctional, targeted, and personalized nanomaterials. Integration with artificial intelligence, microfluidics, gene editing, wearable technologies, and advanced molecular diagnostics may further expand their biological applications.

Overall, nanomaterials have substantial potential to improve the prevention, diagnosis, and treatment of disease. However, their successful translation from laboratory research to routine biological and medical applications will depend on achieving an appropriate balance between performance, reproducibility, safety, affordability, and regulatory acceptability.

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Chapter

4

SMART FARMING: A RECENT APPROACH IN THIS ERA

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ABSTRACT

Smart farming is the use of modern technology, data analytics, and automation to improve the quality, quantity, and sustainability of agricultural production. While new technologies and tools have great integral to food production and farm management, urgent concerns drive the development and adoption of smart farming technologies at present scenario. Chief among them is food security: food production must increase by 70% by 2050 to keep pace with global population growth, according to the International Monetary Fund.

KEYWORDS: Smart Farming, Smart Farmer, IoT, AI, Resource Efficiency, Higher Yields.

INTRODUCTION

Smart agriculture also known as smart farming, is the adoption of advanced technologies and data-driven farm operations to optimize and improve sustainability in agricultural production. Smart farming is the adoption of advanced technologies and data-driven farm operations to optimize and improve sustainability in agricultural production.

HISTORY OF FARMING

Traditional agricultural practices centered on the use of man power, animals and simple tools. Some notable advancement in agricultural technology was the invention of the seed drill for more efficient planting in 1701, steam traction engines that powered grain threshing in the 1800s, and gas-powered tractors in the early 1900s.

The introduction of farm machinery greatly reduced the need for physical work in farming, while data collection and analysis allowed farmers to improve their crop and livestock outputs. This method, called precision agriculture or precision farming, began in the early 1980s with Dr. Pierre Robert, also known as "the father of precision agriculture". He studied how different areas of a field need various amounts of nutrients for the best crop growth. His work led to the creation of farming systems that apply different amounts of resources across a field.

In the 1990s, agri-business technology advanced even further with the creation of the digital crop yield monitor and the growing use of satellite-based Global Positioning Systems (GPS). By combining yield data with GPS, farmers could map their yields, giving them important information about crop characteristics and quality in real time during harvest. Later, GPS technology led to another big breakthrough: automation. The self-driving tractor emerged from a partnership between farm equipment company John Deere and NASA in the early 2000s.

THE 7 COMMON TYPES OF FARMING

Subsistence Farming: Farmers grow crops and raise livestock solely to feed their own families, with little left over to sell.

Commercial Farming: Large-scale production focuses on growing crops or raising animals specifically to sell for a profit in markets.

Plantation Farming: A single cash crop (like tea, coffee, or rubber) is grown on a massive estate primarily for export.

Mixed Farming: Combines crop growing with livestock raising (such as dairy or poultry) on the same farm to balance income and reduce risk.

Intensive Farming: Maximizes crop yields from a small piece of land using high amounts of labor, fertilizers, and machinery.

Dry Farming: Practiced in drier regions with little rainfall, relying on specific water-conservation methods instead of heavy irrigation.

Organic Farming: Avoids synthetic fertilizers and chemical pesticides, using natural manure and crop rotation to protect the environment.

SMART FARMER

A smart farmer uses modern technologies, data, and automation to manage crops and livestock efficiently while reducing waste and protecting the environment.

SMART FARMING

Smart farming is a new way of farming, using technology to help farmers. Smart farming helps you use less water and fertilizer, pesticides or fuel on each hectare of land you work with. In the cyber-physical farm management cycle, smart farming strongly emphasizes the use of information and communication technologies. Smart farming uses sensors and drones to gather data about the soil, crops and livestock. Farmers can use this data to make decisions in their daily work. It is anticipated that emerging technologies like the Internet of Things and cloud computing will take advantage of this progress and expand the use of robotics and artificial intelligence in agriculture.

KEY TECHNOLOGIES

Internet of Things (IoT): Sensors placed in fields or on livestock collect real-time data on soil moisture, temperature, and animal health. IoT refers to a network of physical devices, vehicles, appliances and other physical objects that are embedded with sensors, software and network connectivity that allows them to collect data. In the case of smart farming, IoT devices include many kinds of IoT sensors, including sensors for monitoring crops, tracking livestock and observing the condition of farm equipment. Unmanned aerial vehicles (UAVs) or drones equipped with light detection and ranging (LiDAR) also collect agricultural data through remote sensing.

Drones and Satellites: Unmanned aerial vehicles map fields, monitor crop health, and track growth patterns from above.

Artificial Intelligence (AI) and machine learning: Machine learning models process weather data and sensor readings to forecast yields and spot diseases early. AI and machine learning (ML) can help farmers derive insights from the big data—large, complex data sets—stemming from IoT initiatives. Data analytics and modelling through cloud-based AI and ML tools can inform decision-making and smart farming techniques. For example, predictive analytics, weather data sets and agriculture forecasting models powered by ML can help the agricultural industry manage the production process, including crop production, land utilization and supply chain planning.

Robotics and Automation: Self-driving tractors and robotic harvesters handle repetitive physical tasks like sowing, weeding, and picking. Automation and robotics figure prominently in modern smart farming practices. In addition to autonomous tractors, farmers use robots for tasks like seeding, harvesting and pruning. They can also deploy UAVs to spray fertilizer, pesticides and other agricultural inputs in a manner that can be more efficient and precise than traditional methods. The more precise and limited application of fertilizer, in particular, can have a notable environmental impact: fertilizer is a significant source of greenhouse gas emissions.

Information and communications technology: The US Department of Commerce's National Institute of Standards and Technology defines information and communications technology (ICT) as the capture, storage, retrieval, processing, display, representation, presentation, organization, management, security, transfer and interchange of data and information. Data collection on everything from soil content to weather conditions has become a key facet of smart farming and ICT is helping farmers organize and transfer that data.

Smart soil sensing for water optimization: In Texas, sensors linked to a smartphone app are gathering real-time information on soil conditions, including soil moisture. The app combines this information with other data, including weather forecasts, for an AI-powered analysis that results in watering recommendations. The app sends the recommendations to farmers' mobile devices to help them efficiently deploy water resources for better crop growth in areas affected by droughts and climate change.

Cloud-based irrigation for vine stress: In California, where efficient water use is also a major concern, a winery implemented a cloud-based tool that ingests information from weather forecasts, satellite imagery and sensors to measure vine stress. Analysis of the data yields watering recommendations tailored to the needs of each vine. Since putting the tool in place, yields have increased by 26% while reducing water usage by 16%.

AI-driven climate control in greenhouses: In Kazakhstan's Almaty region, a five-hectare smart greenhouse facility is equipped with IoT technology and AI.

Technologies monitor conditions within the greenhouses and automatically adjust temperatures, light, humidity and irrigation levels as necessary to create the optimal environment for crop growth.

Monitoring animal behaviour for improved dairy production: In the United Kingdom, researchers attached sensors to cattle at dairy farms to track their activity, including steps taken and time spent eating and lying down. Since more active cattle generally display more positive behaviour, such information can help farmers determine whether interventions are necessary — namely, changing the animals’ environment to raise their contentment levels, which tend to improve milk yields.

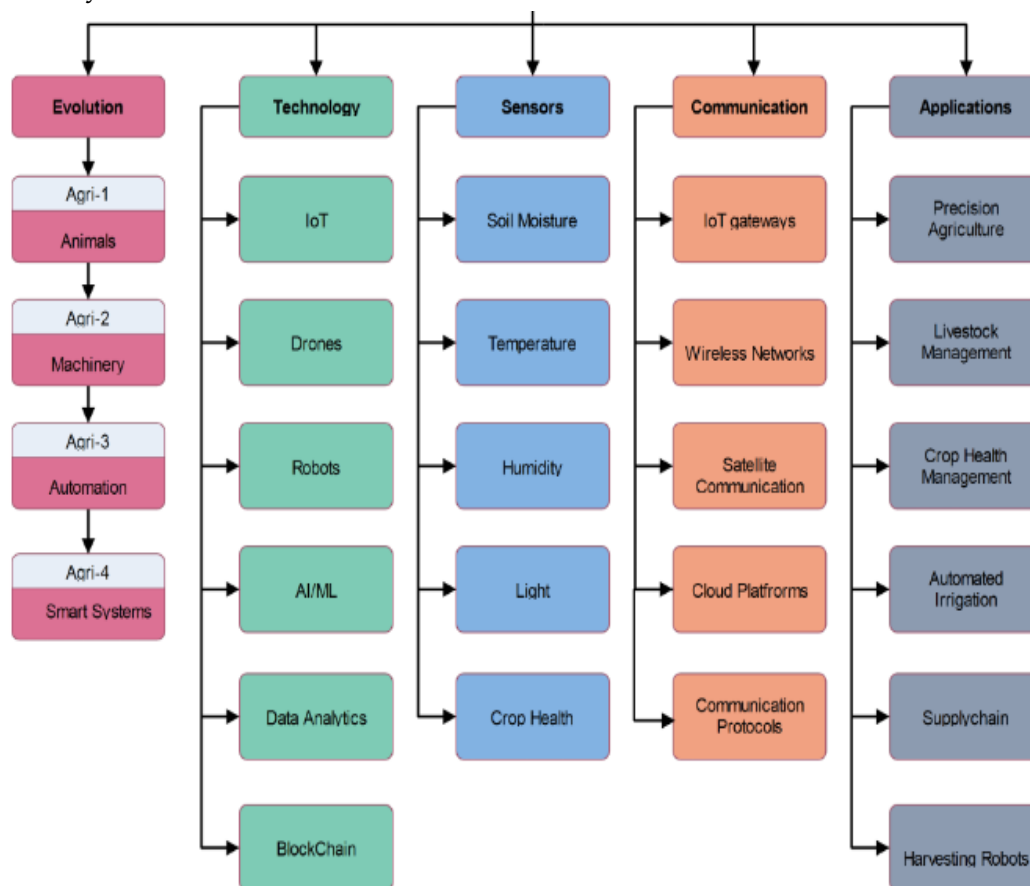


Figure 1: Smart Farming at a Glance

EXAMPLES OF SMART FARMING TECHNOLOGIES

Smart Irrigation Systems: IoT sensors measure soil moisture and local weather to deliver exact amounts of water, cutting down on waste.

Agricultural Drones: Unmanned aerial vehicles map fields, monitor crop health from above, and spray fertilizers or pesticides with high precision.

Autonomous Tractors and Robots: Self-driving machinery and weeding robots perform repetitive tasks like tilling, seeding, and harvesting without human drivers.

Livestock Tracking: Wearable sensors and smart collars monitor animal health, body temperature, and location to catch early signs of illness in herds.

Smart Greenhouses: Automated systems control internal temperature, humidity, lighting, and watering cycles without manual adjustments.

Predictive Analytics Software: Cloud platforms analyze historical weather and soil data to help farmers forecast production output and time their planting.

BENEFITS OF SMART FARMING

Improved efficiency: With smart farming, farmers can better use their resources. This leads to a more efficient system with less waste and more efficient processes.

Reduced costs: Smart farming can also reduce costs because there is less waste in the system, and it uses fewer inputs (such as fertilisers and pesticides) than traditional farming methods.

Increased production: Smart farming allows for increased harvest yields due to improved crop quality, soil health, water quality and farm safety (which means less time spent dealing with pests). This will help increase farm profitability over time and ensure that crops are planted at just the right times so that they reach their full potential before being harvested for sale or consumption.

Fewer greenhouse gas emissions: Smart farms often use more sustainable energy sources such as solar panels or wind turbines instead of fossil fuels. Fuels like gasoline or diesel are used for tractors/trucks during planting/harvesting seasons on these farms (which helps reduce greenhouse gas emissions).

Less water used: Smart farms use less water than traditional farms because they don't need as much irrigation or chemical fertilisers and pesticides to grow crops successfully. This means less pollution from runoff into rivers, streams and lakes when rain falls on fields where chemicals have been applied heavily in previous years.

Reduced use of pesticides and chemical fertilisers: By using sensors, farmers can determine when to apply chemical fertilisers or pesticides at optimal times, reducing their overall use.

Remote Management: Farmers are looking for a better answer to their management problems because their farms are situated in remote regions and foreign countries. Smart farming technology makes smart farming solution possible, allowing farmers to control their fields using smart devices remotely. Farm managers also need to see their fields clearly, regardless of their health, weather, travel ability, or workforce shortages. Smart technology's remote administration enables transparency and real-time crop monitoring, improving production.

CORE BENEFITS

Resource Efficiency: Uses up to 50% less water and cuts down on chemical and fertilizer waste. Precise water, fertilizer, and pesticide application cuts down on waste.

Cost Savings: Automation and optimized inputs lower overall operational expenses.

Higher Yields: Boosts overall crop production through precise, data-backed care. Data-backed decisions lead to healthier crops and more predictable farm output.

Time Efficiency: Reduces daily manual labor by automating monitoring and machinery.

DRAWBACKS TO SMART FARMING

There are drawbacks to smart farming, too. Whilst it's a step forward in reducing waste and improving food production, there are still some issues to be worked out.

- The impact of smart farming on climate change is not yet clear. Smart farming can help reduce greenhouse gas emissions by reducing the need for tractors and other machines

that run on fossil fuels. Still, it may also increase the use of pesticides and fertilisers, which also contribute to global warming.

- Smart farming won't solve all problems--it might even create new ones! Some critics point out that smart farm will follow the same model as conventional farms: large-scale operations with cheap labour from migrant workers who don't speak for themselves about working conditions.

LIMITATIONS

Climate change is making it harder to secure enough food. It reduces crop yields and endangers the availability of natural resources such as water for irrigation. In addition to climate issues, the agricultural sector also faces profitability challenges amid the rising costs of inputs like fertilizer, volatile commodity prices and increasing regulatory requirements.

“Through smart farming, we can better adapt to the uncertainties brought by climate change, mitigate environmental impacts and promote resilience in agricultural production.”

CONCLUSION

Smart farming is a new and exciting concept that many farmers are gradually adopting. It combines the best of traditional farming practices with the latest technologies to increase efficiency and produce higher quality products at lower costs. Whilst this new way of doing things has drawbacks, such as over-reliance on technology or increased dependence on government subsidies, many benefits make it worth considering for those looking to increase their profits while still having fun doing what they love most

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Chapter

5

**ENVIRONMENTAL FATE, TOXICOLOGY, BIOSAFETY, POLICY,
AND ETHICS: EVALUATING THE ECOLOGICAL FOOTPRINT OF
BHATIYATOLA DOLOMITE MINES ON ADJOINING FOREST
ECOSYSTEMS**

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ABSTRACT

Open-cast mining and mechanized mineral processing at Bhatiyatola (Bamhani Banjar) region, Mandla District, Madhya Pradesh, India yield substantial volumes of dolomite [$\text{CaMg}(\text{CO}_3)_2$] dust. While macro-scale fugitive dust emissions are traditionally monitored, high-energy extraction, blasting, pulverization, and haulage generate sub-micron and nanoscale mineral particulates ($\text{PM}_{0.1}$ to $\text{PM}_{2.5}$). This chapter evaluates the nano-environmental fate, transport dynamics, toxicological cascades, and biosafety risks posed by incidental nanoscale dolomite and co-occurring crystalline silica dust on contiguous dry deciduous forest canopies and plantation buffers. We review canopy foliar necrosis, stomatal clogging, soil alkalization, altered rhizosphere biogeochemistry, and trophic bio magnification. Furthermore, we examine existing Indian environmental regulatory structures (EIA Notification 2006, Forest Conservation Act 1980, Mines and Minerals Act), identifying critical policy blind spots regarding nanoscale airborne mineral pollutants. We conclude with a bioethical framework rooted in environmental justice for local tribal populations and outline engineered phyto-barriers and nano-monitoring strategies for sustainable landscape restoration.

KEYWORDS: Dolomite, Nano-environmental Fate, Ecotoxicology, Biosafety, Environmental Ethics, Forest Ecology.

INTRODUCTION

INTRODUCTION AND REGIONAL CONTEXT

Mineral extraction modifies the physical environment by removing geological material and, in open-cast operations, disturbing the land surface. The resulting environmental footprint is determined not only by the area excavated but also by ancillary activities such as road construction, mineral transportation, waste handling, and drainage alteration and vegetation clearance. Dolomite [$\text{CaMg}(\text{CO}_3)_2$] is a carbonate mineral with comparatively low intrinsic chemical toxicity under ordinary environmental conditions. Therefore, the environmental assessment of dolomite mining should focus primarily on exposure generated by mining operations, rather than assuming that dolomite itself behaves as a highly toxic contaminant.

The relevant environmental hazards arise from excavation, drilling, handling, crushing, transportation, waste deposition, particulate emissions, soil disturbance, vegetation clearance, runoff, noise, habitat modification, exposure of ecological receptors and potential ecological response. This distinction is particularly important for forest-edge landscapes, where even moderate changes in environmental conditions can influence plant physiology, regeneration, soil processes and habitat connectivity. The mineral wealth of the Bhatiyatola–Bamhani Banjar belt is rooted in the Mesoproterozoic carbonate-dominated meta-sedimentary lithologies of the Sausar and Chilpi Ghat Groups, along with the adjoining Bijawar transition suites that abut the Deccan Trap basaltic flows covering the surrounding tablelands. Tectonically sheared and metamorphosed, these formations yield high-purity, crystalline dolomite—a stoichiometric double carbonate of calcium and magnesium

The central Indian highlands across the Narmada river basin host significant carbonate mineral deposits, predominantly dolomitic limestone formations. In the Bamhani Banjar tract of Mandla district, Madhya Pradesh, the Bhatiyatola dolomite mining cluster (Figure 1 &2) present in Banjar river basin serves as a major node for refractory-, steel-, and agricultural-grade dolomite extraction. Dolomite, chemically characterized as double carbonate of calcium and magnesium ($\text{CaMg}(\text{CO}_3)_2$), is won via semi-mechanized open-cast quarrying, dry drilling, unconfined blasting, crushing, and road transport from mining site to main road cause major particle pollution in vicinity.

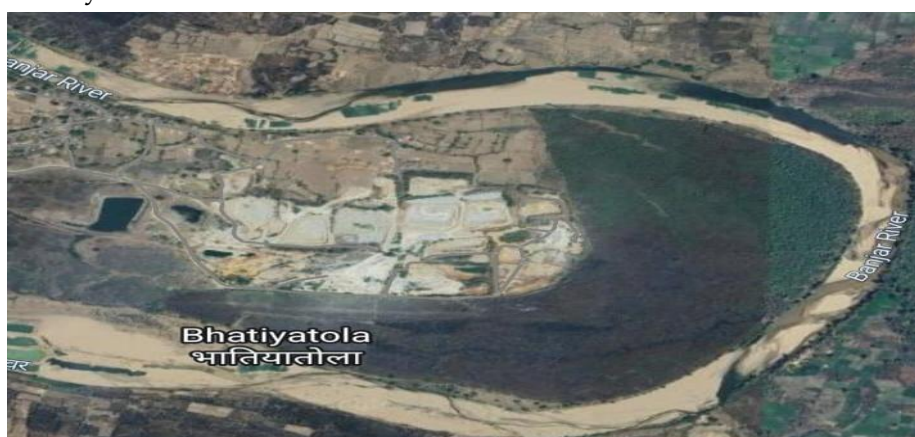


Figure 1: Dolomite mining site at Bhatiyatola, Mandla (Source-Google map image).

Adjoining these concessions are fragile dry tropical deciduous forest tracts dominated by *Tectona grandis* (Teak), *Terminalia tomentosa* (Saja) *Madhuca longifolia* (Mahua), as naturally grown dominating species while afforestation plantation blocks mainly consists mixed species with boundary of pollution tolerant species layer. While mining concessions operate under statutory ambient air quality norms focused on particulate matter (PM_{10} and $\text{PM}_{2.5}$), high-energy processing mechanization inadvertently fragments macro-minerals into ultrafine and nanoscale mineral fractions ($< 100 \text{ nm}$). These incidental nanomaterials possess elevated specific surface areas, unique surface charge profiles, and prolonged atmospheric residence times, bypassing conventional buffer zones and penetrating deep into adjoining forest ecosystems, which affect the growth of plant.



Figure 2: A. Visible impact on adjoining plantation showing growth suppression.

B. Dolomite Mines with current status (Source-Google map image).

THE PROBLEM STATEMENT AND CHAPTER OBJECTIVES

The proximity of mechanized dolomite extraction at Bhatiyatola to fragile deciduous ecosystems and compensatory afforestation blocks creates an unresolved socio-ecological and toxicological dilemma. The core challenge lies in a fundamental structural discrepancy:

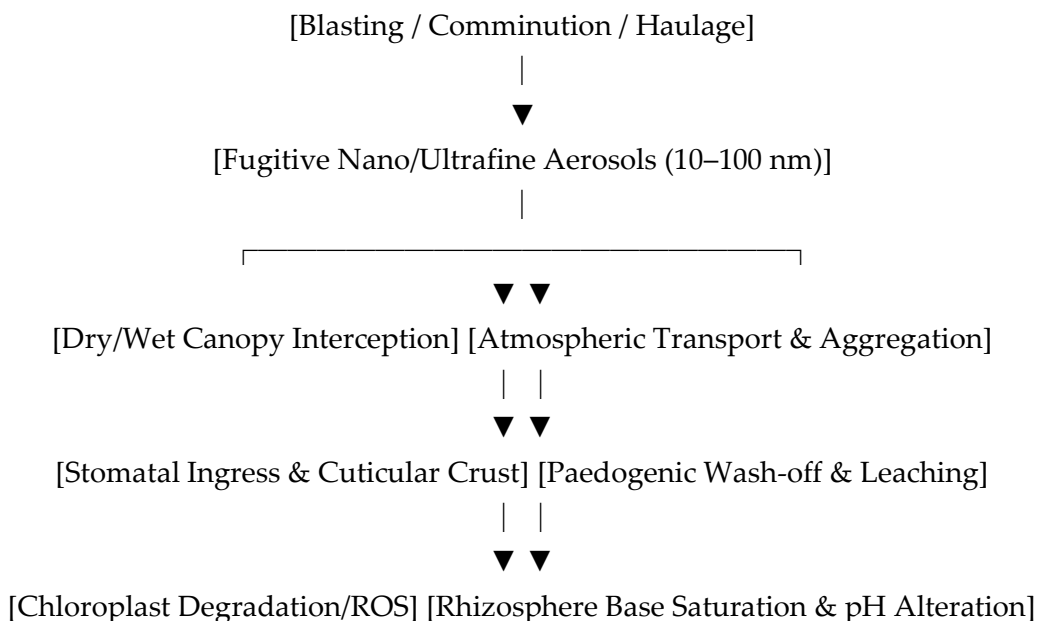
Analytical and Regulatory Gaps: Indian environmental clearance frameworks, compliance regimens under State Pollution Control Boards (SPCBs), and National Ambient Air Quality Standards (NAAQS, 2009) rely solely on gravimetric mass concentration metrics ($\mu\text{g}/\text{m}^3$) for particles down to $\text{PM}_{2.5}$. They lack protocols for particle number concentration (N/cm^3), active mineral surface area, or sub-micron toxicological characterization. High concentrations of reactive nanoparticles can saturate the forest atmosphere without triggering mass-based regulatory thresholds.

Canopy-Level Ecotoxicology: While macro-dust coats external foliage surfaces, incidental nanoparticles penetrate stomatal pores, generate intracellular Reactive Oxygen Species (ROS), trigger foliar chlorosis, and cause alkaline crusting. When washed into the forest floor, they alter the pH of naturally acidic soils, locking up essential phosphorus and suppressing vital ectomycorrhizal fungi.

Bioethics and Indigenous Vulnerability: The landscape is inhabited by indigenous Gond and Baiga communities whose forest-based economies—centred on Non-Timber Forest Products (NTFPs) like Mahua, Tendu, and Sal seeds—suffer direct degradation from chronic mine dust dispersion.

NANO-ENVIRONMENTAL FATE AND TRANSPORT DYNAMICS

At that particular site the atmospheric dispersion, deposition, and paedogenic incorporation of unregulated dolomite mining derived nanoscale particulates follow distinct abiotic transport pathways follow as:-



Atmospheric Suspension and Hetero-Aggregation

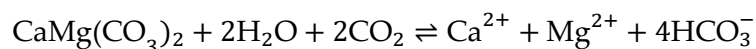
Nanoscale dolomite dust particles stay suspended over kilometres due to low gravitational settling velocities ($v_s \propto r^2$, governed by the Stokes-Cunningham regime). During atmospheric transport:

Hetero-aggregation: Nanoparticles collide with ambient carbonaceous soot, agricultural burn aerosols, and biological organic matter, shifting their hydrodynamic diameters and surface reactivity.

Surface Photo-activation: Solar ultraviolet irradiation drives photochemical weathering on cleaved mineral faces, activating dangling bonds and hydroxyl radicals ($\cdot\text{OH}$) on fractured trace silica (SiO_2) and metal inclusions present within the dolomite matrix.

Foliar Interception and Cuticular Crusting

Tree species along the Bhatiyatola forest beat periphery act as physical particulate sinks. Sub-micron and nanoscale particles deposit onto foliage through Brownian diffusion and impaction. Once settled, moisture from fog, dew, or low precipitation induces dissolution and reprecipitation:



Recrystallization under diurnal solar drying forms hard, alkaline micro-crusts on the adaxial and abaxial foliar surfaces, altering optical reflectance, elevating leaf surface temperature, and modifying cuticular transpiration.

ECOTOXICOLOGICAL MECHANISMS ON FOREST FLORA AND PLANTATION SOIL

Nanoscale mineral aerosols cause harm far beyond mere physical blockage. Upon exposure, these microscopic particles penetrate deep biological barriers, actively triggering complex cellular stress, oxidative inflammation, and reactive biogeochemical cascades that disrupt essential physiological functions while altering broader environmental systems.

Table 1: Eco-Compartments and its Physical, Chemical and Mechanical Consequences

Eco-Compartment	Physical / Chemical Impact	Mechanistic Toxicological Consequence
Foliar Cuticle & Stomata	Size-exclusion breach (< 50 nm particles enter stomatal apertures)	Guard-cell physical pinning; inhibited stomatal conductance; chronic water stress; loss of photosynthetic rate (P_n).
Photosynthetic Apparatus	Nanoparticle trans chelation across cellular walls into the mesophyll	Reactive Oxygen Species (ROS) generation (H_2O_2 , $O_2^{\cdot-}$); lipid peroxidation; chlorophyll <i>a/b</i> degradation.
Forest Soil Edaphon	Carbonate oversaturation; elevated pH(> 8.5)	Induced micronutrient immobilization (Fe, Zn, Mn, P); depletion of ectomycorrhizal fungal hyphae.
Understory & Seedlings	Fine dust deposition on floral reproductive organs	Impaired pollen viability; reduced seed germination in native species (<i>Madhuca longifolia</i> , <i>Buchanania lanzan</i>).

Disruption of the Forest Canopy Biogeochemistry

In sensitive species like *Tectona grandis*, *Terminalia tomentosa* continuous exposure to dolomite dust elevates apolaustic pH. High magnesium-to-calcium ratios displaced into cellular compartments disrupt membrane integrity, leading to marginal leaf chlorosis and premature defoliation. Also check the growth of plants and looks very small in comparison to other adjoining area plantation. The nano-scale fraction exhibits an order-of-magnitude higher dissolution rate than bulk mine tailings, intensifying alkaline shock events during intermittent rainfall.

Soil System and Rhizosphere Alterations

Natural forest soils in the Mandla tract are characteristically Alfi sols and lateritic red soils (slightly acidic to neutral, pH 5.8--6.5). Continuous dry deposition of fine carbonate particulates raises the surface soil pH to alkaline thresholds (pH 8.2--8.8). This alkaline shift converts available phosphates into insoluble calcium phosphates [$Ca_3(PO_4)_2$], precipitating acute nutritional deficiencies that severely affect the afforestation sapling survival rates.

BIOSAFETY ASSESSMENT AND ECOLOGICAL RISK MATRIX

A structured biosafety evaluating both occupational (human workforce) and ecological endpoints of the study area:

Inhalation Hazard (Human & Biodiversity): Nano-particles which bypass upper respiratory clearance via alveolar translocation, triggering chronic pulmonary inflammation, silicosis, and oxidative tissue trauma in both mine workers and local biodiversity of the study area.

Secondary Nanomaterial Leaching: Runoff carrying colloidal and nano-sized carbonate suspensions enters local seasonal nullahs and surface water channels feeding the Banjar and Narmada River catchments, increasing water turbidity and shifting aquatic bicarbonate equilibria.

POLICY, REGULATORY ARCHITECTURE, AND COMPLIANCE CHALLENGES

India's environmental protection framework contains regulatory instruments that govern mineral extraction, yet enforcement remains largely calibrated toward macro-particulates:

Gaps in Current Mining & Pollution Law

The Air (Prevention and Control of Pollution) Act, 1981 & NAAQS (2009): National Ambient Air Quality Standards monitor PM₁₀ and PM_{2.5}. Sub-micron (PM₁) and ultrafine nanoscale aerosols (PM_{0.1}) are not legally recognized or monitored, enabling operators to claim statutory compliance even under high ultrafine dust releases.

Environment Impact Assessment (EIA) Notification, 2006: Environmental Management Plans (EMPs) for small-to-medium dolomite concessions (often under 5 hectares or grouped lease clusters) frequently employ generic mitigation approaches (water tankers, wet drilling) that are ineffective at capturing aerosolized nanoparticles.

The Forest (Conservation) Act, 1980 & Wildlife Protection Act, 1972: Study area to non-notified forests which lack rigorous airshed monitoring process, leaving peripheral forests area vulnerable to cumulative atmospheric pressure.

ENVIRONMENTAL ETHICS AND SOCIO-ECOLOGICAL GOVERNANCE

The exploitation of mineral resources in tribal-dominated districts like Mandla raises fundamental bioethical and environmental justice issues:

Generational Equity and Ecosystem management services: Dolomite extraction provides short-term economic gains in the study area at the cost of long-term depletion of non-timber forest products (NTFPs) such as Mahua, Tendu leaves, and karonda fruits, which form the socio-economic backbone of local Gond and Baiga tribes.

Ecological Justice: Current extraction models prioritize industrial inputs for metallurgical markets elsewhere while externalizing the ecotoxicological and health costs onto indigenous populations and surrounding biotic habitats.

Rights of the Forest Community: Under the Provisions of the Panchayats (Extension to Scheduled Areas) Act (PESA, 1996) and the Forest Rights Act (FRA, 2006), local Gram Sabhas hold legal stewardship over natural resources. Mining concessions that degrade surrounding forest vitality through airborne pollutants infringe on the statutory rights of communities to undisturbed forest ecosystems.

INTEGRATED MITIGATION AND MANAGEMENT STRATEGIES

To mitigate nano-particulate dispersion and rehabilitate impacted canopy buffer zones around Bhatiyatola, a multi-tiered engineering and biological framework is required:

TECHNICAL AND OPERATIONAL INTERVENTIONS

High-Pressure Micro-Mist and Electrostatic Dust Suppression: Replace conventional high-volume water spraying with atomized surfactant-assisted mist cannons at crushing and screening nodes to aggregate ultrafine particles (< 10 µm).

Enclosed Commuting and Conveyor Buffering: Mandate acoustic and physical shrouding on primary and secondary crushers with negative pressure bag-house filters designed for sub-micron capture.

ECO-ENGINEERING AND PHYTO-BARRIERS

Multi-Tiered Green Belts: Establishment of a 100-meter multi-canopy bio screen around mining concessions. The barrier design should be combined:

Outer Tier: Dense, dust-resilient, rough-leaved native species (*Ficus benghalensis*, *Ficus religiosa*, *Azadirachta indica* etc.).

Intermediate Tier: Fast-growing, dust tolerant intermediate-canopy species with trichome-rich leaves (*Alstonia scholaris*, *Dalbergia sissoo*, *Peltophorum* etc.).

Ground Tier: Clump-forming bamboo species (*Dendrocalamus strictus*) and dust tolerant dense shrubs to disrupt ground-level wind currents and capture low-altitude fugitive plumes.

Soil Remediation in Impacted Plantations: Should apply organic amendments (acidified leaf litter compost, humic acid, gypsum) to dust-affected soils to buffer hyper-alkalinity and remobilize locked micronutrients.

CONCLUSION

The open-cast dolomite mines of Bhatiyatola highlight the systemic challenge of managing incidental nanoscale pollutants at the interface of mining activities and forest reserves. Mitigating these impacts requires moving beyond basic macro-particulate monitoring to address the physical and chemical interactions of sub-micron mineral dust.

Strengthening ambient air standards to track ultrafine particles, enforcing cumulative cluster-level impact assessments, respecting tribal governance frameworks, and implementing engineered phyto-barriers provide a clear path to protect the fragile forest ecosystems and biodiversity corridors of the Mandla region. From a policy and ethical perspective, sustainable mining requires more than regulatory approval. It requires demonstrable environmental performance, transparent monitoring, progressive restoration, protection of natural forest and consideration of cumulative landscape-level impacts. Ecological restoration should aim to recover ecosystem functions and biodiversity rather than simply replace cleared vegetation with numerical plantation targets.

Thus, Bhatiyatola represents a suitable model landscape for developing an integrated Dolomite Mining–Forest Ecological Risk Assessment Framework, combining environmental fate, ecotoxicology, biosafety, biodiversity assessment, remote sensing, regulatory compliance and environmental ethics. Such a framework can generate scientifically defensible evidence for balancing mineral-resource utilization with long-term conservation of forest ecosystem services.

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Chapter

6

NANOMATERIALS USED AS A CATALYST IN CHEMICAL TRANSFORMATIONS

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ABSTRACT

Nanomaterials have transformed the field of catalysis by offering unprecedented control over activity, selectivity, and stability in a wide range of chemical transformations. Their high surface-to-volume ratios, tunable physicochemical properties, and unique quantum and confinement effects enable dense populations of accessible active sites, modified electronic structures, and cooperative interactions with supports. This chapter provides an overview of the fundamental principles governing nanomaterial-based catalysis, including size, shape, surface energy, and synergistic effects in composites and supported systems. Major classes of Nano catalysts—metal and metal oxide nanoparticles, magnetic nanomaterials, carbon-based nanostructures, semiconductor nanomaterials, and nanocomposites—are discussed with emphasis on their roles in oxidation, reduction, hydrogenation/dehydrogenation, C–C bond-forming and cross-coupling reactions, photocatalysis, organic synthesis, and environmental remediation. Recent developments such as single-atom catalysts, alloy and intermetallic nanoparticles, and magnetic recyclable Nano catalysts are highlighted as enabling more efficient and sustainable transformations. Key advantages of Nano catalysts include enhanced catalytic efficiency, improved selectivity, reduced catalyst loading, faster reaction rates, and facile recovery. Persistent challenges—aggregation, deactivation, stability, toxicity, and scale-up—are critically examined. Finally, emerging trends, including green synthesis, bio-based nanomaterials, visible-light photocatalysis, and data-driven catalyst design, are outlined to illustrate the future potential of nanomaterials in sustainable chemical manufacturing.

KEYWORDS: Nano Catalysts, Metal Nanoparticles, Carbon-Based Nanomaterials, Photocatalysis, Single-Atom Catalysts, Green Chemistry, Magnetic Recyclable Catalysts, Chemical Transformations.

INTRODUCTION

Catalysis underpins the vast majority of industrial and fine chemical processes, governing the efficiency, selectivity, and sustainability of transformations in basic chemical production, pharmaceuticals, and environmental technologies. Conventional homogeneous and heterogeneous catalysts, though widely deployed, often suffer from limited active-site utilization, poor recyclability, and suboptimal selectivity, leading to energy-intensive and waste-generating processes. The emergence of nanotechnology has created new opportunities

to overcome these limitations by designing catalysts with atomic- to nanometer - scale control over structure and composition (Sharma *et al.*, 2015).

Nanomaterials—typically defined as materials with at least one dimension below 100 nm—exhibit properties distinct from their bulk counterparts due to high surface-to-volume ratios, quantum confinement, altered surface energies, and an increased fraction of under-coordinated atoms. In catalysis, these characteristics translate into a high density of active sites, modified adsorption energies for reactants and intermediates, and the possibility of engineering specific surface facets, defects, and interfaces that promote desired pathways while suppressing side reactions.(Liu & Corma, 2018)

Within this context, nanomaterials have become key platforms for diverse catalytic applications, ranging from thermal and electrocatalytic processes to Photocatalytic and enzyme-mimetic reactions. Supported metal nanoparticles, alloy and intermetallic particles, metal oxides, carbon-based nanomaterials, and more recently single-atom catalysts (SACs) and subnanoclusters have demonstrated superior performance in oxidation, reduction, hydrogenation, C–C coupling, and environmental remediation reactions.(Fan *et al.*, 2021; Liu & Corma, 2018) This chapter provides a concise yet comprehensive overview of the role of nanomaterials as catalysts in modern chemical transformations, emphasizing fundamental principles, classes of Nano catalysts, key applications, advantages, limitations, and future perspectives.

FUNDAMENTALS OF NANOMATERIALS IN CATALYSIS

High surface area and surface-to-volume ratio

Reducing particle size into the nanoscale significantly increases the fraction of atoms located at the surface or near-surface region. This high surface-to-volume ratio leads to a greater number of catalytically accessible sites per unit mass of catalyst, enhancing turnover frequencies and enabling reduced precious metal loading. For supported noble-metal Nano catalysts, activity often scales inversely with particle diameter until deleterious sintering or instability emerges.(Liu & Corma, 2018; Sun *et al.*, 2024)

Size-dependent properties

At the nanoscale, electronic band structures, d-band centers, and density of states can change with particle size, directly affecting adsorption strengths and reaction barriers. For example, metal clusters and intermetallic nanoparticles show size- and composition-dependent activity in oxidation and hydrogenation reactions due to modified metal–adsorbate interactions.(Chung *et al.*, 2015; Liu & Corma, 2018) Single-atom catalysts push this trend to the extreme, with isolated metal atoms stabilized on supports, maximizing atomic utilization and yielding unique reaction pathways.(Shan *et al.*, 2022; Velpandian *et al.*, 2024)

Surface energy, defects, and active sites

Nanoscale materials possess high surface energy, promoting the formation of low-coordination sites such as steps, kinks, and vacancies that often act as highly active centers for bond activation (e.g., O-H, C-H, or N-O bonds). Surface defects in oxides and carbon supports similarly modulate catalytic behavior by altering charge distribution, creating oxygen vacancies,

or anchoring metal species in well-defined coordination environments (e.g., M-N-C moieties, Shan *et al.*, 2022)

Shape and morphology effects

Shape-controlled nanocrystals expose specific high-index facets, terraces, or edges with distinct catalytic properties. For example, Pt- and Pd-based nanocubes, nanorods, and octahedra can exhibit different activities toward oxidation and reduction reactions owing to facet-dependent adsorption energies and activation barriers. (Liu & Corma, 2018) Hollow, core-shell, yolk-shell, and hierarchical architectures further enhance mass transport and provide confined microenvironments that promote selectivity. (Li *et al.*, 2020)

Electronic and optical properties

Nanostructured semiconductors and plasmonic metals exhibit size- and shape-dependent optical absorption, enabling efficient light harvesting for Photocatalytic transformations. Band-gap engineering in materials such as TiO₂, g-C₃N₄, and MXenes expands visible-light response and promotes charge separation, while plasmonic nanostructures (Au, Ag) generate hot carriers that can drive surface reactions under mild conditions (H. Li *et al.*, 2020).

Synergistic effects in nanocomposites

Hybrid nanostructures—such as metal nanoparticles on conductive carbon, bimetallic and intermetallic alloys, and oxide-carbon heterostructures—exhibit synergistic effects through electronic metal-support interactions, strain, and interfacial charge transfer. Bimetallic nanoparticles, single-atom alloy catalysts, and correlated SAC-NP systems have shown enhanced activity and selectivity in oxidation, hydrogenation, and C-C coupling due to cooperative active centers and modified reaction pathways (Gao *et al.*, 2024; Shan *et al.*, 2022).

Heterogeneous and homogeneous nanocatalysis

Most nanomaterials operate as heterogeneous catalysts, dispersed on supports or in multiphase systems, facilitating separation and recycling. However, colloidal and ligand-stabilized nanoparticles can function in quasi-homogeneous regimes, offering high accessibility and tunable microenvironments at the cost of more complex recovery. The design of magnetically recoverable Nano catalysts and supported SACs seeks to combine homogeneous-like activity with heterogeneous recyclability. (Ahmad *et al.*, 2025; Subhadarshini & Pumera, 2024)

TYPES OF NANOMATERIALS USED AS CATALYSTS

Metal nanoparticles

Metal nanoparticles (NPs) of Au, Ag, Pt, Pd, Ni, Cu, and Fe are widely employed due to their high intrinsic activity and tunable size/shape. Supported Pt and Pd NPs are prototypical catalysts for hydrogenation and dehydrogenation, CO and VOC oxidation, and C-C coupling reactions. (Liu & Corma, 2018) Cu nanoparticles have gained attention for sustainable C-C and C-N bond-forming reactions, offering lower cost and good selectivity in coupling and click reactions. (Wang *et al.*, 2022) Bimetallic and intermetallic NPs (e.g., Pt-Fe, Pt-Co, Cu-Ni) further improve activity, stability, and poison tolerance via synergistic interactions. (Bimetallic Nanoparticles: Advances in Fundamental ..., 2024; Chung *et al.*, 2015)

Metal oxide nanoparticles

Transition metal oxides (e.g., TiO_2 , CeO_2 , MnO_x , Co_3O_4 , Fe_2O_3) serve as both active catalysts and supports for metals. Nano structuring enhances oxygen mobility, surface acidity/basicity, and defect density, crucial for selective oxidation of CO, VOCs, alcohols, and aldehydes, as well as redox-mediated environmental remediation.(Liu & Corma, 2018; Sun *et al.*, 2024)

Magnetic nanoparticles

Magnetic nanoparticles, typically Fe_3O_4 or $\gamma\text{-Fe}_2\text{O}_3$, are attractive as catalyst supports owing to their easy magnetic recovery. Functionalized with transition metals or anchored ligands, they catalyze diverse reactions including carbonylations, cross-couplings, and reductions, while enabling efficient separation and re-use, aligning with green chemistry principles.(Ahmad *et al.*, 2025)

Carbon-based nanomaterials

Graphene, graphene oxide (GO), reduced graphene oxide, carbon nanotubes (CNTs), carbon dots, and N-doped carbons act as conductive supports and sometimes as active sites (e.g., M–N–C sites). Their high conductivity, large surface area, and tunable surface chemistry facilitate charge transfer and strong metal–support interactions, beneficial in oxidation, reduction, and electrocatalytic reactions.(Gao *et al.*, 2024; H. Li *et al.*, 2020)

Semiconductor nanomaterials

Semiconductor nanostructures (TiO_2 , ZnO , $g\text{-C}_3\text{N}_4$, metal sulfides, MXenes, and heterojunctions) are central to photocatalysis. Nanoscale engineering and heterostructures formation with metals or carbon materials improve light absorption, charge separation, and surface reaction kinetics in Photocatalytic hydrogen evolution, CO_2 reduction, and organic degradation.(Fan *et al.*, 2021; S. J. Li *et al.*, 2026)

Nanocomposites and hybrid nanomaterials

Nanocomposites combine metal/oxide/carbon/semiconductor components to exploit complementary properties—e.g., metal–carbon composites for improved conductivity and dispersion, or oxide–metal hybrids for bifunctional redox and acid–base catalysis.(*Bimetallic Nanoparticles: Advances in Fundamental ...*, 2024; H. Li *et al.*, 2020)

Supported Nano catalysts and single-atom systems

Immobilizing nanoparticles or single atoms on high-surface-area supports (oxides, carbons, MOFs, covalent organic frameworks) improves stability and enables precise control over active-site environments. Single-atom catalysts (SACs) and single-atom alloys (SAAs) supported on carbon or oxides show exceptional atom efficiency and often unique selectivity in oxidation, hydrogenation, and CO_2 conversion.(S. Wang *et al.*, 2022)

NANOMATERIALS IN IMPORTANT CHEMICAL TRANSFORMATIONS

Oxidation reactions

Single-atom and nanostructured catalysts now dominate low-temperature oxidation of volatile organic compounds (VOCs) and formaldehyde. Co single-atom catalysts on oxide supports achieve complete HCHO oxidation at ambient temperature, attributed to atomically dispersed

Co–O sites that activate O₂ and stabilize reactive intermediates.(Zhang *et al.*, 2023) Noble-metal catalysts spanning nanoparticles, subnanoclusters, and single atoms (Pt, Pd, Au, Rh, Ir) supported on oxides or aerogels similarly provide near-quantitative HCHO conversion at room temperature, with high dispersion and strong metal–support interactions suppressing deactivation.(Sun *et al.*, 2024) Recent reviews emphasize design principles for single-atom catalysts in VOC oxidation, highlighting the role of M–Nx and M–Ox coordination and defect-rich supports in tuning activity and selectivity.(Liu & Corma, 2018; X. Sun *et al.*, 2024)

Reduction and hydrogenation/dehydrogenation

Supported metal catalysts from nanoparticles to single atoms have been systematically optimized for chemoselective hydrogenations (alkynes/dienes, α , β -unsaturated carbonyls, nitroarenes). Strategies such as alloying (single-atom alloys), confinement in porous supports, and construction of intermetallic phases improve site isolation and suppress over-hydrogenation, enabling high selectivity at lower metal loadings.(Fígoli *et al.*, 1996) For light alkane transformations, single-atom alloy catalysts have been reported for ethane dehydrogenation, where isolated active atoms embedded in a host metal enhance activity and coke resistance relative to conventional nanoparticle catalysts, demonstrating the power of atomic-scale control in dehydrogenation chemistry.(*Ethane Dehydrogenation over the Single-Atom Alloy Catalysts*, 2021)

Carbon–carbon bond formation and cross-coupling

Copper-based Nano catalysts have become prominent in C–C coupling due to their low cost and tunable redox properties. Recent reviews show that CuO nanoparticles efficiently catalyze a range of C–C cross-coupling reactions (e.g., Ullman-type, C–O/C–N couplings), often under ligand-free or mild conditions, with recyclability over multiple cycles.(Soni *et al.*, 2022) Monometallic copper nanoparticles (supported and unsupported) have also been widely applied in click chemistry, particularly Cu-catalyzed azide–alkyne cycloadditions, where high surface area and controlled oxidation state enable fast reactions in green solvents or aqueous media.(Alonso *et al.*, 2015) Broader surveys of copper nanocatalysts in coupling transformations confirm that nanoscale Cu systems outperform bulk analogues in activity and substrate scope for C–C and C–N bond formation.

Photocatalytic transformations

Nanostructured semiconductors decorated with atomically dispersed metals have markedly advanced photocatalytic degradation of persistent organic pollutants. A representative example is the study by Ruta and co-workers on the photodegradation of gemfibrozil, a widely used lipid-regulating drug and emerging contaminant, using metal single-atom catalysts supported on mesoporous carbon nitride (mpg-C₃N₄). (Ruta *et al.*, 2022) In this work, a series of carbon nitride photocatalysts was systematically engineered to disentangle the roles of textural properties and metal single atoms (e.g., Ag) on degradation performance. Under UV–visible irradiation, the Ag single-atom catalyst on mesoporous carbon nitride (Ag@mpg-C₃N₄) achieved >90% gemfibrozil removal within 60 min, far outperforming bare carbon nitride or materials

containing metal nanoparticles.(Ruta *et al.*, 2022) The enhanced activity was attributed to the high surface area of the mesoporous support and the atomically dispersed Ag sites, which promote efficient charge separation, extend carrier lifetimes, and provide well-defined active centers for O₂ activation and reactive oxygen species generation. Detailed analysis of intermediates and products confirmed extensive mineralization, demonstrating that rational Nano engineering of the semiconductor support combined with single-atom metal sites can deliver highly efficient, selective, and reusable photocatalysts for water purification and other light-driven transformations.(Ruta *et al.*, 2022).A recent comprehensive review on single-atom catalysts for advanced oxidation of organic compounds highlights noble-metal and non-noble-metal single atoms on oxide and carbon nitride supports for photocatalytic degradation of dyes, VOCs, and emerging contaminants, where atomically dispersed sites promote charge separation and lower activation barriers.(Recent Progress of Single-Atom Catalysts (SACs) for the ..., 2026) In formaldehyde photocatalytic oxidation, single Mn atoms anchored on TiO₂ and related systems significantly enhance O₂ activation and mineralization rates under UV/visible light compared with Nanoparticulate counterparts.(G. Sun *et al.*, 2025)

Organic synthesis and carbonylations

Magnetic nanoparticle-supported transition-metal catalysts (e.g., Fe₃O₄-supported Pd or Ni) have been successfully applied to carbonylation and multi-component organic transformations, combining high activity with facile magnetic separation and reuse; recent accounts summarize numerous examples of alkoxy-, amino-, and thio-carbonylations using such recyclable nanocatalysts under relatively mild conditions.(C. Sun *et al.*, 2026) Copper- and nickel-based nanocatalysts similarly enable tandem and cascade organic reactions, benefiting from their high surface area and tailored surface ligands to control chemo- and regioselectivity.

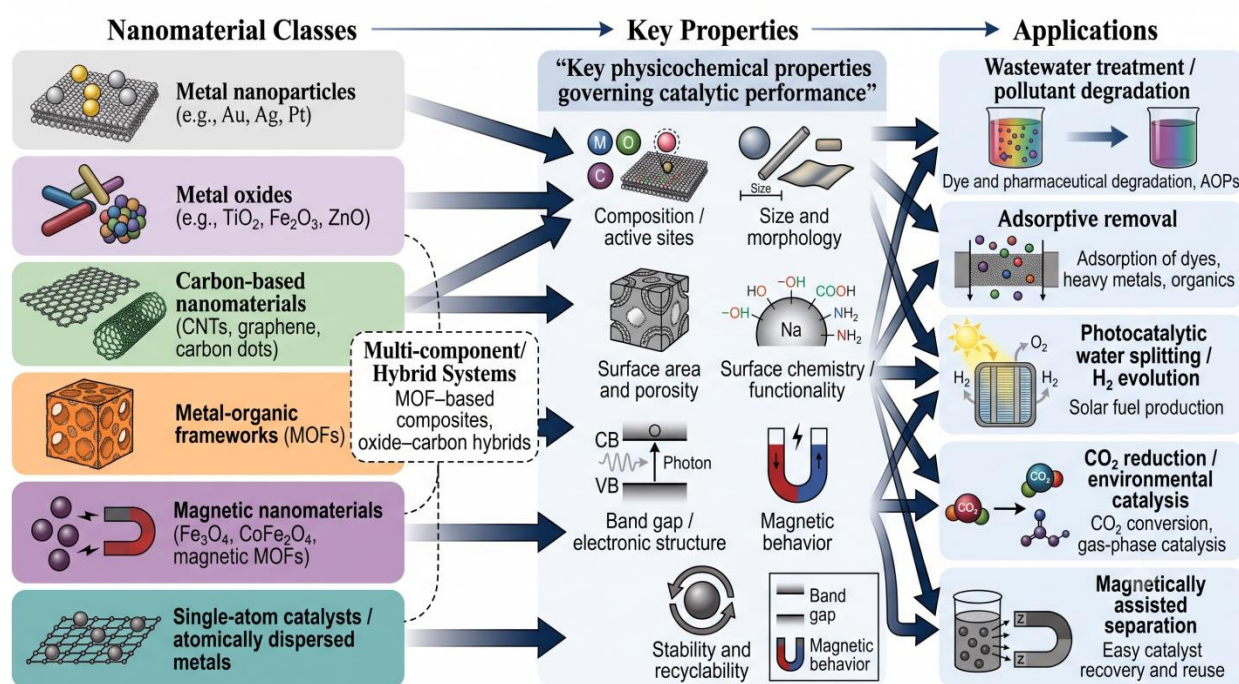


Figure 1: Schematic illustration of nanomaterials in catalytic transformations

Environmental remediation and green transformations

In environmental catalysis, nanomaterials are central to low-temperature oxidation of indoor pollutants and advanced oxidation processes for wastewater treatment. Noble-metal nanocatalysts from the nanoparticle to single-atom regime have been extensively reviewed for formaldehyde and VOC removal in indoor air, where maximizing dispersion on high-surface-area supports reduces noble-metal usage while maintaining high activity and durability.(X. Sun *et al.*, 2024) Single-atom catalysts on oxides and carbon nitride are also emerging for photocatalytic and electrocatalytic degradation of organic contaminants and for advanced oxidation of wastewater-borne organics, offering high turnover frequencies and tunable selectivity under mild, often visible-light-driven conditions.(*Recent Progress of Single-Atom Catalysts (SACs) for The ...*, 2026) Collectively, these recent studies demonstrate that rationally engineered nanocatalysts enable more efficient, selective, and sustainable chemical and environmental transformations than conventional bulk catalysts.(C. Sun *et al.*, 2026; X. Sun *et al.*, 2024).

ADVANTAGES OF NANOMATERIAL-BASED CATALYSTS

Nanocatalysts provide several advantages over conventional bulk and molecular catalysts: High catalytic efficiency and turnover due to large surface areas and high densities of accessible active sites, enabling lower loadings of noble metals.(Liu & Corma, 2018)

- **Improved selectivity** arising from facet, composition, and coordination control at the nanoscale, including in alloy and single-atom systems that favor specific adsorption geometries and pathways.(Gao *et al.*, 2024; Shan *et al.*, 2022)
- **Enhanced reaction rates and lower activation barriers**, particularly in photocatalytic and electrocatalytic processes where Nano structuring facilitates light absorption, charge separation, and mass transport.(Fan *et al.*, 2021)
- **Reduced catalyst loading and cost**, especially for SACs and subnanoclusters that maximize atomic utilization of precious metals.(Fan *et al.*, 2021; Velpandian *et al.*, 2024)
- **Easy recovery and recyclability**, particularly for supported and magnetic nanocatalysts, which can be separated magnetically or by simple filtration and reused with minimal loss of activity.(Ahmad *et al.*, 2025)
- **Compatibility with green chemistry principles**, enabling solvent-free conditions, milder temperatures, alternative energy inputs (light, electricity), and reduced waste generation.(Sharma *et al.*, 2015)
- **Scalability potential**, as advances in colloidal synthesis, deposition, and continuous-flow preparation allow controlled production of nanocatalysts at increasing scales.(Liu & Corma *et.al.*, 2018)

CHALLENGES AND LIMITATIONS

Despite these benefits, several challenges hinder the widespread industrial deployment of nanomaterial-based catalysts:

- **Nanoparticle aggregation and sintering**, especially at elevated temperatures or under reductive conditions, which reduce active surface area and alter active-site structure.(Liu & Corma, 2018)
- **Catalyst deactivation** due to poisoning, coking, or structural transformations (e.g., dissolution–reprecipitation, support corrosion) over prolonged operation.(Chung *et al.*, 2015)
- **Stability and leaching**, particularly for colloidal and ligand-stabilized nanoparticles and for SACs with weak anchoring, can lead to metal loss and contamination of products.(Velpandian *et al.*, 2024; F. Wang *et al.*, 2024)
- **Recovery and separation issues** in quasi-homogeneous systems, where complete removal of Nano species from liquid products remains challenging despite advances in magnetic and supported catalysts.(Ahmad *et al.*, 2025)
- **Toxicity and environmental concerns**, as certain nanomaterials (e.g., some metal oxides or small nanoparticles) may pose ecotoxicological or health risks if released, necessitating rigorous life-cycle and risk assessments.(Fan *et al.*, 2021)
- **Scalability and reproducibility**, since achieving consistent size, shape, and dispersion across large batches can be difficult, leading to variability in catalytic performance.(*Bimetallic Nanoparticles: Advances in Fundamental ...*, 2024)
- **High production costs**, especially for complex architectures, SACs, and intermetallic nanoparticles that require sophisticated synthetic control and post-treatment.(Shan *et al.*, 2022)

Addressing these limitations requires integrated efforts in synthetic chemistry, in situ characterization, mechanistic studies, and process engineering.

CURRENT TRENDS AND FUTURE PERSPECTIVES

Several emerging directions are shaping the future landscape of nanomaterial-based catalysis:

- **Green synthesis of nanocatalysts:** Sustainable routes employing benign solvents, bio-derived reducing agents, and low-energy processes are increasingly adopted to reduce the environmental footprint of nanocatalysts synthesis.(Sharma *et al.*, 2015)
- **Bio-based and bio-inspired nanomaterials:** Biomolecule-templated synthesis, enzyme-mimetic nanozymes, and bio-derived carbon supports are being explored to merge catalytic efficiency with biocompatibility and renewability.(Fan *et al.*, 2021)
- **Single-atom and subnanometer catalysts:** SACs and supported metal clusters offer atomic-level precision and maximum atom utilization, with significant advances in CO₂ hydrogenation, electrocatalytic oxygen and nitrogen conversions, and selective hydrogenations.(Shan *et al.*, 2022; Velpandian *et al.*, 2024; F. Wang *et al.*, 2024) Understanding metal–support coordination and metal–metal correlations is central to further improvements.(Shan *et al.*, 2022)
- **Magnetic recyclable nanocatalysts:** Rational design of magnetic cores with robust shells and active phases (e.g., Fe₃O₄@SiO₂@metal) combines high performance with facile

magnetic separation, particularly relevant to carbonylation and coupling chemistry.(Ahmad *et al.*, 2025)

- **Photocatalysis and visible-light-driven processes:** Advances in g-C₃N₄-based SACs, heterostructures, and plasmonic–semiconductor hybrids are enabling more efficient solar-driven water splitting, CO₂ reduction, and selective organic transformations under visible light.(Fan *et al.*, 2021; S. J. Li *et al.*, 2026)
- **Data-driven and computational catalyst design:** Density functional theory, machine learning, and high-throughput screening are increasingly used to predict active-site structures, adsorption energies, and reaction pathways, accelerating the discovery of optimal compositions for SACs, alloys, and intermetallics. (Shan *et al.*, 2022)
- **Toward industrial-scale applications:** Industrial adoption requires long-term stability, reactor-compatible morphologies, and cost-effective synthesis. Progress in intermetallic nanoparticle catalysts and Pt-based intermetallics for oxygen reduction illustrates how nanocatalysts can meet stringent durability and activity requirements in energy-conversion devices.(Chung *et al.*, 2015; C. Li *et al.*, 2025)

Future research should integrate operando spectroscopy and microscopy with kinetic modeling to elucidate structure–activity relationships, extend nanocatalyst concepts to multi-step cascade and tandem reactions, and implement circular-economy strategies for catalyst recovery and recycling.

CONCLUSION

Nanomaterials have redefined the paradigm of catalysis across basic chemistry, pharmaceuticals, energy, and environmental remediation. Their exceptional surface area, tunable size and morphology, and versatile electronic and optical properties enable high activity, tailored selectivity, and improved stability compared with conventional catalysts. Metal and metal oxide nanoparticles, carbon-based nanostructures, semiconductor photocatalysts, magnetic nanomaterials, and emerging single-atom and subnanocluster systems collectively underpin a broad spectrum of oxidation, reduction, hydrogenation, C–C coupling, photocatalytic, and environmental remediation reactions.

At the same time, challenges related to aggregation, deactivation, toxicity, and large-scale manufacturing must be addressed before full industrial deployment is realized. Advances in green synthesis, bio-based and recyclable nanocatalysts, and data-driven design are expected to accelerate the translation of nanoscale insights into robust catalytic technologies. Looking ahead, nanomaterial-based catalysts will remain central to the development of sustainable, energy-efficient, and environmentally benign chemical transformations, aligning closely with global priorities in green chemistry and circular manufacturing.

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Chapter

7

**BIOLOGICAL APPLICATIONS OF NANOMATERIALS:
ADVANCES IN BIOMEDICAL, DIAGNOSTIC AND
THERAPEUTIC APPLICATIONS**

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ABSTRACT

Nanotechnology has emerged as an interdisciplinary field with significant applications in biology, medicine, biotechnology and healthcare. Nanomaterials generally possess dimensions in the nanoscale range and exhibit distinctive physicochemical properties, including high surface-area-to-volume ratio, tunable surface chemistry, optical properties, electrical conductivity, magnetic behavior and enhanced biological interactions. These characteristics make nanomaterials valuable tools for drug delivery, cancer diagnosis and therapy, biosensing, antimicrobial applications, gene delivery, medical imaging, tissue engineering and regenerative medicine. Nanoparticles can improve the solubility, stability, bioavailability and targeted delivery of therapeutic molecules, while their surfaces can be functionalized with antibodies, peptides, nucleic acids and other biomolecules for specific biological targets. Nanomaterial-based biosensors have also demonstrated considerable potential for sensitive detection of proteins, nucleic acids, metabolites, pathogens and cancer biomarkers. In cancer research, multifunctional Nano platforms are being investigated for combined diagnosis and therapy, commonly referred to as theranostics. However, biological applications of nanomaterials also present challenges related to toxicity, biodistribution, biodegradation, immunological responses and long-term safety. Therefore, understanding nano-bio interactions are essential for the safe and effective development of nanotechnology-based biomedical products. This chapter discusses the major biological applications of nanomaterials, their mechanisms of action, advantages, limitations, biosafety considerations and future perspectives.

KEYWORDS: Nanomaterials, Nanoparticles, Nanobiotechnology, Drug Delivery, Biosensors, Cancer Therapy, Nanomedicine, Tissue Engineering, Nanotoxicology.

INTRODUCTION

Nanotechnology involves the design, characterization and application of materials and structures at the nanoscale. Nanomaterials exhibit properties that can differ considerably from those of their bulk counterparts because of their small dimensions and large surface-area-to-volume ratio. These properties have created new opportunities in biology, biotechnology and medicine.

The interaction between nanomaterials and biological systems has developed into an important area known as **nanobiotechnology** or **nanomedicine**. Nanomaterials can interact with cells, proteins, nucleic acids and biological membranes, allowing researchers to exploit them for therapeutic and diagnostic purposes. Their surfaces can also be modified with specific ligands to improve targeting and biological compatibility.

Nanotechnology has particularly attracted attention in cancer treatment because conventional therapeutic agents often suffer from poor solubility, nonspecific distribution, toxicity and limited delivery to tumor tissues. Nanoparticle-based systems can improve drug stability and delivery and can be designed for passive or active targeting.

In addition, nanomaterials are increasingly being investigated for biosensors, imaging, tissue regeneration, antimicrobial treatments and nucleic-acid delivery. Recent studies also emphasize the importance of understanding the biological effects of nanoparticles independently of their intended therapeutic functions.

CLASSIFICATION OF NANOMATERIALS

Nanomaterials used in biological applications can broadly be classified into several groups.

Metallic Nanoparticles

Metallic nanoparticles include:

- Gold nanoparticles (AuNPs)
- Silver nanoparticles (AgNPs)
- Platinum nanoparticles
- Copper nanoparticles
- Iron nanoparticles

Gold nanoparticles are particularly useful because their optical properties and easily modifiable surfaces make them suitable for biosensing, imaging and drug delivery.

Silver nanoparticles are extensively investigated for antimicrobial applications because of their ability to interact with microbial membranes and cellular components.

Metal Oxide Nanoparticles

Important metal oxide nanomaterials include:

- Zinc oxide (ZnO)
- Titanium dioxide (TiO₂)
- Iron oxide (Fe₃O₄/γ-Fe₂O₃)
- Cerium oxide (CeO₂)
- Silicon dioxide (SiO₂)

Iron oxide nanoparticles have attracted considerable interest in magnetic separation, drug delivery and magnetic resonance imaging.

Carbon-Based Nanomaterials

Carbon-based nanomaterials include:

- Carbon nanotubes
- Graphene

- Graphene oxide
- Fullerenes
- Nano diamonds

Their unique electrical, mechanical and structural characteristics have resulted in applications in biosensors, drug delivery and tissue engineering.

Polymeric Nanomaterials

Polymeric nanoparticles can be prepared from materials such as:

- Chitosan
- Poly(lactic-co-glycolic acid) (PLGA)
- Polyethylene glycol (PEG)
- Polycaprolactone

They are especially important for controlled and sustained drug release.

Lipid-Based Nanomaterials

Liposomes, solid lipid nanoparticles and lipid nanoparticles are important biological nanocarriers. Their ability to encapsulate hydrophilic and hydrophobic molecules makes them useful in drug and nucleic-acid delivery.

DNA-Based Nanomaterials

DNA nanostructures have emerged as programmable nanoscale systems for biosensing, imaging, therapeutics, tissue regeneration and targeted drug delivery.

PHYSICOCHEMICAL PROPERTIES RELEVANT TO BIOLOGICAL APPLICATIONS

The biological behavior of nanomaterials is strongly influenced by their:

- Particle size
- Shape
- Surface area
- Surface charge
- Chemical composition
- Surface functionalization
- Aggregation state
- Solubility
- Hydrophobicity/hydrophilicity

Particle size is particularly important because smaller nanoparticles generally have a greater surface-area-to-volume ratio and may exhibit different cellular uptake and biological distribution.

Surface charge also affects interactions with cellular membranes and proteins. Positively charged nanoparticles may interact strongly with negatively charged cell membranes, whereas surface modification can be used to control nonspecific interactions.

The formation of a **protein corona** around nanoparticles after exposure to biological fluids can substantially modify their biological identity and cellular interactions.

NANO–BIO INTERACTIONS

When nanomaterials enter a biological environment, they immediately interact with biomolecules such as proteins, lipids and carbohydrates.

These interactions can influence:

1. Cellular uptake
2. Biodistribution
3. Immune response
4. Toxicity
5. Cellular signaling
6. Intracellular trafficking
7. Clearance from the body

Nanoparticles may enter cells through mechanisms such as endocytosis, phagocytosis and receptor-mediated uptake. Their physicochemical properties strongly influence these processes. Understanding nano–bio interactions is therefore essential for designing safe and efficient nanomedicines.

BIOLOGICAL APPLICATIONS OF NANOMATERIALS

Drug Delivery

Drug delivery is one of the most important applications of nanomaterials.

Conventional drug delivery may result in:

- Poor drug solubility
- Rapid degradation
- Nonspecific distribution
- Low bioavailability
- Systemic toxicity

Nanocarriers can overcome some of these limitations by encapsulating or attaching therapeutic molecules.

Major nanocarriers include:

- Liposomes
- Polymeric nanoparticles
- Dendrimers
- Micelles
- Metallic nanoparticles
- Magnetic nanoparticles
- Lipid nanoparticles
- Nanogels

Nanoparticles can protect drugs from premature degradation and provide controlled release. Surface modification with targeting molecules can further improve delivery to specific cells or tissues.

Cancer Diagnosis and Therapy

Cancer is one of the major areas of nanomedicine research.

Nanomaterials can be used for:

- Tumor imaging
- Cancer biomarker detection
- Targeted drug delivery
- Photothermal therapy
- Photodynamic therapy
- Magnetic hyperthermia
- Gene therapy
- Immunotherapy

Nanoparticles can be functionalized with antibodies, peptides or other targeting molecules to recognize cancer-associated receptors.

Nanotheranostics

The combination of diagnosis and treatment using single nanosystems is known as **Nanotheranostics**.

A theranostic nanoparticle may simultaneously:

Detect tumor → Deliver therapeutic agent → Monitor treatment response

Magnetic nanoparticles, quantum dots and multifunctional polymeric nanoparticles are among the platforms investigated for theranostic applications.

Biosensors

Nanomaterials have significantly improved biosensor technology because of their high surface area and favorable electrical, optical and catalytic properties.

Nano biosensors can detect:

- DNA
- RNA
- Proteins
- Enzymes
- Glucose
- Pathogens
- Hormones
- Cancer biomarkers

Gold nanoparticles, graphene, carbon nanotubes and quantum dots are commonly investigated in biosensor development.

Nanomaterial-based electrochemical sensors have been extensively studied for the detection of anticancer drugs and cancer biomarkers.

Recent optical Nano biosensor research has further expanded applications in biomedical and biopharmaceutical analysis.

ANTIMICROBIAL APPLICATIONS

Nanomaterials have attracted considerable attention as antimicrobial agents.

Silver nanoparticles

Silver nanoparticles exhibit antimicrobial activity against a broad range of microorganisms. Their activity may involve:

- Interaction with microbial membranes
- Release of silver ions
- Generation of reactive oxygen species
- Interaction with proteins and nucleic acids

Zinc oxide nanoparticles

ZnO nanoparticles have also been investigated for antibacterial and antifungal applications.

Potential applications include:

- Antimicrobial coatings
- Wound dressings
- Medical devices
- Food packaging
- Surface disinfection

However, antimicrobial efficacy must be balanced against potential toxicity to human cells.

GENE AND NUCLEIC-ACID DELIVERY

Nucleic-acid therapeutics such as DNA, RNA, siRNA and mRNA require efficient delivery into target cells.

Nanomaterials can protect nucleic acids from enzymatic degradation and facilitate cellular uptake.

Potential applications include:

- Gene replacement
- Gene silencing
- RNA interference
- mRNA delivery
- Genome editing
- Cancer gene therapy

DNA nanomaterials are particularly interesting because their structures can be rationally designed and functionalized for biological applications, including gene delivery and therapeutics.

MEDICAL IMAGING

Nanomaterials can improve medical imaging because of their unique optical and magnetic properties.

MAJOR EXAMPLES

Ironoxide nanoparticles:

Used for magnetic-based imaging and investigated extensively in MRI-related applications.

Gold nanoparticles:

Useful in optical imaging and photothermal applications.

Quantum dots:

Possess unique fluorescence properties and can be used for cellular labeling and imaging.

Nanomaterials can also be functionalized with targeting molecules so that imaging agents preferentially accumulate in particular cells or tissues.

TISSUE ENGINEERING AND REGENERATIVE MEDICINE

Nanomaterials can mimic some structural characteristics of the extracellular matrix.

Nanostructured scaffolds can provide:

- Cell attachment
- Cell proliferation
- Cell differentiation
- Controlled drug release
- Improved tissue regeneration

Applications include:

- Bone regeneration
- Cartilage regeneration
- Skin regeneration
- Neural tissue engineering
- Cardiovascular tissue engineering

Recent research emphasizes the ability of nanostructured scaffolds and cell-instructive surfaces to influence stem-cell behavior and tissue regeneration.

NANOMATERIALS IN BIOSEPARATION

Magnetic nanoparticles are particularly useful in biological separation processes.

They can be functionalized with antibodies, enzymes or other ligands and subsequently used to isolate:

- Cells
- Proteins
- DNA
- RNA
- Pathogens
- Biomarkers

After binding to the target, the nanoparticles can be separated using an external magnetic field.

This provides a relatively rapid and efficient approach for sample preparation and biomolecule purification.

NANOMATERIALS IN DIAGNOSTICS

Nanotechnology has enabled the development of highly sensitive diagnostic platforms.

Nanomaterial-based diagnostic systems can detect disease-associated biomarkers at low concentrations.

Potential applications include diagnosis of:

- Cancer
- Infectious diseases
- Cardiovascular diseases
- Diabetes
- Neurological disorders

The combination of nanomaterials with molecular recognition elements such as antibodies, aptamers and nucleic acids provides highly specific diagnostic systems.

NANOMATERIALS IN AGRICULTURAL BIOTECHNOLOGY

Nanomaterials also have potential applications in agricultural biology.

They can be used for:

- Controlled delivery of fertilizers
- Controlled pesticide delivery
- Plant disease detection
- Seed treatment
- Plant growth regulation
- Stress monitoring

However, the environmental fate and potential toxicity of nanoparticles in soil, plants and aquatic systems need careful evaluation before large-scale applications.

MECHANISMS OF NANOMATERIAL ACTION

The biological activity of nanomaterials may involve several mechanisms.

Reactive Oxygen Species Generation

Some nanoparticles can increase the production of reactive oxygen species (ROS), resulting in oxidative stress.

Membrane Interaction

Nanoparticles may interact with cellular membranes and alter membrane permeability.

Mitochondrial Effects

Some nanomaterials can affect mitochondrial function and energy metabolism.

DNA Damage

Certain nanoparticles may induce oxidative or direct damage to DNA.

Apoptosis

Nanomaterials can activate cellular signaling pathways associated with programmed cell death. These mechanisms can be useful therapeutically—for example, in cancer treatment—but may also contribute to unwanted toxicity.

NANOTOXICOLOGY AND BIOSAFETY

Despite their enormous potential, nanomaterials cannot be considered automatically safe.

Potential adverse effects include:

- Cytotoxicity
- Oxidative stress

- Inflammation
- Genotoxicity
- Immunotoxicity
- Mitochondrial dysfunction
- Organ accumulation

Toxicity is influenced by nanoparticle size, shape, composition, surface charge, surface chemistry, dose and aggregation.

Therefore, nanomaterial safety assessment should include both *In vitro* and *in vivo* studies.

Important parameters include:

- Cell viability
- ROS production
- DNA damage
- Cytokine production
- Mitochondrial activity
- Histopathological changes
- Biodistribution
- Clearance

ADVANTAGES OF NANOMATERIALS IN BIOLOGY

Application	Major Advantage
Drug delivery	Controlled and targeted delivery
Cancer therapy	Improved tumor targeting
Biosensors	High sensitivity
Imaging	Enhanced signal and contrast
Antimicrobial therapy	Broad antimicrobial activity
Gene delivery	Protection of nucleic acids
Tissue engineering	Improved cellular interaction
Bioseparation	Efficient target isolation
Diagnostics	Early biomarker detection

CHALLENGES AND LIMITATIONS

Although nanomaterials have substantial potential, several challenges remain.

Major challenges include:

1. Nano toxicity
2. Long-term biological effects
3. Poor reproducibility between nanoparticle preparations
4. Difficulties in large-scale manufacturing
5. High production costs
6. Regulatory challenges

7. Biodistribution and clearance problems
8. Potential immune reactions
9. Environmental accumulation
10. Limited long-term clinical data

A major challenge is that the same physicochemical characteristics that make nanoparticles biologically active can also produce unintended biological effects.

FUTURE PERSPECTIVES

The future of biological nanotechnology is likely to focus on the development of multifunctional, biodegradable, stimuli-responsive and highly targeted nanomaterials.

Emerging approaches include:

- Smart drug-delivery systems
- Personalized nanomedicine
- AI-assisted nanoparticle design
- Nano-immunotherapy
- RNA and mRNA Nano delivery
- CRISPR/Cas-based delivery
- Nanorobotics
- Advanced Nano biosensors
- 3D nanostructured tissue scaffolds
- Nano-enabled regenerative medicine

Stimuli-responsive nanoparticles can be designed to release their cargo in response to conditions such as pH, temperature, enzymes or redox state. This approach may improve the specificity of drug delivery.

Future nanomedicine will therefore increasingly combine diagnosis, targeted therapy, imaging and monitoring within multifunctional nanosystems.

CONCLUSION

Nanomaterials have become important tools at the interface of nanotechnology, biology and medicine. Their unique physicochemical properties provide opportunities for targeted drug delivery, cancer diagnosis and therapy, biosensing, antimicrobial treatment, gene delivery, medical imaging, tissue engineering and regenerative medicine. The ability to functionalize nanoparticle surfaces allows researchers to modify their interactions with cells and biological molecules and to develop application-specific nanosystems.

At the same time, the biological activity of nanomaterials can produce undesirable effects, including oxidative stress, inflammation, genotoxicity and immune responses. Consequently, future development should emphasize the relationship between nanomaterial structure, biological function and safety. A better understanding of nano–bio interactions, standardized toxicity testing and appropriate regulatory frameworks will be essential for translating laboratory discoveries into safe and effective biomedical applications.

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ABSTRACT

Nanomaterials have emerged as important functional materials in modern chemistry because their nanoscale dimensions provide distinctive physicochemical properties, including high specific surface area, enhanced surface energy, tunable electronic structure, quantum confinement, and abundant active sites. These properties make nanomaterials highly attractive for chemical applications ranging from heterogeneous catalysis and photocatalysis to chemical sensing, adsorption, electrochemistry, energy conversion, and environmental remediation. Nanostructured catalysts can improve reaction rates, selectivity, conversion efficiency, and catalyst recovery while potentially reducing energy consumption and the formation of unwanted by-products. Semiconductor nanomaterials such as TiO_2 , ZnO , WO_3 and various heterostructures have been extensively investigated for photocatalytic degradation of pollutants, water splitting and selective organic transformations. Metallic nanoparticles, including Pt, Pd, Au, Ag and Cu, possess remarkable catalytic and electrocatalytic properties because of their surface-active sites and electronic characteristics. Nanomaterials are also increasingly used in chemical sensors because their large surface-to-volume ratios allow sensitive interactions with target molecules.

This chapter discusses the fundamental chemical properties of nanomaterials and their major applications in catalysis, photocatalysis, electrocatalysis, chemical sensing, adsorption, organic synthesis, environmental remediation, hydrogen production, carbon dioxide conversion, batteries and fuel cells. Recent developments, limitations, toxicity considerations and future perspectives are also discussed.

KEYWORDS: Nanomaterials, Nanocatalysis, Photocatalysis, Electrocatalysis, Chemical Sensors, Adsorption, Environmental Chemistry, Energy Conversion, Green Chemistry.

INTRODUCTION

Nanotechnology involves the design, synthesis and application of materials with dimensions generally in the nanoscale range. At the nanoscale, materials can exhibit properties that differ substantially from their bulk counterparts. These differences arise from increased surface-to-volume ratio, surface energy, quantum effects, altered electronic structures and changes in optical and chemical behavior.

Chemistry is one of the major disciplines benefiting from nanotechnology. Nanomaterials can function as catalysts, adsorbents, photocatalysts, electrode materials, chemical sensors and reaction-supporting materials. Their properties can be controlled through particle size, morphology, composition, crystallinity, surface functionalization and heterostructures formation.

Nanocatalysts are particularly important because their large specific surface area provides a high number of accessible active sites. This can increase reaction rates and improve selectivity. Research has demonstrated applications of nanomaterials in fine chemical synthesis, hydrocarbon processing, biomass conversion and renewable-energy-related reactions.

IMPORTANT CHEMICAL PROPERTIES OF NANOMATERIALS

The chemical performance of nanomaterials is strongly related to their physical and electronic characteristics.

High Surface-to-Volume Ratio

When particle size decreases, the fraction of atoms located at or near the surface increases. Consequently, nanomaterials provide a greater number of active sites for adsorption and chemical reactions.

This property is particularly important in:

- Heterogeneous catalysis
- Adsorption
- Gas sensing
- Electrochemical reactions
- Photocatalysis
- Environmental remediation.

Surface Energy

Nanoparticles generally possess high surface energy. Surface atoms have fewer neighboring atoms than atoms inside the bulk material, making them more chemically reactive.

High surface energy contributes to the catalytic behavior of metallic nanoparticles and semiconductor nanomaterials. Nanomaterials containing Pt, Pd, Au and metal oxides such as TiO₂ and SnO₂ have been extensively studied for catalytic and energy-related applications.

Tunable Electronic Properties

The electronic structure of nanomaterials can be modified through:

- Particle-size control
- Doping
- Alloy formation
- Defect engineering
- Surface functionalization
- Heterostructures formation.

These approaches can alter charge-transfer behavior and improve catalytic and sensing performance.

Surface Functionalization

Chemical functional groups can be introduced onto nanoparticle surfaces to modify:

- Adsorption capacity
- Selectivity
- Dispersibility
- Chemical stability
- Catalytic activity.

Functionalization is particularly useful for chemical sensors and selective adsorption.

NANOMATERIALS AS CATALYSTS

Catalysis is one of the most important chemical applications of nanomaterials.

A catalyst accelerates a chemical reaction without being consumed overall. Nanocatalysts can provide a greater number of active sites than conventional bulk catalysts.

Heterogeneous Nanocatalysis

Heterogeneous nanocatalysts exist in a different phase from the reactants. Examples include:

- Pt nanoparticles
- Pd nanoparticles
- Au nanoparticles
- Ag nanoparticles
- Ni nanoparticles
- Fe₃O₄ nanoparticles
- TiO₂ nanoparticles
- ZnO nanoparticles
- Carbon-based nanomaterials.

Nanostructured catalysts have been investigated extensively for fine chemical synthesis, hydrocarbon processing and renewable energy reactions.

Advantages of Nanocatalysts

Nanocatalysts can offer:

1. High catalytic surface area
2. Large numbers of active sites
3. Improved reaction rates
4. Enhanced selectivity
5. Lower reaction temperatures in some systems
6. Improved catalyst utilization
7. Possibility of catalyst recovery
8. Compatibility with green chemistry approaches.

A review of nanomaterial-based catalysis reports that nanoscale catalysts can facilitate reactions at lower temperatures, reduce side reactions and improve catalyst recovery and energy efficiency.

NANOMATERIALS IN ORGANIC SYNTHESIS

Nanomaterials have become important in modern organic chemistry because they can catalyze a variety of transformations.

Examples include:

- Oxidation reactions
- Reduction reactions
- Hydrogenation
- Coupling reactions
- Condensation
- C–c bond formation
- C–n bond formation
- C–o bond formation
- Selective reduction of nitro compounds.

Gold Nanoparticles

Gold nanoparticles possess unusual catalytic properties compared with bulk gold. Their catalytic activity depends strongly on particle size, support material and surface structure.

Palladium Nanoparticles

Pd nanoparticles are widely studied for:

- Hydrogenation
- Suzuki coupling
- Heck reaction
- Carbon–carbon coupling
- Oxidation reactions.

Platinum Nanoparticles

Pt nanoparticles are important in:

- Hydrogenation
- Oxidation
- Fuel-cell reactions
- Hydrogen evolution
- Oxygen reduction.

The catalytic performance of noble-metal nanoparticles has been associated with their nanoscale structure and accessible surface active sites.

PHOTOCATALYTIC APPLICATIONS OF NANOMATERIALS

Photocatalysis is a chemical process in which light energy activates a semiconductor or other photoactive material to drive chemical reactions.

Common photocatalytic nanomaterials include:

- TiO_2
- ZnO
- WO_3

- Fe_2O_3
- Cds
- G- C_3N_4
- Graphene-based composites
- Semiconductor heterostructures.

Semiconductor nanoparticles have suitable light absorption and charge-transfer properties and are widely investigated for energy production and environmental remediation.

Mechanism of Photocatalysis

When a semiconductor absorbs photons with sufficient energy:



The generated electron-hole pairs participate in reduction and oxidation reactions.

The photo generated electrons may reduce electron acceptors, while holes oxidize donor molecules or water.

Reactive oxygen species such as:

- Hydroxyl radicals ($\bullet\text{OH}$)
- Superoxide radicals ($\text{O}_2\bullet^-$)
- Hydrogen peroxide (H_2O_2)

May be generated during photocatalytic reactions.

These reactive species can attack organic molecules and convert them into smaller molecules and, under suitable conditions, ultimately to CO_2 and H_2O .

PHOTOCATALYTIC DEGRADATION OF ORGANIC POLLUTANTS

One of the important chemical applications of photocatalytic nanomaterials is degradation of environmental contaminants.

Photocatalytic nanomaterials have been investigated for degradation of:

- Textile dyes
- Phenols
- Pesticides
- Pharmaceuticals
- Antibiotics
- Industrial organic pollutants.

Nanomaterial-based adsorption and photocatalysis have received considerable attention for water treatment. Adsorption removes contaminants from the aqueous phase, while photocatalysis can chemically degrade persistent organic compounds.

General reaction



The actual degradation pathway depends on pollutant structure, catalyst composition, pH, light intensity and reaction conditions.

ELECTROCATALYTIC APPLICATIONS

Nanomaterials are increasingly used as electrocatalyst because their surface properties can enhance electrochemical reactions.

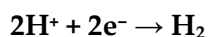
Important applications include:

- Hydrogen evolution reaction (HER)
- Oxygen evolution reaction (OER)
- Oxygen reduction reaction (ORR)
- CO₂ reduction
- Fuel cells
- Water electrolysis.

Two-dimensional nanomaterials and nanostructured catalysts have shown considerable potential in photocatalytic and electrocatalytic energy conversion.

Hydrogen Evolution Reaction

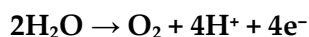
Nanostructured catalysts can facilitate hydrogen generation from water.



Pt is highly active for HER, while considerable research is focused on developing less expensive alternatives based on transition metals, metal sulfides, phosphides, carbides and carbon-based materials.

Oxygen Evolution Reaction

The OER is an important reaction in water electrolysis:



Nanostructured Ni-, Co-, Fe- and Mn-based materials are being investigated as alternatives to expensive noble-metal catalysts.

CARBON DIOXIDE CONVERSION

Nanomaterials are being investigated for CO₂ conversion because of their ability to modify adsorption and reaction pathways.

Potential products include:

- Carbon monoxide
- Methane
- Methanol
- Formic acid/formate
- Other carbon-containing chemicals.

Low-dimensional nanomaterials and heterostructures have been investigated for both hydrogen evolution and CO₂ reduction.

Nano structuring can improve:

- CO₂ adsorption
- Charge separation
- Electron transfer
- Active-site density

- Reaction selectivity.

CHEMICAL SENSORS

Nanomaterials are highly suitable for chemical sensing because their large surface area allows interaction with small quantities of target molecules.

Nanomaterial-based chemical sensors can detect:

- Toxic gases
- Volatile organic compounds
- Heavy metals
- Pesticides
- Industrial pollutants
- Biomolecules.

Recent research on photocatalytic chemical sensors emphasizes the importance of surface chemistry, heterojunctions, doping and band engineering for improving sensing performance.

Gas Sensors

Metal oxide nanomaterials such as:

- ZnO
- SnO₂
- WO₃
- TiO₂
- Fe₂O₃

Are widely investigated for gas sensing.

Target gases may include:

- NH₃
- NO₂
- CO
- H₂S
- H₂
- Volatile organic compounds.

Gas molecules interact with the nanoparticle surface and modify charge-carrier concentration, resulting in measurable changes in electrical resistance.

ELECTROCHEMICAL SENSORS

Nanomaterials can improve electrochemical sensors by increasing electrode surface area and accelerating electron-transfer reactions.

Nanomaterials used in electrochemical sensing include:

- Gold nanoparticles
- Silver nanoparticles
- Platinum nanoparticles
- Carbon nanotubes
- Graphene

- Graphene oxide
- Metal oxide nanoparticles
- Metal–organic frameworks.

Applications include detection of:

- Glucose
- Hydrogen peroxide
- Heavy metals
- Pesticides
- Phenolic compounds
- Pharmaceutical residues.

ADSORPTION APPLICATIONS

Nanomaterials can function as highly effective adsorbents because of their large surface area and tunable surface chemistry.

Important nano-adsorbents include:

- Graphene oxide
- Magnetic Fe_3O_4 nanoparticles
- Carbon nanotubes
- Nano-alumina
- Nano-silica
- Metal–organic frameworks
- Layered nanomaterials.

They can remove:

- Pb^{2+}
- Cd^{2+}
- Hg^{2+}
- Cr(VI)
- Dyes
- Pharmaceuticals
- Pesticides
- Organic contaminants.

Magnetic nanoparticles are particularly useful because they can potentially be separated from treated water using an external magnetic field.

NANOMATERIALS IN ENVIRONMENTAL CHEMISTRY

Nanomaterials have significant applications in environmental chemical processes.

Major applications include:

Water Treatment

Nanomaterials can be used for:

- Adsorption
- Photocatalysis

- Membrane filtration
- Disinfection
- Heavy-metal removal
- Degradation of organic pollutants.

Air Pollution Control

Nanomaterials can contribute to:

- Catalytic oxidation
- Gas sensing
- Pollutant adsorption
- Photocatalytic air purification.

Soil Remediation

Nanomaterials have been investigated for immobilization or transformation of selected contaminants in contaminated soils.

However, environmental release and nanoparticle fate must be carefully considered before large-scale application.

NANOMATERIALS IN GREEN CHEMISTRY

Nanotechnology and green chemistry have overlapping objectives, including:

- Minimizing waste
- Reducing energy consumption
- Improving atom economy
- Increasing reaction selectivity
- Reducing hazardous reagents
- Enabling catalyst recycling.

Nanocatalysts can potentially improve chemical processes by increasing conversion and selectivity under milder reaction conditions.

The combination of nanotechnology and green chemistry has therefore become an important research area for sustainable chemical manufacturing.

NANOMATERIALS FOR ENERGY CONVERSION

Nanomaterials play important roles in several energy technologies.

Fuel Cells

Nanostructured Pt and Pt-alloy catalysts are widely studied for:

- Hydrogen oxidation
- Oxygen reduction
- Methanol oxidation.

Solar Energy

Nanomaterials are used in:

- Solar cells
- Photocatalytic systems
- Photo electrochemical cells

- Light-harvesting systems.

Batteries

Nanostructured electrode materials can provide:

- Shorter ion-diffusion pathways
- Larger active surface area
- Improved charge-transfer kinetics.

Nanomaterials are being investigated in lithium-ion, sodium-ion and other advanced battery systems.

Recent reviews emphasize the importance of nanostructure engineering for improving energy conversion and storage technologies.

NANOMATERIALS IN CHEMICAL SEPARATION

Nanostructured materials can also be applied to chemical separation.

Examples include:

- Nanofiltration membranes
- Graphene-based membranes
- Nanoporous materials
- Molecularly selective nanomaterials
- Metal–organic frameworks.

Potential applications include separation of:

- Salts
- Heavy metals
- Organic molecules
- Gases
- Hydrocarbons.

The high surface area and tunable pore structures of nanomaterials can provide enhanced separation performance.

NANOMATERIALS IN ANALYTICAL CHEMISTRY

Nanomaterials have transformed analytical chemistry by improving sensitivity and selectivity.

Applications include:

- Colorimetric detection
- Electrochemical detection
- Fluorescence sensing
- Surface-enhanced raman spectroscopy (sers)
- Gas sensing
- Optical detection.

Gold and silver nanoparticles are particularly important in optical sensing because their localized surface plasmon resonance produces strong optical responses.

SURFACE-ENHANCED RAMAN SPECTROSCOPY

Surface-enhanced Raman spectroscopy is an important analytical application of nanostructured metals.

Noble-metal nanostructures, particularly Ag and Au, can strongly enhance Raman signals from molecules adsorbed on or near their surfaces.

SERS has potential applications in:

- Chemical identification
- Environmental monitoring
- Trace contaminant detection
- Pharmaceutical analysis
- Food analysis.

The enhancement is associated with electromagnetic effects and, in some systems, chemical interactions between analytes and the nanostructured surface.

NANOMATERIALS IN BIOMASS CONVERSION AND BIOREFINERY

Nanocatalysts can facilitate chemical conversion of biomass into useful products.

Potential applications include:

- Cellulose conversion
- Lignin valorization
- Bio-oil upgrading
- Carbohydrate conversion
- Hydrogen production
- Synthesis of platform chemicals.

The high activity and tunable surface chemistry of nanocatalysts can support selective biomass conversion and potentially reduce severe reaction conditions.

FACTORS AFFECTING CHEMICAL PERFORMANCE

The chemical performance of nanomaterials depends on several parameters.

Particle Size

Smaller particles generally provide higher surface area, although extremely small particles may exhibit aggregation or altered electronic properties.

Morphology

Nanoparticles may occur as:

- Spheres
- Rods
- Wires
- Tubes
- Plates
- Cubes
- Flowers
- Hierarchical structures.

Different morphologies expose different crystal facets and active sites.

Surface Chemistry

Surface functional groups strongly influence adsorption, catalytic activity and sensing.

pH

pH can affect:

- Surface charge
- Adsorption
- Catalyst stability
- Reaction mechanism
- Pollutant degradation.

Temperature

Temperature influences reaction kinetics, adsorption and catalyst stability.

Light Intensity and Wavelength

For photocatalytic systems, light wavelength and intensity strongly affect photon absorption and charge generation.

CHARACTERIZATION OF NANOMATERIALS FOR CHEMICAL APPLICATIONS

Proper characterization is essential for understanding chemical performance.

Technique	Major Information Obtained
UV-Visible spectroscopy	Optical absorption and plasmonic behavior
FTIR	Surface functional groups and chemical bonds
XRD	Crystal structure and phase
SEM	Surface morphology
TEM	Particle size and morphology
DLS	Hydrodynamic particle size
Zeta potential	Surface charge and colloidal stability
XPS	Surface elemental composition and oxidation state
BET	Surface area and pore characteristics
Raman spectroscopy	Molecular and structural information
TGA/DSC	Thermal behavior

The combination of structural, surface and optical characterization is particularly important when correlating nanomaterial properties with catalytic or sensing performance.

ADVANTAGES OF NANOMATERIALS IN CHEMICAL APPLICATIONS

Major advantages include:

1. High surface area
2. High density of active sites
3. Enhanced catalytic activity
4. Improved selectivity

5. Tunable electronic properties
6. Enhanced adsorption capacity
7. Improved electrochemical performance
8. Potential for catalyst recycling
9. Integration into multifunctional systems
10. Potential reduction in energy requirements.

LIMITATIONS AND CHALLENGES

Despite their advantages, several challenges remain.

Aggregation

Nanoparticles may aggregate during storage or reaction, reducing their effective surface area.

Reproducibility

Small changes in synthesis conditions can influence particle size, morphology and surface chemistry.

Scale-Up

A major challenge is translating laboratory-scale nanomaterial synthesis and catalytic performance to industrial processes.

Catalyst Recovery

Nanoparticle separation from reaction mixtures can be difficult.

Stability

Some nanomaterials may undergo:

- Oxidation
- Dissolution
- Sintering
- Surface poisoning
- Structural transformation.

Environmental and Toxicological Concerns

The release of nanoparticles into water, soil or air requires careful assessment. Their toxicity can depend on:

- Particle size
- Surface chemistry
- Concentration
- Dissolution
- Aggregation
- Exposure route.

Therefore, chemical efficiency should be evaluated together with environmental safety.

FUTURE PERSPECTIVES

The future of chemical applications of nanomaterials is expected to focus on rational material design and sustainable manufacturing.

Important research directions include:

- Single-atom catalysts
- Bimetallic nanoparticles
- Metal-free nanocatalysts
- Two-dimensional materials
- Mof-derived nanomaterials
- Nanostructured carbon catalysts
- Photocatalytic CO₂ conversion
- Green hydrogen production
- Artificial photosynthesis
- Advanced chemical sensors
- Ai-assisted catalyst design
- Recyclable nanocatalysts
- Bio-derived nanomaterials.

Recent research is increasingly emphasizing heterostructure engineering, doping, surface modification and precise control of nanostructures to improve catalytic performance.

An especially important direction is the development of earth-abundant and non-toxic nanocatalysts to reduce dependence on expensive noble metals.

CONCLUSION

Nanomaterials have become powerful tools in modern chemical science because their nanoscale dimensions provide unique surface, electronic, optical and catalytic properties. Their high surface-to-volume ratio and tunable surface chemistry make them particularly valuable in heterogeneous catalysis, photocatalysis, electrocatalysis, chemical sensing and adsorption.

Nanomaterials can facilitate organic transformations, pollutant degradation, water purification, energy conversion, hydrogen production and CO₂ reduction. Semiconductor nanomaterials are particularly important for photocatalytic processes, whereas metallic and carbon-based nanomaterials have demonstrated important applications in catalysis and electrochemical sensing.

Future progress will depend on controlling nanoparticle size, morphology, composition, surface chemistry and active sites while simultaneously addressing reproducibility, recovery, scalability, environmental fate and toxicity. The integration of nanotechnology with green chemistry, renewable energy and sustainable chemical engineering may provide new routes toward cleaner and more efficient chemical processes.

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Chapter

9

**PHARMACEUTICAL APPLICATIONS OF METALLIC
NANOPARTICLES**

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ABSTRACT

Metallic nanoparticles (MNPs) have emerged as important nanomaterials in pharmaceutical and biomedical research because of their distinctive physicochemical, optical, electrical, catalytic, magnetic, and biological properties. Their nanoscale dimensions provide a high surface-area-to-volume ratio and enable interactions with biological molecules, cells, tissues, and microorganisms that are substantially different from those of their bulk counterparts. Among the various metallic nanomaterials, gold (Au), silver (Ag), platinum (Pt), and selenium (Se), titanium (Ti) nanoparticles have attracted considerable attention for pharmaceutical applications. These materials have been investigated as drug-delivery carriers, antimicrobial agents, anticancer therapeutics, diagnostic and imaging probes, biosensors, photothermal agents, and platforms for controlled and targeted drug release. Surface functionalization with polymers, peptides, proteins, antibodies, nucleic acids, and other biomolecules can further improve their stability, targeting ability, biocompatibility, and therapeutic performance. However, challenges involving toxicity, biodistribution, biodegradation, immune responses, manufacturing reproducibility, and regulatory approval remain important barriers to clinical translation. This chapter discusses the fundamental characteristics, synthesis, surface modification, pharmaceutical applications, mechanisms of action, advantages, limitations, effects on plants and future prospects of metallic nanoparticles.

KEYWORDS: Metallic Nanoparticles; Pharmaceutical Nanotechnology.

INTRODUCTION

Nanotechnology has become an important multidisciplinary field at the interface of chemistry, materials science, biology, medicine, and pharmaceutical sciences. Nanomaterials generally possess dimensions in the nanometer range and exhibit physicochemical properties that differ significantly from those of their bulk materials. These properties arise from their small size, large specific surface area, quantum effects, surface energy, and ability to interact with biological structures at the molecular and cellular levels.

Within pharmaceutical nanotechnology, nanoparticles have attracted considerable interest because they can modify the pharmacokinetic and pharmacodynamic behavior of therapeutic agents. Nanoparticle-based systems can potentially improve the aqueous solubility of poorly soluble drugs, protect active pharmaceutical ingredients from degradation, prolong circulation, facilitate targeted delivery, and provide controlled or stimuli-responsive release.

Metallic nanoparticles represent a particularly important class of nanomaterials. They consist of elemental metals, metal oxides, or metal-containing nanoscale structures and possess unique optical, electronic, magnetic, catalytic, and antimicrobial characteristics. Their surfaces can also be readily functionalized with different chemical and biological ligands, allowing the development of multifunctional pharmaceutical systems.

The pharmaceutical importance of metallic nanoparticles is therefore not limited to their role as passive drug carriers. They may themselves possess therapeutic activity. For example, silver nanoparticles exhibit strong antimicrobial properties, gold nanoparticles can be engineered for targeted delivery and photothermal therapy, and iron oxide nanoparticles have been investigated extensively for magnetic targeting and imaging.

PHARMACEUTICAL APPLICATIONS OF METALLIC NANOPARTICLES

Drug Delivery

One of the most extensively investigated pharmaceutical applications of metallic nanoparticles is drug delivery.

Metallic nanoparticles can function as:

- Drug carriers
- Drug reservoirs
- Targeting platforms
- Controlled-release systems
- Stimuli-responsive delivery systems

Drugs may be attached to nanoparticle surfaces through adsorption, covalent bonding, electrostatic interactions, or incorporated into a coating surrounding the nanoparticle.

ADVANTAGES

Metallic nanoparticle-based drug delivery can potentially:

- Increase drug solubility
- Protect drugs against degradation
- Improve cellular uptake
- Reduce nonspecific distribution
- Facilitate targeted delivery
- Enable controlled release
- Combine diagnosis and therapy

Gold Nanoparticles

Gold nanoparticles are among the most extensively studied metallic nanomaterials in nanomedicine.

AuNPs possess several characteristics that make them attractive for pharmaceutical applications:

- Relatively high chemical stability
- Tunable size and shape
- Strong surface plasmon resonance
- Easy surface functionalization

APPLICATIONS OF AUNPS:

Drug delivery: Drugs can be attached directly to gold surfaces or incorporated into functional coatings.

Targeted cancer therapy: AuNPs can be functionalized with antibodies, peptides, aptamers, or other ligands for preferential interaction with tumor-associated targets.

Photothermal therapy: Gold nanoparticles can convert absorbed electromagnetic radiation into heat. This localized heating can damage cancer cells.

Gene delivery: Functionalized AuNPs have been investigated as carriers for DNA, RNA, and other nucleic acids.

Biosensing: Their optical properties enable highly sensitive detection of biomolecules.

SILVER NANOPARTICLES

Silver nanoparticles are particularly well known for their antimicrobial activity. They have been investigated against a broad range of microorganisms, including bacteria and fungi.

AgNPs have been investigated for:

- Wound-care materials
- Antimicrobial coatings
- Topical formulations
- Dental materials
- Antibacterial packaging
- Infection-control technologies

However, antimicrobial efficacy must be balanced against potential toxicity to mammalian cells.

PLATINUM NANOPARTICLES

Platinum nanoparticles possess strong catalytic and redox properties.

PtNPs have been investigated for:

- Antioxidant activity
- Catalytic applications
- Biosensing
- Cancer therapy
- Drug delivery
- Diagnostic applications

Their enzyme-mimetic properties are particularly interesting. Depending on their size, surface chemistry, and biological environment, PtNPs may demonstrate catalytic activities resembling those of certain antioxidant enzymes.

COPPER AND COPPER OXIDE NANOPARTICLES

Copper-containing nanoparticles have attracted interest because of their antimicrobial, catalytic, optical, and biological properties.

Potential pharmaceutical applications include:

- Antimicrobial formulations
- Drug-delivery systems
- Biosensors
- Cancer-related research
- Antifungal materials

However, copper nanoparticles can exhibit significant biological reactivity, and therefore their concentration, surface chemistry, particle size, and exposure conditions must be carefully controlled.

SELENIUM NANOPARTICLES

Selenium is an essential trace element involved in several biological processes. Selenium nanoparticles have been investigated as a potentially useful nanoscale form of selenium.

Potential applications include:

- Antioxidant research
- Drug delivery
- Anticancer research
- Antimicrobial applications
- Nutraceutical and pharmaceutical formulations

An important research objective is to control selenium nanoparticle dose and physicochemical properties to maximize beneficial biological effects while minimizing toxicity.

TITANIUM DIOXIDE (TiO₂)

It is also known as titania, is an inorganic metal oxide with high chemical stability, photocatalytic activity, UV-absorbing ability, and a large surface area when prepared at the nanoscale. These properties have made TiO₂ nanoparticles attractive for pharmaceutical and biomedical applications. Recent research particularly focuses on drug delivery, antimicrobial therapy, cancer therapy, biosensing, and implant coatings.

EFFECTS ON PLANTS

Metallic nanoparticles can enter plants through roots and, in some cases, leaves. Depending on the material and concentration, they may influence:

- Seed germination
- Root and shoot growth
- Photosynthesis
- Nutrient uptake
- Oxidative stress
- Antioxidant enzyme activity

CONCLUSION

Metallic nanoparticles represent a versatile and rapidly developing class of nanomaterials with significant potential in pharmaceutical science. Their distinctive physicochemical characteristics allow them to perform functions that are difficult to achieve using conventional pharmaceutical materials. Gold, silver, platinum, titanium and selenium nanoparticles have been investigated for applications ranging from drug and gene delivery to antimicrobial therapy, cancer treatment, imaging, biosensing, and theranostics.

However, successful pharmaceutical translation requires more than demonstrating biological activity. Detailed understanding of nanoparticle physicochemical characteristics, surface chemistry, biological interactions, pharmacokinetics, toxicity, manufacturing reproducibility, and long-term fate is essential. Future progress will depend on integrating nanomaterials science with pharmaceutical formulation, molecular biology, toxicology, advanced characterization, and regulatory science. Properly engineered metallic nanoparticles therefore have the potential to become important components of next-generation precision medicines and diagnostic technologies. Some nanoparticles can provide beneficial micronutrients at appropriate doses, while excessive exposure may produce phytotoxic effects.

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Chapter

10

**BIOLOGICAL APPLICATIONS OF NANOMATERIALS:
RECENT ADVANCES, MECHANISMS, CHALLENGES AND
FUTURE PERSPECTIVES**

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ABSTRACT

Nanomaterials have become central tools in modern biology and medicine because their nanoscale dimensions, large surface-to-volume ratio, and tunable optical, electrical, magnetic, and catalytic properties allow them to interact with cells and biomolecules in ways that bulk materials cannot. This chapter reviews the major biological applications of nanomaterials, including drug and gene delivery, cancer diagnosis and therapy, antimicrobial treatment, biosensing, tissue engineering, and agricultural use, together with the underlying mechanisms such as protein corona formation, cellular uptake, and reactive-oxygen-species generation. Emerging strategies such as green synthesis, biodegradable carriers, and stimulus-responsive multifunctional systems are highlighted as ways to improve therapeutic precision and safety. However, biological activity cannot be separated from potential toxicity, and nontoxicity remains dependent on particle size, shape, surface charge, dose, and route of exposure. The chapter concludes that safe and effective translation of nanomaterials into clinical and environmental use will depend on standardized safety evaluation, rational material design, and closer integration with computational tools such as artificial intelligence.

KEYWORDS: Nanomaterials, Nanomedicine, Drug Delivery, Biosensors, Antimicrobial Nanoparticles, Theranostics, Nanotoxicity.

INTRODUCTION

Nanotechnology involves the design and use of materials whose critical dimensions lie within the nanoscale, a size regime at which optical, electrical, catalytic, and magnetic behaviour often differs markedly from that of the corresponding bulk material. Because biological systems themselves operate at comparable length scales, nanomaterials can interface with proteins, nucleic acids, membranes, and whole cells in ways that conventional macro scale materials cannot. Once introduced into a biological environment, nanoparticle surfaces are rapidly coated by adsorbed biomolecules, forming a dynamic “protein corona” that strongly influences subsequent cellular recognition, uptake, distribution, degradation, and clearance (Saravanan *et al.*, 2024). Research in this field has consequently moved beyond simple particle synthesis toward the rational, function-driven design of multifunctional nanosystems that combine

sensing, imaging, targeted delivery, and therapy within a single platform, motivating this review of current biological applications, mechanisms, limitations, and future directions.

TYPES OF NANOMATERIALS USED IN BIOLOGICAL APPLICATIONS

Nanomaterials applied in biology are commonly grouped by composition and structure. Metal and metal-oxide nanoparticles – including silver, gold, iron oxide, zinc oxide, and titanium dioxide – offer distinctive optical, magnetic, catalytic, and antimicrobial behaviour; gold nanoparticles are particularly suited to optical sensing, imaging, and photothermal therapy, while iron oxide nanoparticles support magnetic separation, imaging, and targeted delivery. Biodegradable polymeric carriers such as poly(lactic-co-glycolic acid) enable controlled drug release and ligand functionalization, whereas lipid-based systems such as liposomes and lipid nanoparticles efficiently transport both hydrophilic and hydrophobic cargo and have become key platforms for nucleic-acid delivery (Jadhav *et al.*, 2024). Carbon-based nanomaterials, including graphene derivatives and carbon nanotubes, combine high surface area with strong electrical conductivity, making them attractive for biosensing and delivery. Additional platforms – mesoporous silica nanoparticles, dendrimers, quantum dots, nanoemulsions, and nanocomposites – extend the toolbox for specialised biological functions. Material selection ultimately depends on the intended biological role, physicochemical stability, biocompatibility, biodegradability, and toxicity profile of each candidate system.

BIOLOGICAL INTERACTIONS AND MECHANISMS

The biological fate of a nanomaterial is governed largely by its physicochemical identity. Particle size influences cellular uptake and tissue penetration; surface charge affects electrostatic interactions with membranes and proteins; and shape, roughness, hydrophobicity, aggregation state, and surface functionalization together shape biodistribution and clearance. As noted above, adsorption of serum and cytosolic proteins onto the nanoparticle surface generates a protein corona that can mask or expose targeting ligands and redirect intracellular processing following endocytic uptake. A recurring mechanistic theme across therapeutic and toxic outcomes alike is the generation of reactive oxygen species (ROS): controlled, localized ROS production can be harnessed for antimicrobial action and tumour-cell killing, while excessive or uncontrolled oxidative stress can damage proteins, lipids, DNA, and mitochondria, triggering inflammatory and cytotoxic responses (Saravanan *et al.*, 2024). Surface engineering with ligands, antibodies, peptides, polymers, or carbohydrates is the principal strategy used to steer these interactions toward a desired biological outcome.

BIOMEDICAL APPLICATIONS

Drug Delivery

Conventional drugs are frequently limited by poor aqueous solubility, rapid enzymatic or chemical degradation, short circulation half-life, and nonspecific tissue distribution. Nanocarriers – polymeric nanoparticles, liposomes, lipid nanoparticles, dendrimers, nanoemulsions, and inorganic nanoparticles – address these limitations by encapsulating or conjugating therapeutic molecules, extending circulation time, and enabling controlled or

sustained release, while surface modification with targeting ligands adds a layer of active, receptor-mediated selectivity (Jadhav *et al.*, 2024). A further refinement is the design of stimuli-responsive carriers that release their payload preferentially in response to local pH, temperature, enzyme activity, redox potential, or light, thereby limiting the exposure of healthy tissue to cytotoxic agents.

Cancer Diagnosis and Therapy

Because a single Nano platform can simultaneously carry a therapeutic payload and an imaging agent, nanomaterials have enabled the theranostic paradigm, in which detection, treatment, and monitoring of disease progression occur within one integrated system (Paramasivam *et al.*, 2024). Beyond improving chemotherapeutic delivery, certain nanomaterials support entirely new treatment modalities: gold-based nanostructures, for instance, strongly absorb specific light wavelengths and convert this energy into localized heat, forming the basis of photothermal cancer therapy, while related constructs enable photodynamic treatment. Conjugation with antibodies, peptides, or aptamers further improves selective interaction with malignant cells.

Gene and Nucleic-Acid Delivery

DNA, messenger RNA, and small interfering RNA are powerful therapeutic agents but are intrinsically unstable and poorly membrane-permeant, so effective delivery requires protective, cell-penetrating carriers. Lipid nanoparticles and engineered polymeric systems now constitute the principal platforms for nucleic-acid delivery, with surface engineering used to tune tissue distribution, cellular uptake, and intracellular release; continued development of biodegradable, targeted carriers is expected to expand their role in gene therapy and precision medicine.

Tissue Engineering and Regenerative Medicine

Nanomaterials can also reshape the physical and chemical environment presented to cells within engineered tissue scaffolds. Nanostructured scaffolds that mimic the extracellular matrix promote cell attachment, proliferation, and differentiation, and nanocomposite scaffolds incorporating polymers, ceramics, or graphene derivatives are under active investigation for bone, cartilage, skin, and neural repair, particularly when combined with controlled local delivery of growth factors.

ANTIMICROBIAL APPLICATIONS

The spread of multidrug-resistant pathogens has intensified interest in antimicrobial nanomaterials, which – unlike single-target conventional antibiotics – can act through several simultaneous mechanisms, including membrane disruption, metal-ion release, ROS-mediated oxidative damage, and direct interference with microbial proteins and nucleic acids (Roy *et al.*, 2023). Silver, copper, zinc oxide, and titanium dioxide nanoparticles have demonstrated broad-spectrum antimicrobial activity and are increasingly incorporated into coatings for medical devices, wound dressings, and packaging. Bacterial biofilms remain an especially difficult target because their protective extracellular matrix limits the penetration of conventional agents; nanocarriers can improve antimicrobial penetration into biofilms, while intrinsically antimicrobial nanoparticles can interfere with microbial adhesion and disrupt mature biofilm

architecture, offering a promising strategy against ESKAPE-type pathogens (Mukherjee *et al.*, 2023; Wu *et al.*, 2023). Nanotechnology-based antimicrobial and diagnostic strategies are similarly being explored for broader infectious-disease and public-health applications (Chen *et al.*, 2023). Even so, antimicrobial efficacy must be balanced against cytotoxicity toward human cells and beneficial microbiota, making biocompatibility and environmental safety essential design considerations.

BIOSENSORS AND DIAGNOSTIC APPLICATIONS

The large surface area and distinctive optical, electrical, magnetic, and catalytic behaviour of nanomaterials make them well suited to signal amplification in biosensing, supporting the detection of proteins, nucleic acids, enzymes, pathogens, and other biomarkers. Gold nanoparticles, graphene-based materials, quantum dots, metal oxides, and nanozymes have each been used to enhance sensor sensitivity and improve signal transduction, extending nanomaterial-based sensing into biomolecule detection and therapeutic-agent delivery within combined theranostic platforms (Paramasivam *et al.*, 2024). Diagnostic applications relevant to microbial infection – including pathogen detection and treatment monitoring – illustrate this convergence of sensing and therapy (Zou *et al.*, 2023). Integration of such sensors with microfluidics, wearable devices, and digital connectivity is expected to further support rapid, decentralized diagnostic testing at the point of care.

AGRICULTURAL AND ENVIRONMENTAL BIOLOGICAL APPLICATIONS

Beyond human medicine, nanomaterials are being explored as nano-fertilizers, nano-pesticides, and carriers for controlled delivery of nutrients or agrochemicals, potentially improving the efficiency of active ingredients while lowering the effective dose required for plant protection and seed treatment. In environmental biotechnology, related nanomaterials support pollutant biosensing, water treatment, and antimicrobial surface control. However, the environmental persistence, transformation, bioaccumulation, and ecological interactions of these materials with plants, microorganisms, and animals must be carefully characterized before large-scale agricultural or environmental deployment.

NANOTOXICITY AND BIOSAFETY

The same physicochemical properties that make nanomaterials biologically active also underlie their potential toxicity. Nanotoxicity depends on particle size, morphology, surface chemistry, composition, dose, exposure duration, aggregation behaviour, solubility, and route of administration, and reported biological effects include oxidative stress, inflammation, membrane damage, mitochondrial dysfunction, genotoxicity, and disrupted cell signalling (Saravanan *et al.*, 2024). Because different nanomaterials behave differently within biological systems, no single, universally applicable toxicity threshold currently exists; standardized physicochemical characterization, reliable dose metrics, long-term *in vivo* studies, and validated *In vitro* models are still needed. Green synthesis routes and biodegradable carrier design may reduce certain environmental and biological risks, but an environmentally benign synthesis route does not, by itself, guarantee biological safety.

FUTURE PERSPECTIVES

Biological nanotechnology is expected to progress toward multifunctional, biodegradable, stimuli-responsive, and precision-engineered systems designed for specific cellular or molecular targets. Artificial intelligence and machine-learning methods offer a complementary route to this goal, with potential use in predicting nanoparticle properties, optimizing synthesis parameters, identifying early toxicity signatures, and guiding the rational design of materials for particular biological functions. A closely related priority is “safer-by-design” nanotechnology, in which toxicological and environmental impact are evaluated during, rather than after, material development. Greater integration of nanotechnology with genomics, proteomics, microfluidics, and personalized medicine should further improve diagnostic precision and therapeutic outcomes. Nevertheless, translating promising laboratory-scale nanomaterials into approved clinical or commercial products will continue to require reproducible large-scale manufacturing, rigorous long-term safety assessment, and favourable regulatory and cost considerations.

CONCLUSION

Nanomaterials have expanded the possibilities of biological research by providing highly tunable platforms for drug and gene delivery, cancer therapy, antimicrobial treatment, biosensing, diagnostics, and tissue engineering, allowing increasingly precise control over how materials interact with cells and tissues. This biological activity, however, is inseparable from the possibility of toxicity, and successful application demands careful attention to particle safety, biodegradability, dosage, and environmental impact. Continued progress will depend on rational, evidence-based material design, sustainable and green synthesis routes, standardized toxicity evaluation, and closer integration with emerging computational tools such as artificial intelligence. Developing nanomaterials that are simultaneously safe, multifunctional, and clinically translatable is likely to remain a central and interdisciplinary research priority for years to come.

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Chapter

11

FOUNDATIONS, PRINCIPLES AND TYPES OF NANOMATERIALS

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ABSTRACT

Nanotechnology focuses on the design and study of materials at the nanoscale, where changes in size can produce properties that differ from those observed in conventional materials. Nanomaterials are increasingly studied because of their distinctive physical and chemical characteristics and their usefulness in several scientific and technological fields. This chapter introduces the fundamental concepts of nanomaterials and explains the relationship between atomic dimensions and the nanoscale. The two major strategies used for nanomaterial preparation, are top-down and bottom-up approaches, are described. Major forms of nanomaterials, including nanoparticles, nanoclays and nanoemulsions, are also discussed. In addition, the chapter outlines important physicochemical characteristics such as mechanical, thermal, magnetic, electronic, optical and catalytic properties. A basic understanding of nanoscale principles, classification and properties is useful for the applications of nanomaterials in modern science and technology.

KEYWORDS: Nanotechnology, Nanomaterials, Nanoparticles, Nanoscale, Nanoclays, Physicochemical Properties.

INTRODUCTION

Nanotechnology deals with the understanding, manipulation and application of matter at extremely small dimensions. It generally focuses on structures and materials having dimensions between 1 and 100 nanometres (nm). A nanometre is one-billionth of a meter. The unique characteristics of nanomaterials have made them useful in many areas of science and technology. Depending on their size, shape and composition, they can show distinctive physical, chemical, optical, electrical and biological properties. Because of these properties, nanomaterials are being explored for applications in areas such as healthcare, pharmaceuticals, food technology, agriculture, energy, environmental protection, electronics and engineering. Nanotechnology therefore brings together knowledge from several disciplines, including physics, chemistry, biology, materials science and engineering (Kumar Yadav & Choudhari, 2022). The concept of controlling matter at the atomic level was discussed by Richard Feynman

in 1959, while the term “nanotechnology” was introduced by **Norio Taniguchi in 1974**(Kumar Yadav & Choudhari, 2022; Sadiku *et al.*, 2021).

FOUNDATIONS OF NANOMATERIALS

Nanomaterials are that substance which is having a minimum one dimension is less than 100 nanometres. In another word’s nanomaterial, the prefix word nano means a billionth. A billionth part of meter is called as Nano (10^{-9} meter). The size of nanomaterial is near about to 100nm. If the size range of nanomaterials increases above 100nm then it is said to be a bulk material. In fact, the radius of an atom is lower than a nanometre. A group of 1nm radius consist of almost 25 atoms. (Chauhan, 2025).

Some facts that is unimaginable like:

- a) Human hair having a diameter of 75000nm.
- b) A hydrogen atom having a 0.1nm diameter and nucleus of 0.00001nm diameter.

Some materials which are commonly used for synthesis of nanomaterials, they are defined in Table 1.

Table 1: Some commonly used materials for synthesis of nanomaterial

Materials	Production Methods	Applications
Carbon fullerenes	Using two carbon electrodes in a helium or neon atmosphere and generated arc to results in formation of fullerenes	Targeted drug delivery, lubricants, Catalysts, Nano-scale chemical sponges
Metals	Various methods to build materials such as combustion synthesis, mechanochemical processing, chemical precipitation, sol-gel processing, laser ablation, pyrolysis	Wound dressing, Electromagnetic interference / radio frequency interference shielding
Carbon nanotubes	Produced by three techniques such as carbon-arc discharge, laser ablation of carbon or chemical vapour deposition	Scanning probe microscopy, Antistatic materials, carbon nanotube-enhanced plastic
Metal oxides	Combustion synthesis, mechanochemical processing, chemical precipitation, sol-gel processing, laser ablation, pyrolysis	Water and strain repellent textiles, sunscreens

Sources: Bankar A, Joshi B, Kumar AR, Zinjarde S. Banana peel extract mediated novel route for the synthesis of silver nanoparticles. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2010; 368(1-3):58-63

Nanomaterials can originate through different processes. Naturally occurring nanomaterials may be produced through physicochemical processes in the environment. Incidental nanomaterials can arise unintentionally from human activities and industrial processes. In contrast, engineered nanomaterials are deliberately produced under controlled laboratory or industrial conditions to obtain particular characteristics. Bioinspired nanomaterials are developed by taking ideas or structural features from naturally occurring materials and biological systems.

The development of nanoscale materials has created opportunities in several fields, including healthcare, energy, environmental protection, construction, food processing and agriculture. Their usefulness is closely associated with the ability to control their dimensions, structure and surface characteristics (Mekuye & Abera, 2023).

NANOSCALE AND ATOMIC SCALE

The nanoscale lies between the atomic scale and the larger dimensions that we encounter in everyday materials. Although a nanometer is much larger than the size of an individual atom, working at the nanoscale provides an important opportunity to arrange and control atoms and molecules to develop useful structures and materials. An atom is approximately 0.1 nm in diameter, while its nucleus occupies an extremely small region within it. Atoms are the basic units that make up all matter.

The ability to organize atoms and molecules is one of the important features of nanotechnology. Nature itself provides many examples of precise organization at very small scales. Living systems, for example, are made up of cells that carry out highly organized processes through interactions occurring at the molecular level. These natural processes demonstrate how complex structures can be formed through the controlled arrangement of smaller building blocks.

At the atomic scale, matter is considered in terms of its fundamental building units. The nanoscale provides a larger level at which these units can be arranged and combined to produce functional structures. By controlling the size, arrangement and interaction of atoms and molecules, scientists can develop materials with specific characteristics and functions. Therefore, the nanoscale serves as an important link between individual atomic building blocks and practical materials or technologies.

PRINCIPLES AND PHYSICOCHEMICAL PROPERTIES OF NANOMATERIALS

MECHANICAL PROPERTIES

Mechanical properties indicate how a material behaves when subjected to an applied force. Important characteristics include strength, hardness, elasticity, plasticity. At the nanoscale, these characteristics can change because particles have a much greater proportion of surface atoms than bulk materials. The forces acting between nanoparticles and between nanoparticles and surrounding surfaces can also influence their mechanical behaviour.

Thermal Properties

The thermal behaviour of nanoparticles is closely related to their particle size and surface characteristics. Properties such as thermal conductivity, heat capacity, thermoelectric behaviour and thermal stability may change when a material is present in nanoscale form. As the particle becomes smaller, its surface area relative to its volume increases. This change can affect the way heat is transferred through the material. Nanoparticles may also melt at lower temperatures than their corresponding bulk materials, showing that particle size can influence thermal behaviour.

Magnetic Properties

The magnetic behaviour of a material can also be affected when its dimensions are reduced to the nanoscale. Such particles can become strongly magnetized when an external magnetic field is applied, but they generally do not retain magnetization after the field is removed.

Electronic and Optical Properties

Nanoparticles can interact with light and electrical energy in ways that are different from bulk materials. For example, changing the size or shape of metallic nanoparticles can alter their interaction with light and consequently change their optical response. These properties make nanomaterials useful in applications that require specific optical or electronic characteristics.

Catalytic Properties

Nanoparticles can exhibit considerable catalytic activity because chemical reactions take place at their surfaces. Their catalytic performance is influenced by several factors, including particle size, shape, composition, oxidation state and surface arrangement.

A reduction in particle size generally results in an increase in the surface area available for interactions with reactants. Consequently, a larger number of active sites may become accessible for chemical reactions. Control over particle characteristics is therefore an important factor in designing nanomaterials for catalytic applications.

APPROACHES / METHODS FOR SYNTHESIS OF NANOMATERIALS

Nanomaterials can broadly be prepared through two major strategies: the **top-down approach** and the bottom-up approach. Although both methods are used to obtain nanoscale structures, they differ in the way the final material is produced.

TOP-DOWN APPROACH

In the top-down strategy, a larger or bulk material is reduced to smaller dimensions. External mechanical or physical forces are applied to break down the starting material and generate nanoscale structures.

Common techniques associated with this approach include grinding, mechanochemical processing and mechanical alloying. Depending on the material and process requirements, grinding may be performed under dry or wet conditions.

The main principle of the top-down method is therefore the reduction of a relatively large starting material into progressively smaller structures.



Figure 1: Top-down approach

BOTTOM-UP APPROACH

The bottom-up strategy follows the opposite principle. Instead of breaking down a larger material, nanoscale structures are assembled from smaller building blocks such as atoms, molecules or ions.

Processes such as molecular assembly, condensation and related chemical transformations can be used to form nanoscale structures. Through controlled interactions among the smaller components, materials with specific structures and properties can be developed.

Thus, the essential distinction is that the top-down approach begins with a larger material and reduces its dimensions, whereas the bottom-up approach constructs the required structure from smaller units.

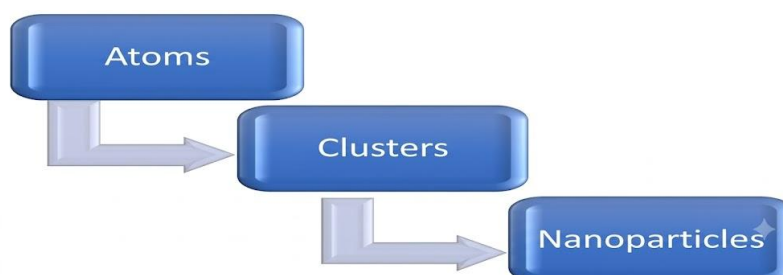


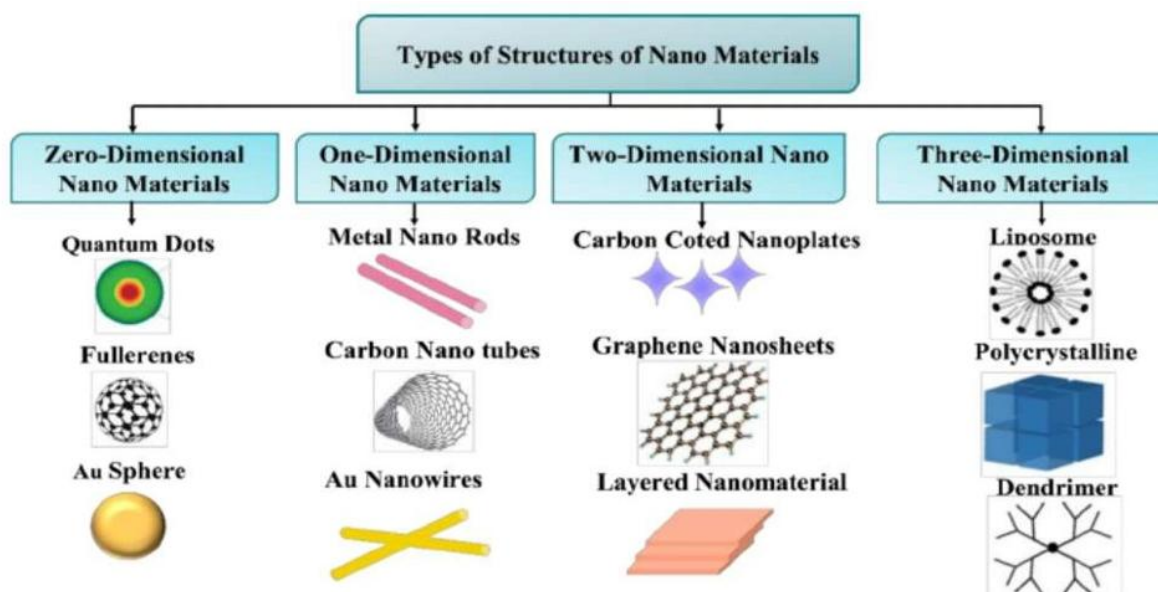
Figure 2: Bottom-up approach

CLASSIFICATION OF NANOMATERIALS

In general, Nanomaterials are classified into three classes such as Nanoparticles, Nanoclays and Nanoemulsions.

Nanoparticles

Nanoparticles are nanoscale materials that can occur either as individual nanostructures or as part of composite materials. They can be classified according to the number of dimensions in which their size is restricted at the nanoscale. Based on this classification, nanomaterials are commonly described as zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) materials.



In zero-dimensional nanomaterials, such as quantum dots, the movement of electrons is confined in all three spatial directions. In one-dimensional nanomaterials, such as quantum wires, electron movement is restricted in two directions and can occur more freely along one direction. Two-dimensional nanomaterials, including thin films, allow movement mainly within a two-dimensional plane. In three-dimensional nanomaterials, nanoscale building blocks are assembled to form larger nanostructured materials, allowing movement in all three spatial directions.

Sources: Mekuye, B., & Abera, B. (2023). Nanomaterials: An overview of synthesis, classification, characterization, and applications. *Nano Select*, 4(8), 486–501.

NANOCLAYS

Nanoclays are nanoscale clay-based materials that can be modified by exchanging the ions present between their clay layers with suitable organic ions. During this process, the spacing between individual clay sheets can increase, allowing organic cations to enter the interlayer region. The surface characteristics of the clay may also change from hydrophilic to more hydrophobic or organophilic behaviour.

Different analytical techniques can be used to study the composition and structural characteristics of nanoclays. These include gravimetric analysis, inductively coupled plasma analysis, X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR). These methods help in understanding the chemical composition and structural changes associated with nanoclay formation.

Nanoemulsions

Nanoemulsions are fine dispersions in which one phase is distributed as very small droplets within another continuous phase. An emulsion generally contains a dispersed phase and a continuous phase, with an emulsifying agent helping to maintain the stability of the system. Depending on the formulation, the dispersed phase may also be referred to as the internal phase, while the surrounding medium is known as the external phase.

Nano emulsions can be produced using either high-energy or low-energy techniques. High-energy methods include ultrasonication, high-pressure homogenization and micro fluidization. These processes supply external energy to reduce droplet size and generate a fine dispersion. Low-energy approaches include phase inversion temperature, solvent displacement and phase inversion composition. The most suitable preparation method depends on the composition of the system and the physical characteristics required in the final nano emulsion.

CONCLUSION

Nanomaterials represent an important area of modern science because reducing material dimensions to the nanoscale can produce changes in surface-related and size-dependent characteristics. The two principal preparation strategies namely top-down and bottom-up approaches, provide different routes for producing nanoscale structures. Classification based on dimensional characteristics further helps in understanding the structural diversity of

nanomaterials. Nanoparticles, nano clays and nano emulsions are important examples, each possessing distinctive structural and functional characteristics.

The mechanical, thermal, magnetic, electronic, optical and catalytic properties of nanomaterials contribute to their potential use across a wide range of scientific and technological fields. A clear understanding of their fundamental principles, preparation methods, classification and physicochemical characteristics is therefore important for the responsible development and application of nanomaterials.

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Chapter

12

**GREEN SYNTHESIS OF COPPER OXIDE NANOPARTICLES
USING *FLUEGGEA LEUCOPYRUS* WILLD FRUIT:
CHARACTERIZATION AND PHOTOCATALYTIC
DEGRADATION OF METHYLENE BLUE DYE**

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ABSTRACT

In this study copper oxide nanoparticles (CuO NPs) were synthesized through a green, eco-friendly approach using fruit extract of *Flueggea leucopyrus* Willd as a reducing and stabilizing agent which provide a simple, rapid, low-cost and efficient alternative to the traditional chemical synthesis method. The synthesized nanoparticles were characterized by UV-Visible spectroscopy, Fourier Transform Infrared spectroscopy (FT-IR) and X-ray diffraction (XRD) technique. UV-Visible spectral analysis revealed an absorption maximum wavelength at 463 nm which was related to surface plasmon resonance excitation of copper atoms. FT-IR analysis proved the functional groups involved in reduction and capping of the CuO NPs. The XRD analysis demonstrated that the CuO NPs have an average crystalline size of 26 nm calculated using the Debye-Scherrer equation. Photocatalytic property of the prepared CuO NPs was determined through the degradation of methylene blue (MB) dye, achieving a degradation efficiency of 98% after 240 minutes of UV light exposure. The green synthesized CuO nanoparticles could be used as an effective photocatalyst for the degradation of organic pollutants from industrial waste water and could also be promising for the future biomedical applications.

KEYWORDS: CuO NP, *Flueggea Leucopyrus*, UV- Vis, FT-IR, XRD, Photocatalytic Degradation.

INTRODUCTION

In recent years, interest in obtaining antimicrobial agents from medicinal and aromatic plants has grown significantly: drugs derived from plants are generally safe, do not cause any side effects [1]. Many cultures have developed unique traditional medicine systems using various drugs and preparations. Spices are an essential part of the Indian diet and at the same time is a

source of biologically active antimicrobial substances [2]. Nanoparticles have received considerable attention in recent years: their properties, depending on the conditions, can be very different from the characteristics of bulk substances, and these differences are caused by the special state of matter on a nanometres scale [3-5]. Metallic nanoparticles are finding their way into many areas of science, including medicine. Particles of metals have a number of advantages: a large specific surface area, high surface energy, good chemical and optical properties, and high electrical conductivity [6]. Copper nanoparticles are among the most promising. Molecules from natural sources, in particular medicinal and aromatic plants, have considerable interest due to their wide range of biological activity and great diversity [7]. Metallic nanoparticles are used in many areas of science and technology, including medicine. Particles of metals have a number of advantages: a large specific surface area, high surface energy, good chemical and optical properties, and high electrical conductivity. Copper nanoparticles are among the most promising metallic nanoparticles. They are used in batteries, optoelectronics, polymers, multilayer metal ceramics, in pharmacology as drug delivery carriers. In addition, they are used as antimicrobial, antioxidant agents [8]. The development of methods for producing pharmaceutical compositions and phytomedicines using antimicrobial agents is a promising direction. Spices are known to be healthy. Many of them have anti-oxidative, anti-inflammatory, anti-hepatotoxic, anti-tumour, antimicrobial effects, which are caused by the antimicrobial action of the substances contained in them. Therefore, reducing the negative impact of microorganisms and obtaining antimicrobial substances from spices are of great research interest [9].

The phytochemicals present in the plant extract like sugars, flavonoids and polyphenols act as reducing and stabilizing agents which reduce Cu^{2+} ions to Cu^0 or Cu^+ and capping the nanoparticle surfaces [10]. Quercetin facilitates the reduction of Cu ions, via keto-enol reaction [11]. Various plants sources and agricultural residues have been used and different parts of the plants acted as good bioreagents [12, 13].

Flueggea leucopyrus Willd. (Commonly known as Katupila) is a member of the Phyllanthaceae family. This plant grows widely across Sri Lanka, particularly as shrubs in dry-zone regions [14]. In traditional Sri Lankan medicine, the leaves of *F. leucopyrus* have long been employed for treating cancer, boils, external ulcers, and sores. More broadly, various species within the *Flueggea* genus are utilized across numerous African and Asian countries to manage a range of conditions, including epilepsy, malaria, jaundice, intestinal parasites, edema, menorrhagia, infertility, poliomyelitis, and aplastic anemia [15]. To date, more than ten secondary metabolites have been identified in *F. leucopyrus* [16, 17]. The objective of the present study was to synthesize and characterize the copper oxide nanoparticles using *Flueggea leucopyrus* Willd. Fruit extract and to evaluate their photocatalytic activity.

MATERIALS AND METHODS

PLANT COLLECTION AND EXTRACT PREPARATION

Fresh fruits of *Flueggea leucopyrus* Willd. Were collected from the foot hills of the Western Ghats, specifically from the Agasthiyarpatti region of Ambassamudram Taluk, Tirunelveli District, Tamil Nadu, India. Following collection, the fruits were thoroughly washed and blotted dry using blotting paper. They were then spread out and allowed to dry under shade at room temperature. Once dried, the samples were coarsely powdered and stored under refrigeration for subsequent use.



Figure 1: *Flueggea leucopyrus* Fruit

PREPARATION OF GREEN EXTRACT

About 20 g of the dried fruit was ground into a fine powder and transferred into a clean and dry beaker with 250 mL of deionized water, boiled about 30 minutes and cooled to room temperature. The obtained filtrate was separated by passing through Whatman filter paper.

SYNTHESIS OF COPPER OXIDE NANOPARTICLES

Copper oxide nanoparticles (CuO NPs) were synthesized by using *F. leucopyrus* fruit extract as a capping agent, via a modified procedure [18]. $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ was taken as a precursor with continuous stirring while adding Copper Sulphate solution when a colour change was observed from brown to dark green by eye. The solutions were stirred for about an hour to complete the reduction process, and then they were left to stand for 24 hours. The obtained black suspension of CuO NPs was then centrifuged at 4000 rpm for 15 min., washed with ultrapure deionized water and ethanol, dried at 70 °C, calcined at 400 °C and stored in an appropriate receptacle for further processing.

PHOTOCATALYTIC DEGRADATION OF METHYLENE BLUE

The photocatalytic capability of the CuO NPs was determined by carrying out the MB degradation in the presence of sunlight. CuO NPs were dispersed in 100 mL MB solution for 10 minutes using ultra sonication. The obtained solution was adjusted to pH = 6 and stirred in the dark for 30 min to achieve an adsorption equilibrium. Then, the solution was exposed to sunlight and centrifuged for 10 min. at 6000 rpm [19]. The MB degradation rate was identified

by absorbance at 664 nm using a UV-Visible spectrophotometer. The efficiency of photocatalytic degradation was determined by

$$\text{Degradation (\%)} = (A_0 - A)/A \times 100$$

Where, A_0 represents MB's initial absorbance, A is MB's absorbance after degradation. Moreover, the photodegradation rate was determined by calculating the rate constant, k (min^{-1}), based on the pseudo-first-order reaction kinetics curves, as shown as below [20]

$$\ln(C_0/C) = kt$$

Where, C_0 and C are the concentration of MB at initial and t time, respectively and k is the rate constant and calculated from the graph between $\ln(C/C_0)$ verse irradiation time.

RESULTS AND DISCUSSION:

PHYTOCHEMICAL SCREENING

The aqueous extract from the fruit of *F. leucopyrus* contained various active principles such as flavonoids, tannins and saponins. All these compounds are known to act as reducing, capping and stabilizing agents participate in the formation of CuO-Nps. Thus, it can be concluded that the aqueous extract of *F. leucopyrus* fruit could be used for the synthesis of copper oxide nanoparticles.

CHARACTERISATION OF CUONPS

UV – VISIBLE SPECTROSCOPY

The UV-Visible spectroscopy analysis was performed by using a Shimadzu UV-1700 spectrophotometer in a wavelength range of 200-900 nm to explore the properties of the green synthesized copper oxide nanoparticles. Figure 2 illustrates the absorption spectrum obtained for the CuO nanoparticles prepared by using the *Flueggea leucopyrus* fruit extract. Indeed, a distinct absorption peak was observed at 463 nm, confirming the successful synthesis of copper nanoparticles. The presence of this peak suggests that copper atoms on the surface of nanoparticles undergo surface plasmon resonance, and thus, it could be concluded that CuO nanoparticles were formed [21].

FT-IR SPECTROSCOPY

FTIR spectrum, as shown in figure 3, of the synthesized CuO NPs revealed the presence 1639.49 cm^{-1} for C-H asymmetric stretching, the weak absorption peak at 3792 cm^{-1} that can be attributed to the phenolic O-H stretching vibration A broad peak at 3435.22 cm^{-1} is obtained because of hydrogen bonded O-H stretching vibration of the hydroxyl group. 1400.32 cm^{-1} correspond to aromatic C-C stretching vibration [22]. The absorption band at 1078.21 cm^{-1} is due to the C-O stretching vibration. Absorption peaks observed from 510 cm^{-1} attributed due to the presence of CuO.

XRD ANALYSIS

The crystalline nature and the average particle size of the CuO nanoparticles was examined using powder x-ray diffraction (XRD) technique using Cu-K α radiation ($\lambda = 1.5406 \text{ \AA}$) with a scan range of 10° – 80° 2θ . Figure 4 shows the XRD spectrum of CuO nanoparticles prepared using the *F. leucopyrus* fruit extract. The peaks were visualized clearly by smoothing out the raw

data peaks with ORIGIN software. Clearly, sharp peaks were obtained at 2θ values of 11.179° , 16.127° , 32.533° , 35.746° , 53.298° , and 66.218° , out of which the peak at 32.533° exhibited the highest intensity. From the Debye-Scherrer formula, the average crystallite size was calculated to be 26 nm. Additionally, the peaks were matched well with the standard reference data (JCPDS/PDF Card No. 89-2531) and indexed the Miller indices of (110), ($\bar{1}11$), (111), ($\bar{1}02$), (020), (202), ($\bar{1}13$), ($\bar{3}11$), ($\bar{2}21$), and (004) crystal planes respectively. It is worth mentioning that no extra peaks from other impurity phase were observed and also the pattern is well matched with the standard reference data. Thus, XRD analysis reveals that the synthesized nanoparticles possess a pure monoclinic phase crystalline structure [23].

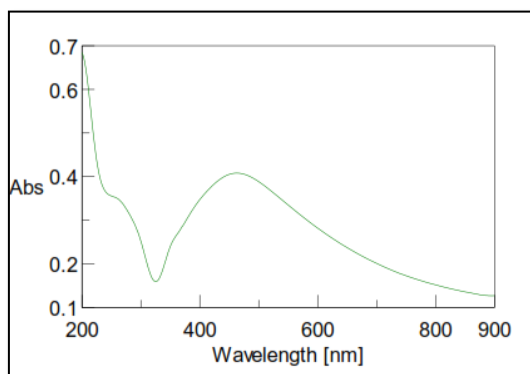


Figure 2: UV- Vis spectrum

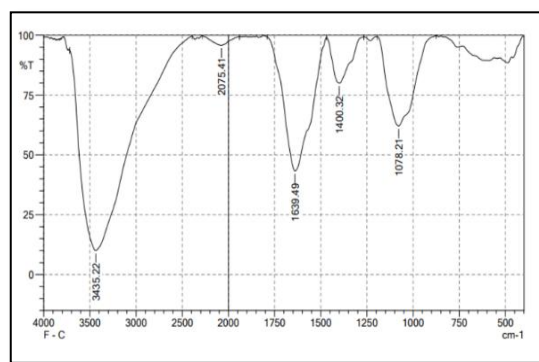


Figure 3: FT- IR spectrum

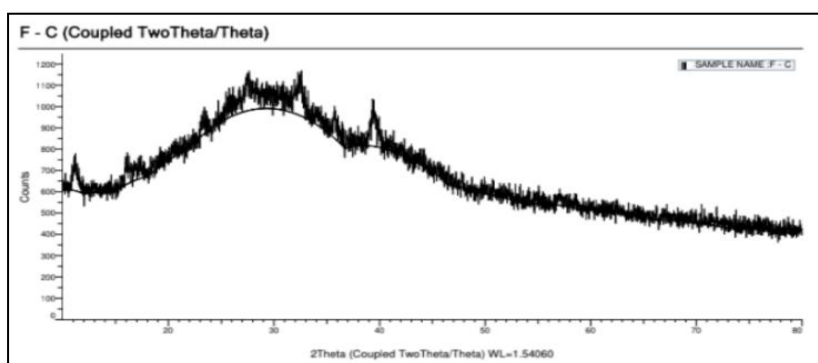


Figure 4: XRD spectrum

PHOTOCATALYTIC DEGRADATION OF MB DYE

Photocatalysis is considered one of the most hopeful techniques for degrading hazardous organic dyes. Irradiation of the photocatalyst with sunlight generates sufficient energy to excite conduction electrons from the valence belt to the conduction belt, resulting in the formation of electron-hole pairs on the catalyst surface. They are increasingly being explored for environmental restoration since they can break down pollutants in air and water [24]. Researchers are now investigating nano catalytic materials with unique nanoscale characteristics as possible solutions to energy and ecological problems [24], [25]. In the present study, the photocatalytic efficiency of the synthesized CuO nanoparticles for dye degradation was evaluated. The results showed effective degradation of methylene blue (MB) dye within a

period of 240 minutes, with the CuO nanoparticles achieving a remarkable degradation efficiency of 98%.

Table 1: Comparison of the MB degradation of biosynthesized CuO NPs with previous reports

Biosynthesized CuONps	Light source	Dose of catalyst (mg)	Dose of MB	Degradation time (min)	Degradation percentage (%)
<i>F. Leucopyrus</i> - CuO Nps	Sunlight	30	15 mL, 0.06 mM	240	98

CONCLUSION

In this present study, copper oxide nanoparticles were successfully synthesized using *Flueggea leucopyrus* Willd. The nanoparticles were characterized by UV-Visible, FT-IR, and XRD analysis. UV Visible spectroscopy is based on the absorption of the ultraviolet or visible region of the electromagnetic spectrum by a chemical compound which leads to the generation of complementary colours. FT-IR analysis was carried out to determine the functional groups present on the surface of the nanoparticles. From the results of the XRD it was also determined that the CuO nanoparticles have a crystalline structure with a face centered cubic lattice. In general, the method of green synthesis presented is simpler, faster, and more economical compared to the chemical methods. The nanoparticles obtained through green synthesis will soon be used in the field of medicine for the treatment of various diseases and pathologies in the human body, which will significantly contribute to health care.

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Chapter

13

**NANOCATALYSIS: FUNDAMENTAL PRINCIPLES,
CLASSIFICATION, AND INDUSTRIAL APPLICATIONS**

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ABSTRACT

Nanocatalysis is an interdisciplinary field that exploits nanoscale materials to control catalytic activity, selectivity, and stability through deliberate manipulation of surface structure, electronic properties, particle size, morphology, defects, and metal-support interactions. At the nanoscale, a large fraction of atoms is exposed at surfaces or interfaces, creating catalytic sites that can differ substantially from those of bulk materials. Consequently, nanocatalysts provide opportunities to improve reaction rates, lower activation barriers, tune product distributions, and reduce the use of scarce or expensive elements. This chapter presents the fundamental principles of nanocatalysis, and major classes of nanocatalysts. Particular emphasis is placed on industrial applications in Biodiesel production, hydrogen production, environmental remediation, waste water treatment, drug delivery and energy conversion.

KEYWORDS: Nanocatalysis, Nanocatalysts, Heterogeneous Catalysis, Single-Atom Catalysts, Metal-Support Interactions, Industrial Catalysis, Sustainable Catalysis.

INTRODUCTION

Catalysis plays a crucial role in chemical reactions, from small-scale laboratory experiments to large industrial applications. It helps speed up reactions while lowering energy use, minimizing waste, and improving selectivity. Nanotechnology involves the design and application of nanoscale materials with unique physical and chemical properties^{1, 2}. Its integration with catalysis has led to the development of highly efficient nanocatalysts with improved activity, selectivity, stability, and recyclability^{1, 2}. Nanocatalysis plays a key role in green chemistry, Industrial level and sustainable development due to the unique properties of nanoparticles in terms of surface area, reaction rate and catalytic efficiency². Nanocatalysts are typically made up of nanoparticles with sizes ranging from 1 to 100 nanometers, offering a large surface-to-volume ratio. This expanded surface area improves their catalytic performance and renders them more active than traditional catalysts. Owing to their small size and high surface-area-to-volume ratio, nanocatalysts provide a large number of accessible active sites, facilitating faster and more efficient chemical reactions^{2,3}. Nanocatalysis has become an important approach in green chemistry and sustainable development because it can reduce energy consumption, waste generation, and the use of harmful reagents and solvents³. Nanocatalysts can also combine

advantages of homogeneous and heterogeneous catalysis, offering efficient interaction with reactants along with relatively easy separation and reuse³. Current chapter focuses on controlling nanocatalyst size, morphology, composition, and surface properties to achieve enhanced catalytic performance⁴. Heterogeneous nanocatalysts commonly employ materials such as alumina, silica, titania, and zeolites as supports for finely dispersed active metals⁵. Various nanomaterials, including aluminum, iron, titanium dioxide, clays, silica, and carbon nanotubes, have demonstrated promising catalytic applications. These advances are contributing to cleaner chemical processes, improved resource efficiency, energy conservation, and reduced environmental impact across several industrial sectors³⁻⁵.

Nanocatalysts differ from conventional catalysts primarily due to their nanoscale dimensions and unique physicochemical properties. Traditional catalysts generally exhibit lower surface areas, limited reactivity, and reduced durability over repeated use. In contrast, nanocatalysts offer:

1. **Higher surface area-to-volume ratio**, associated the more active sites and faster reaction rates.
2. **Size-dependent properties**, including tunable selectivity and activity through controlled synthesis.
3. **Tailored nanostructures**, such as core-shell configurations, which enhance performance and stability.
4. **Greater sustainability**, as they can be synthesized from earth-abundant materials, reused efficiently, and aligned with renewable resource utilization.

These distinctions enable nanocatalysts to exhibit higher catalytic activity, improved selectivity, longer operational lifetimes, and lower energy demand, making them more efficient and environmentally compatible than traditional catalysts.⁶

FUNDAMENTAL PRINCIPLES OF NANOCATALYSIS

Nanoparticles have emerged as highly important catalytic materials and represent one of the most significant applications of nanotechnology. A wide range of materials, such as aluminum, iron, titanium dioxide, and silica, have been employed in the development of nanocatalysts because of their distinctive physicochemical characteristics². The high surface-to-volume ratio of nanoparticles is one of the primary reasons for their enhanced catalytic activity, as it provides a greater number of active sites and can accelerate chemical reactions. In addition to surface area, the morphology, size, and structural characteristics of nanoparticles strongly affect their catalytic behavior². Controlled synthesis and precise regulation of nanoparticle size and shape enable researchers to improve the selectivity and efficiency of chemical transformations, thereby supporting more sustainable catalytic processes³. These developments in nanocatalysis can promote better utilization of resources, reduce energy consumption, and minimize waste generation in industrial operations, consequently lowering their environmental impact. Nanocatalysts have therefore found extensive applications in areas including chemical production, energy conversion, and energy-storage technologies³.

Nanocatalysis primarily examines the relationship between the intrinsic properties of nanomaterials and their catalytic performance. These properties can broadly be classified into four categories:

- (1) Parameters associated with bond lengths, including lattice constants and binding energies;
- (2) Properties governed by cohesive energy;
- (3) Characteristics related to binding-energy density; and
- (4) Properties arising from the combined effects of atomic cohesive energy and binding-energy density. Knowledge of these factors is essential for the rational design and development of nanocatalysts with improved catalytic performance for specific applications ³ (**Fig. 1**).

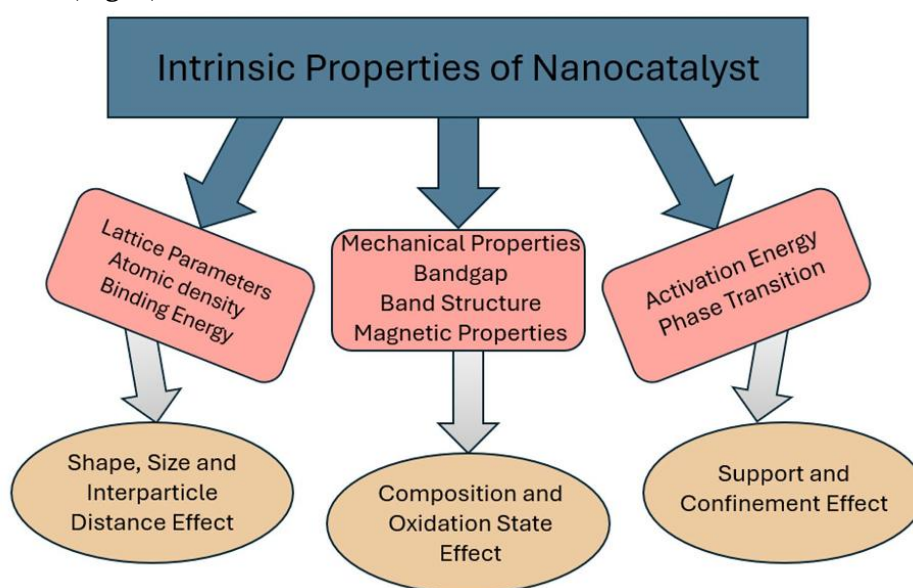


Figure 1: Intrinsic properties of nanocatalyst

The properties and behavior of nanoscale materials or atomic clusters can differ considerably from those of isolated atoms or particles, primarily because of interactions occurring at atomic interfaces. Such interfaces play a fundamental role in determining the physicochemical and catalytic properties of nanomaterials ⁷. Atomic coordination is particularly important because it influences the strength of atomic bonds and the associated energy. Surface atoms generally possess lower coordination than atoms within the bulk crystal, resulting in changes in bonding characteristics, structural stability, and interactions with electrons and phonons⁷. By controlling parameters such as particle size, morphology, spatial arrangement, surface composition, and electronic structure, researchers can systematically modify nanocatalysts to achieve enhanced thermal and chemical stability. These engineered nanoscale catalysts have consequently been utilized in numerous industrial applications, where they provide improved catalytic efficiency and overall performance ⁸. Their increasing relevance has generated substantial interest in both academic research and industrial applications, emphasizing the considerable potential of nanocatalysts in modern catalysis.

CLASSIFICATION OF NANOCATALYSTS

HOMOGENEOUS NANOCATALYSTS

Homogeneous nanocatalysts operate in the same phase as the reactants and are commonly dispersed as nanoparticles in a suitable solvent⁹. A major limitation of these systems is nanoparticle aggregation, which can significantly reduce catalytic efficiency. The formation of larger aggregates decreases the available surface area and consequently lowers catalytic performance. To minimize aggregation, long-chain molecules or stabilizing agents are often attached to the nanoparticle surface. These molecules prevent direct particle-to-particle contact and improve colloidal stability in solution ⁴. However, excessive surface stabilization may also hinder the accessibility of active sites, thereby decreasing catalytic activity ⁴.

Another important challenge is the recovery and reuse of homogeneous nanocatalysts. Since the nanoparticles remain dispersed in the reaction medium, their separation after the reaction can be difficult, reducing overall process efficiency and limiting recyclability. Inadequate recovery may also increase environmental concerns and operating costs. A typical example is palladium nanoparticles suspended in organic solvents, which are extensively utilized in hydrogenation reactions and carbon–carbon bond-forming coupling reactions.

HETEROGENEOUS NANOCATALYSTS

Heterogeneous catalysis is an environmentally favorable catalytic approach in which the catalyst and reactants are present in different phases, most commonly involving a solid catalyst or a catalyst immobilized on a solid support. This phase difference facilitates the separation and recycling of the catalyst, thereby reducing waste and improving process efficiency. In contrast to homogeneous catalysts, heterogeneous catalysts can generally be recovered by simple techniques such as filtration, making them particularly attractive for industrial applications. A wide range of nanoparticle-supported catalysts has been developed for heterogeneous catalytic processes. Frequently studied systems include palladium, iron, gold, nickel, and platinum nanoparticles supported on materials such as silica, alumina, and carbon-based fibers ¹⁰

Heterogeneous catalysts enhance chemical transformations by altering reaction pathways, lowering activation energies, and improving reaction efficiency ¹¹. They generally contain active metal sites, particularly transition metals, dispersed on solid supports to increase the accessible surface area and reaction rates. Nevertheless, the development of catalysts that simultaneously provide high activity, stability, and low cost remains challenging because of limitations associated with current preparation methods ¹.

Metal nanoparticles are particularly important in nanocatalysis because their high surface area promotes strong interactions between catalyst surfaces and reactant molecules. Consequently, they can efficiently facilitate transformations such as oxidation, reduction, and carbon–carbon bond formation, often under relatively mild reaction conditions. Although metal nanoparticles were initially associated mainly with homogeneous catalytic systems, they are now considered an important link between homogeneous and heterogeneous catalysis, combining advantages of both approaches¹. Controlled synthesis of these nanoparticles provides opportunities to tune

their structural and surface properties, optimize catalytic performance, and improve industrial catalytic processes. The key differences among homogeneous, heterogeneous, and nanocatalysts are illustrated in **Fig. 2**.

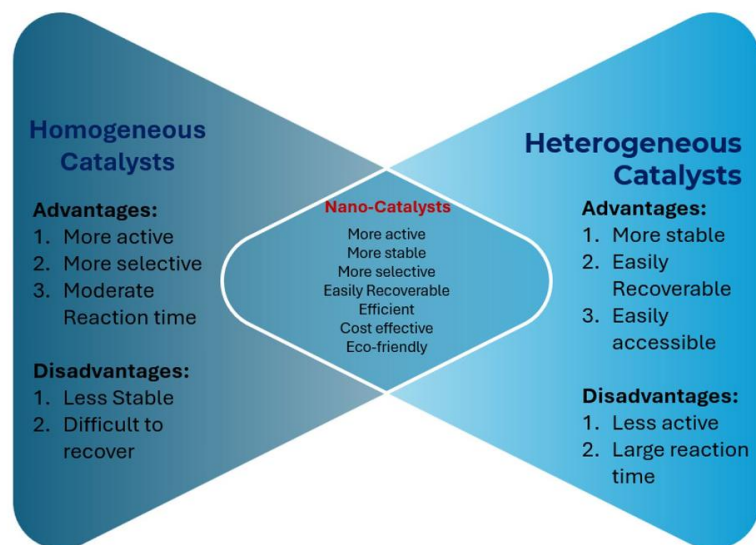


Figure 2: Differences between homogenous, heterogeneous and nanocatalysts

COMPARISON BETWEEN HOMOGENEOUS & HETEROGENEOUS NANOCATALYSTS

Single-atom catalysis (SAC) is an important development in heterogeneous catalysis. It has attracted considerable attention because it combines the advantages of both homogeneous and heterogeneous catalysts. SACs contain isolated single metal atoms that act as active sites, similar to homogeneous catalysts. At the same time, they offer the stability and easy separation of heterogeneous catalysts ¹. Therefore, SACs can act as a bridge between homogeneous and heterogeneous catalytic systems. The potential of SACs was first experimentally demonstrated in 2016. Since then, researchers have studied their use in many different catalytic reactions. Recent studies have shown promising results for using SACs in reactions commonly performed with homogeneous catalysts ². For example, Rh/ZnO and Rh/CoO single-atom catalysts have been successfully used for the hydroformylation of olefins and have shown activity comparable to the well-known homogeneous Wilkinson catalyst ². Similarly, Pt/Al₂O₃ SACs have shown high efficiency in hydrosilylation reactions. M–N–C SACs, where M can be metals such as Fe or Co, have also been found to be effective for C–H bond activation.

These developments show the great potential of SACs in catalysis. By carefully designing suitable single-atom catalysts, homogeneous catalysts can be converted into heterogeneous systems with improved stability and easier separation. This approach can contribute to the development of more efficient and sustainable chemical processes ².

INDUSTRIAL APPLICATIONS OF NANOCATALYSIS

Nanocatalysis has become an important technology in modern industry because nanoparticles provide a very high surface area, large number of active sites, tunable surface properties, and enhanced catalytic activity. The industrial significance of nanocatalysis arises from the possibility of improving catalytic efficiency while reducing energy consumption, raw-material

use, waste generation, and environmental impact. However, laboratory-scale activity must be accompanied by stability, reproducibility, process compatibility, and economic feasibility¹²⁻¹⁵. These characteristics allow industrial reactions to proceed faster, at lower temperatures and pressures, and sometimes with improved selectivity. Major plications include the following (Fig.3)

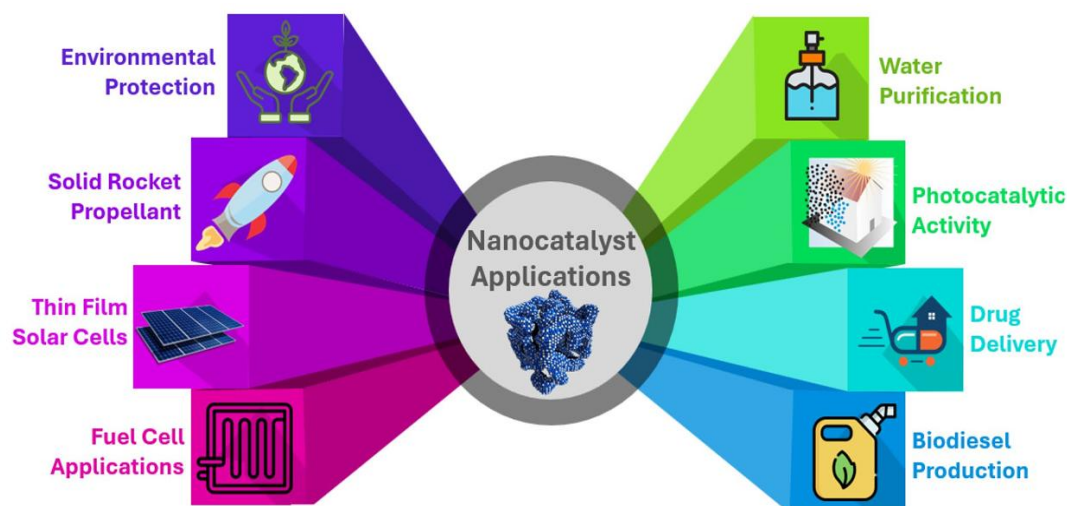


Figure 3: Applications of nanocatalyst

PETROLEUM REFINING AND PETROCHEMICAL INDUSTRY

Nanocatalysts have important applications in petroleum refining and petrochemical industries because of their high surface area, large number of active sites, and enhanced catalytic activity. They are used in processes such as hydrosulfurization, hydrocracking, hydrogenation, catalytic cracking, and reforming. Nanostructured catalysts containing metals such as Ni, Co, Mo, Pt, and Pd can improve the conversion of heavy hydrocarbons and remove sulfur-containing compounds from petroleum fuels. Their high activity can also help reduce reaction temperature, energy consumption, and catalyst requirement. Thus, nanocatalysis offers a promising approach for efficient, selective, and cleaner petroleum processing¹⁶⁻¹⁸.

WATER PURIFICATION

Hydrogen is increasingly recognized as an important energy source because of its various social, economic, and environmental advantages. Approximately 40% of the total hydrogen consumption is associated with the chemical industry, highlighting its growing demand both at present and in the future¹⁹. A considerable amount of hydrogen is consumed in reduction processes, particularly for converting metal catalysts into their active metallic forms for different chemical reactions. Therefore, developing methods to prepare catalysts directly in their metallic state without using hydrogen can contribute to reducing overall hydrogen consumption. To promote the sustainable use of hydrogen, researchers have developed an advanced electrochemical deposition method for producing nano-sized metallic silver particles. These particles are deposited onto a carbon-covered alumina (CCA) support, producing a highly efficient silver-based catalyst for water purification through microbial control.

Furthermore, studies have demonstrated that these silver-supported catalysts can be recovered and reused, which improves their efficiency and practical applicability ²⁰.

BIODIESEL PRODUCTION

Growing environmental awareness and the gradual depletion of petroleum resources have increased interest in biodiesel as a renewable fuel. Biodiesel, which is produced from fatty acids, is widely utilized in countries such as Germany, France, Italy, the USA, and Japan ²⁰. Conventionally, biodiesel is synthesized through a chemical process known as transesterification, in which oil reacts with alcohol in the presence of a liquid or homogeneous catalyst. However, this conventional process has several limitations, including difficulties in separating the final product, high water consumption, and environmental pollution caused by liquid waste. The use of solid or heterogeneous catalysts provides a more sustainable alternative and has therefore attracted considerable interest in biodiesel production. Despite ongoing research, their industrial application is still limited because of problems such as low reaction rates and inadequate efficiency.²¹ Nanocatalysts, owing to their large surface area and high catalytic activity, provide a promising approach for overcoming these limitations. Studies have demonstrated that the solid base nanocatalyst KF/CaO can produce biodiesel with a yield exceeding 96% [40]. This catalyst is particularly effective for converting oils containing high levels of free fatty acids into biodiesel. The KF/CaO nanocatalyst possesses particle sizes of approximately 30–100 nm and a porous structure that contributes to its enhanced catalytic efficiency. X-ray diffraction (XRD) studies have shown that the catalyst produces a new crystalline phase, K₂CaF₆, which enhances both its catalytic activity and stability. Its high surface area and pore size facilitate improved contact between the catalyst and reactants, thereby increasing the effectiveness of the biodiesel production process. Furthermore, the use of Chinese tallow seed oil as a biodiesel feedstock promotes the sustainable utilization of agricultural and forestry resources.²²

IN DRUG DELIVERY

Carbon nanomaterials, particularly carbon nanotubes (CNTs), are gaining importance in biomedical applications. CNTs have hollow nanometer-sized structures that can trap and transport small molecules, while their modifiable surfaces make them useful for drug delivery and biorecognition ²³. However, concerns about biocompatibility and the complexity of surface modification limit their practical use. To address these issues, carbonized polypyrrole nanoparticles (CPyNs) have been developed for imaging and drug delivery³. CPyNs possess controlled sizes, high microporosity, and magnetic properties, making them suitable for storing, targeting, and releasing drug molecules. They can be prepared by micelle templating in an oil–water system with sizes of 55, 76, and 99 nm. After carbonization, their high microporosity enables efficient loading and release of guest molecules. Their magnetic nature also allows selective targeting and easy separation. Studies using pyrene and ibuprofen demonstrated controlled drug release, while amine-functionalized smaller CPyNs showed improved sustained release, highlighting their potential for biomedical applications.^{1,3}

WASTEWATER TREATMENT

Halogenated organic compounds (HOCs) are widespread industrial pollutants, particularly in water, and are commonly used as solvents and additives in pharmaceutical and technology industries. They are highly toxic, persistent, and may cause serious health effects, including cancer and genetic damage, making their complete removal essential and sometimes legally required. Conventional wastewater treatment is generally ineffective for HOCs, while methods such as activated carbon adsorption, chemical oxidation, and incineration are costly and energy-intensive. Activated carbon requires large quantities, whereas oxidation may need excess oxidants and can produce harmful byproducts if incomplete. Biological treatment is also ineffective for many HOCs. Therefore, decentralized selective dehalogenation, which specifically removes halogen atoms from HOCs, offers a more efficient, economical, and sustainable option for medium-sized industries by reducing waste-disposal costs.^{2,3}

IN ENVIRONMENT PROTECTION

Sulfate radical-based advanced oxidation technologies (SR-AOTs) are promising for removing organic pollutants from water because sulfate radicals (SRs) are highly effective oxidants. However, challenges remain in developing efficient activation methods, nanoscale catalysts, and easy catalyst recovery after treatment¹. To overcome these limitations, Fe–Co mixed oxide nanocatalysts, particularly CoFe_2O_4 , have been investigated for activating peroxymonosulfate (PMS) to degrade pollutants such as 2,4-dichlorophenol. CoFe_2O_4 offers several advantages: Co(II) provides more effective PMS activation than Co(III), strong Fe–Co interactions reduce cobalt leaching, and its ferromagnetic nature allows easy catalyst separation and reuse. In addition, iron increases surface hydroxyl groups and promotes the formation of Co(II)–OH species, which enhance PMS activation²⁴.

PRODUCTION OF HYDROGEN FOR FUEL CELL

Hydrogen is a clean energy carrier, and fuel cells provide an efficient and sustainable alternative to fossil fuels. However, wider adoption requires advances in hydrogen production, storage, and utilization. Renewable methods such as water electrolysis, photochemical processes, and biological routes can provide an abundant and environmentally friendly source of hydrogen. Current storage materials, including hydrides, are still limited for transportation applications. Nanotechnology offers promising solutions for improving hydrogen storage efficiency. Fuel cells can also generate clean electricity for vehicles and power grids, although further improvements in materials and performance are needed. Thus, hydrogen energy has significant potential to support the transition toward renewable and sustainable energy systems.²⁵

IN SOLID ROCKET PROPELLANTS

Nano-aluminum particles (~50 nm) incorporated into ammonium perchlorate/HTPB composite propellants increase the burning rate by about 100% compared with micro-aluminum, while maintaining low pressure exponents at high pressures.²⁶ The enhanced burning is attributed to near-surface ignition and diffusion-controlled combustion of nano-aluminum agglomerates (~5

μm). Increasing nano-aluminum particle size decreases the burning rate, whereas the opposite trend occurs with micro-aluminum. In bimodal formulations, the burning rate increases with nano-aluminum concentration. Nano-scale catalysts further enhance the burning rate by about 5%.

FUTURE PERSPECTIVES

The future of nanocatalysis will depend on the ability to control not only particle size but also atomic arrangement, interfaces, defects, dynamic restructuring, and reaction environments. Industrially relevant research should prioritize realistic catalyst models, operando measurements, durability testing, techno-economic analysis, and life-cycle assessment. Greater integration between computational chemistry, materials science, reaction engineering, and process design will be essential.

A major challenge is the laboratory-to-industry gap. Many nanocatalysts exhibit exceptional activity under controlled conditions but lose performance during long-term operation because of sintering, poisoning, leaching, or structural evolution. Addressing these limitations will require catalyst architectures that combine high activity with structural robustness and scalable manufacturing routes.^{14,15}

CONCLUSION

The field of nanocatalysis has experienced rapid expansion over the past decade in both homogeneous and heterogeneous catalysis. Due to their high surface-to-volume ratio compared with bulk materials, nanoparticles are highly attractive for use as catalysts. Catalysts routinely accelerate and enhance thousands of chemical reactions, thereby forming the foundation of the multibillion-dollar global chemical industry as well as essential environmental protection technologies. In summary, owing to their numerous benefits, broad industrial applicability, and continuous progress in nanoscience and catalytic research, the adoption of nanocatalysts in industrial chemistry continues to increase. Nanocatalysts also have exciting applications in renewable energy and environmental cleanup. They can improve hydrogen production, fuel cells, and wastewater treatment, helping reduce reliance on fossil fuels and minimize pollution. Close collaboration among scientists, industries, and policymakers is essential for the safe and effective development of nanocatalysts. Through collective efforts and responsible innovation, nanotechnology can play a significant role in advancing sustainable chemistry, protecting the environment, and transforming industrial and biotechnological processes.

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ABSTRACT

Plant-mediated synthesis is usually presented as a benign substitute for chemical reduction, in which a leaf, peel or root extract supplies both reductant and stabiliser in water at moderate temperature. This chapter argues that the framing is mistaken, and that the mistake explains why two decades of publication have produced almost no manufactured or clinically used material. A plant extract is not a natural reducing agent but an uncontrolled, multi-component reaction medium whose composition is set by species, plant part, growth conditions and extraction protocol, and whose composition propagates into nucleation kinetics, surface chemistry and performance. Following that causal chain exposes five points at which it is not evidenced: extract composition is rarely measured; the mechanistic sequence has not been observed in situ in any plant system, though the techniques exist for defined inorganic systems; the identity of surface-bound species is not established by the methods used to claim it; biological activity is confounded with released ions and residual extract; and no continuous process has been demonstrated with a crude extract. Materials are organised by precursor chemistry rather than by plant, separating genuine bio reduction of noble metals from the templated precipitation that yields zinc and titanium oxides. Sustainability claims are shown to be boundary-dependent and contested rather than settled. Six specific, testable questions close the chapter.

KEYWORDS: Phytosynthesis, Plant Extract, Nucleation and Growth, Capping Agent, Nanoparticle Characterisation, Life-Cycle Assessment, Reproducibility.

Abbreviations: DLS: Dynamic Light Scattering; FTIR: Fourier-Transform Infrared Spectroscopy; HR-TEM: High-Resolution Transmission Electron Microscopy; LCA: Life-Cycle Assessment; MIC: Minimum Inhibitory Concentration; TEM: Transmission Electron Microscopy; XPS: X-Ray Photoelectron Spectroscopy; XRD: X-Ray Diffraction.

INTRODUCTION

Introduction and the central problem

Two decades of work on plant-mediated nanoparticle synthesis have produced a literature large enough that new reviews now survey other reviews ^{1, 2}. Across it the case is made in almost identical terms: an extract replaces a hazardous reductant, water replaces an organic solvent,

the reaction runs near room temperature, and no separate capping agent is needed ^{3, 4}. Against that volume stands a second observation, which the same reviews record and then set aside: almost nothing made this way has been manufactured at scale or entered clinical use ⁵.

Explaining that gap requires abandoning the framing that produced it. A plant extract is not a natural reducing agent but an uncontrolled, multi-component reaction medium whose composition is set by species, plant part, growth conditions and extraction protocol, and that composition propagates forward into nucleation kinetics, surface chemistry and therefore performance ^{1, 6, 7}. Calling it a reagent implies a stoichiometry no crude extract possesses.

That reframing turns the field's difficulty into one technical problem. The route is not unsafe and not ineffective. It is unpredictable: given a species, a plant part and a set of conditions, no published framework returns the size distribution, the surface chemistry or the catalytic rate that will result. Figure 1 sets out the chain of causes that would make such a prediction possible, and five of its links do not survive examination — extract composition is rarely measured; the mechanistic sequence has not been observed in situ in a plant system; surface-bound species are not identified by the techniques used to claim them; bioactivity is confounded with released ions and residual extract; and no continuous process has been demonstrated with a crude extract. These five breaks organise what follows and return as six testable questions.

The extract as reaction medium, and the reagents inside it

An extract delivers reductant, stabiliser and solvent in one addition, and the reducing molecules remain at the interface, so the particle arrives stabilised ^{1, 8}. The cost is that chemical routes with defined reagents achieve control no extract-based route has matched — silver across a 5–100 nm range on one protocol ⁹, with morphology-directing behaviour assignable to a specific reagent function ¹⁰ — because they depend on knowing what is in the flask.

Matched comparisons are rare. One study synthesised silver from an extract of *Ceratophyllum demersum* (whole plant) alongside a borohydride route with polyvinylpyrrolidone ¹¹. The plant route was tunable, giving 16–55 nm at the lowest extract volume and 2–4 nm at the highest, and it beat the chemical control on radical scavenging, 78.87% against 32.12% — which is the chapter's problem in miniature, since radical scavenging is exactly what the polyphenols in the capping layer do in their own right, and no extract-only control was reported.

The underlying chemistry is oxidation of a catechol or galloyl group to the corresponding *ortho*-quinone, releasing two electrons and two protons to a metal ion ^{12, 8}; it becomes more favourable as pH rises and the phenol deprotonates to the more strongly reducing phenolate, which is the reason behind the pH effect in Section 4. Polyphenols also chelate metal ions rather than reducing them immediately, lowering free-ion concentration and so competing with reduction for control of supersaturation ¹².

The strong evidence comes from isolated compounds. Quercetin alone reduces and stabilises silver and copper, giving MIC values against *Escherichia coli* of 2.11 ± 1.22 and 7.50 ± 0.00 $\mu\text{g mL}^{-1}$ ¹³; elsewhere it gave silver particles of 11.35 nm by TEM ¹⁴. Tannic acid alone yields monodisperse silver with measurable kinetics, its role distinguished experimentally from that of

citrate^{15, 16}. These are demonstrated reagents. Terpenoids, alkaloids and reducing sugars are credited with reduction and shape direction throughout the review literature^{7, 17}, but the compound-isolated experiments that would support those assignments were not located by this chapter's search; they remain proposed. Writing that flavonoids act as reducing and capping agents in a given extract is demonstrated for an isolated flavonoid and an inference for a crude one; identifying the responsible compounds chromatographically rather than assuming them¹⁸ remains the exception.

Mechanism: demonstrated, and assumed

Burst nucleation followed by diffusion-limited growth, aggregative growth as a separate pathway, and Ostwald ripening are established descriptions with direct experimental support^{19, 20, 21} — obtained almost entirely in defined inorganic systems studied in situ by X-ray scattering and absorption spectroscopy^{22, 23}.

None of that work was done in a plant extract. This is the most consequential statement in the chapter, and it is easy to miss because the literature does not present it as an absence. Diagrams running from reduction to nucleation to growth to capping appear in most treatments, drawn with the confidence of a mechanism that has been watched. What has been watched is a plasmon band rising in a spectrophotometer and particles imaged after the reaction stopped; the sequence between is reconstructed from those two endpoints and from systems that are not this one. It is plausible, not demonstrated, and this chapter treats it as poorly understood.

The processes are also unseparated, not merely unobserved. In a medium holding many reducing species at different potentials and many binding species at different affinities, there is no reason to expect reduction, nucleation, growth and capping to be temporally distinct, and a crude extract is one in which nucleation and capping almost certainly overlap. Burst nucleation in particular cannot be assumed: it needs the monomer concentration to rise sharply through the threshold and fall below it, which depends on how fast free metal is generated, and if chelation dominates early no sharp burst occurs. That measurement has not been made in a plant system.

Shape control is real but unexplained. Plant extracts do produce anisotropic particles^{24, 25}, which requires selective passivation of the slower-growing faces; which molecules bind to which facets is established in neither case. The morphology is demonstrated, the facet-selection mechanism proposed. A defined phytochemical, a defined precursor and an in-situ probe would settle most of this section. Because no universal mechanism has been demonstrated, none is offered here.

Control, materials, and what characterisation can prove

Control. Raising pH deprotonates phenolic hydroxyls to the more strongly reducing phenolate, so reduction accelerates, nucleation outcompetes growth, and mean size falls; optima of pH 11–13 at 70 °C and pH 9 at 65 °C have been reported for neem (*Azadirachta indica*) and green tea (*Camellia sinensis*) leaf extracts^{26, 27}. Extract volume has the largest effect, moving the electron-

microscopy range from 16–55 nm to 2–4 nm between 1 mL and 20 mL ¹¹, because more reducing molecules make more nuclei from the same metal.

And then the exception. Those are parameters the experimenter chooses. The parameter that is not chosen is at least as influential. One study prepared zinc oxide from zinc acetate dihydrate under a single protocol using three plant sources and a chemical control ²⁸. The control gave 19 nm by HR-TEM; pomegranate peel gave 27 nm, Seder leaf 15 nm, beetroot root 42 nm. Band gaps moved with them: 3.16 eV for the control against 2.84, 2.63 and 2.59 eV. One laboratory, one protocol, one precursor salt, a 2.8-fold spread in size and 0.57 eV in band gap. Figure 2 draws that comparison with the unmeasured middle stage shown as such. The variable producing the largest property change sits upstream of the parameter list, and in most published syntheses it is reported as nothing more than a species name.

Materials differ by precursor, not by plant. Silver(I) and gold(III) are reduced to the metal by phenolic components — bioreduction in the strict sense ²⁹. Copper and iron sit where reduction competes with oxidation, so mixed products are normal: plant-mediated copper spans roughly 10–110 nm and commonly holds metallic Cu and Cu₂O alongside CuO ³⁰, while an iron system from two extracts gave magnetite with hematite in different proportions and reversed its metal selectivity, adsorbing 78 and 74 mg g⁻¹ of Cd²⁺ but 64.8 and 80 mg g⁻¹ of Ni²⁺ ³¹. Zinc oxide and titanium dioxide are not reduced at all: extract components complex the metal ion and template its precipitation, and the oxide forms on heating ^{28, 32}. Calling the extract a reducing agent there is a widespread category error. Biomass-derived carbon dots belong with none of these, since heating carbonises the biomass and no metal is reduced ³³. Table 1 gives the classes with their values.

What characterisation can prove. Table 2 lists each technique as *establishes* → *cannot establish* → *common misinterpretation*, and four misreadings recur: a plasmon band read as monodisperse spheres, an infrared shift read as proof of capping, a Scherrer width read as particle size, and a light-scattering z-average read as particle size ^{34, 35, 36, 37, 38}.

The consequences appear whenever two techniques meet one sample. Silver from green tea measured 5.6 nm by microscopy and 12.5 nm by Scherrer ²⁷; silver and gold from one extract measured 15 ± 3 and 5.25 ± 1.00 nm by HR-TEM against 21 and 8 nm by Scherrer ³⁹. In the *Ceratophyllum* series, microscopy showed sizes falling smoothly from 16–55 nm to 2–4 nm while light scattering on the same five samples returned 280, 162, 603, 43 and 78 nm — not merely larger, but not even monotonic ¹¹. Both are correct measurements of different quantities. This matters because a biogenic particle presents not a metal surface but an adsorbed phytochemical layer, over which a protein corona forms in a biological medium and can overwrite the engineered surface ⁴⁰. Minimum-reporting frameworks exist and are widely unapplied here ^{41, 42}; the set in Table 2 builds on them, and its final clause is the consequential one — any bioactivity claim requires an extract-only control and an equimolar metal-salt control.

Table 1: Plant-mediated nanomaterials organised by precursor chemistry

Precursor Class	What The Extract Does	Example And Reported Size	Honest Limitation
Noble metal, M(I)/M(III) → M(0)	true bioreduction and capping	Ag, green tea leaf: 5.6 nm (TEM), 12.5 nm (XRD) ²⁷ ; Ag and Au, one extract: 15 ± 3 and 5.25 ± 1.00 nm (HR-TEM) ³⁹	outcome strongly source-dependent
Same, one purified compound	a single molecule reduces and caps	Ag from quercetin: 11.35 nm (TEM) ¹⁴ ; Ag and Cu from quercetin: 113.9 and 66.7 nm (SEM) ¹³	crude extract adds no measured advantage here ¹⁴
Redox-ambiguous metal (Cu, Fe)	reduction competes with oxidation	Cu: ≈10–110 nm, CuO with metallic Cu and Cu ₂ O ³⁰ ; Fe: magnetite with hematite ³¹	two extracts reverse the metal-selectivity order ³¹
Non-reducible oxide (ZnO, TiO ₂)	no reduction; templated precipitation, oxide forms on heating	ZnO, three plant sources: 27 / 15 / 42 nm, control 19 nm (HR-TEM) ²⁸	“reducing agent” here is a category error
Carbon dots from biomass	supplies carbon feedstock; heat does the chemistry	thermal carbonisation of biomass waste ³³	not a reduction reaction at all

Table 2: What each technique establishes and what it cannot

Technique	Establishes	Cannot Establish	Frequent Misinterpretation
UV–Vis	a plasmonic species formed	size distribution, shape, purity	single band read as “monodisperse spheres” ³⁴
FTIR	which functional groups are present	that a molecule is <i>bound</i> , its identity	peak shift read as proof of capping ³⁵
XRD + Scherrer	phase; crystallite size in one direction	particle size; strain contribution	crystallite size reported as particle size ^{36, 37}
TEM / HR-TEM	primary particle size and shape	bulk representativeness	unrepresentative fields read as the distribution
DLS	aggregation state; stability trend	primary particle size	z-average reported as particle size ³⁸
Zeta potential	stabilisation at that pH and ionic strength	absolute surface charge	a bare number without pH or medium ⁵⁸
XPS	surface oxidation state, with fitting	bulk composition	survey scan read as oxidation state ⁵⁹

Minimum characterisation set proposed here, built on existing frameworks ^{41, 42}: (1) TEM distribution, $n \geq 100$, mean $\pm$ SD, counting method stated; (2) XRD phase identification, with a strain-separated value if Scherrer is used; (3) DLS and zeta potential with pH and ionic strength; (4) XPS with fitted components for any mixed-valence metal; (5) organic content by TGA rather than an FTIR peak list; (6) extract metadata — species, part, harvest, solvent, extraction time, total phenolic content; (7) for any bioactivity claim, an extract-only control and an equimolar.

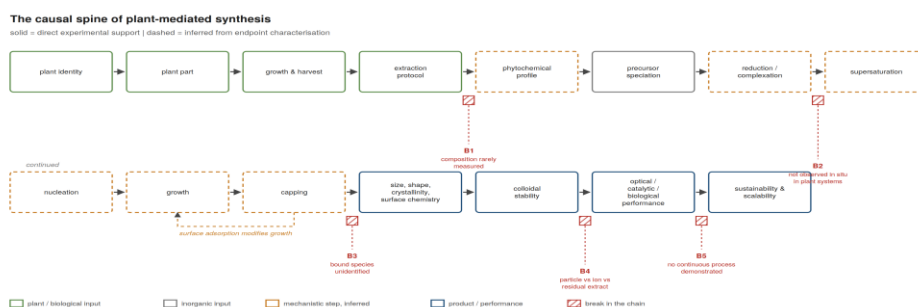


Figure 1: The causal spine of plant-mediated synthesis. Each arrow denotes a determining relationship. Solid boxes mark steps with direct experimental support; dashed boxes mark steps inferred from endpoint characterisation. Markers B1–B5 identifies the five points at which the chain is not currently evidenced; each returns as a research question in Section 6.

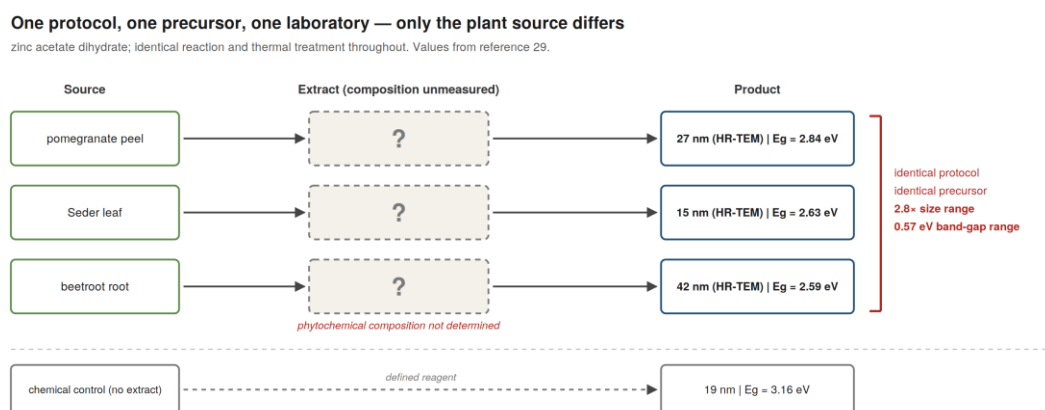


Figure 2: Propagation of source identity to product properties under a fixed protocol. Three plant sources and one chemical control were processed identically with the same zinc precursor in a single study; particle size varies by a factor of 2.8 and the band gap by 0.57 eV across the plant routes. The unmeasured middle stage is drawn as such: extract composition was not determined, so the mechanism connecting source to product cannot be recovered.

Values from ref.²⁸.

Applications and the evidence behind them

Environmental performance is the best-evidenced part of the field, because the endpoint is a measurable concentration rather than an inference about a living system. Zinc oxide from a pine rosin route, band gap 3.15 eV, removed methylene blue completely within 210 minutes under ultraviolet light and 82.78% of methyl orange over the same period ³². Two qualifications apply throughout: decolourisation is not mineralisation, and a model dye in clean water is not an

effluent. Adsorptive removal is similarly demonstrated ³¹, with recovery of the nanomaterial as the bottleneck.

Pharmaceutical claims are weaker. That silver nanoparticles are antibacterial is demonstrated ⁴³. To what the activity should be attributed is another matter. Released Ag⁺ acts on thiol-containing proteins and membrane transport while particle-specific effects include direct membrane disruption, and their relative importance varies with the medium, so studies that separate ionic from particulate effects experimentally are the model to follow ⁴⁴. Plant-mediated synthesis adds a third possible source, the extract itself, since a particle carrying polyphenols is not a bare silver particle. Establishing that activity belongs to the nanoparticle therefore needs an extract-only control and an equimolar salt control, and this chapter's search found them to be the exception. Where they were run the result is informative: silver nanoparticles from an *Ocimum sanctum* leaf extract and from pure quercetin both reached complete inhibition of *E. coli* at 150 µg mL⁻¹, and both exceeded the extract alone, the quercetin alone and silver nitrate alone ¹⁴. That is properly controlled, and it shows the crude extract conferred no measured advantage over one purified molecule.

Reporting is also inconsistent enough to block pooling, since mass-based MIC values ¹³ and zone-of-inhibition diameters ²⁷ do not convert. Anticancer and delivery claims rest almost entirely on cell-line data, which shows the material kills cells under those conditions but not selectivity, tumour delivery or a therapeutic index; in-vivo evidence is thin and as often about toxicity as efficacy ⁴⁴, ⁴⁵, ⁴⁶. No plant-mediated nanomaterial at clinical stage was identified, and Table 3 is drawn so the empty column is visible.

Table 3: Applications, governing property, and depth of evidence. The clinical column is empty on every row

Application	Governing Property	<i>In vitro</i>	<i>In Vivo</i>	Clinical
Dye photodegradation	band gap; surface area	demonstrated ³²	—	—
Heavy-metal removal	surface charge; binding sites	demonstrated ³¹	—	—
Antibacterial	ion release; size; surface	abundant ¹⁴ , ²⁷	sparse ⁴⁴ , ⁴⁵	none found
Anticancer, cytotoxicity	uptake; corona; dissolution	reported	limited	none found
Antioxidant	capping-layer chemistry	reported ¹¹	—	none found

Sustainability, reproducibility, and what to do next

The claim that a synthesis is green because it uses a plant is the most repeated statement in this field and the least examined. Five words are used as synonyms and are not: *green* has a technical meaning fixed by metrics such as atom economy, E-factor and process mass intensity ⁴⁷, ⁴⁸; *bio-derived* describes feedstock origin; *renewable*, whether it regenerates; *environmentally*

benign, a toxicity endpoint; and *sustainable*, all of these plus economics across a life cycle. A route can be bio-derived and renewable while being neither green by metric nor benign in product. The metrics are rarely reported, so for most published syntheses the green claim is not merely unproven but unfalsifiable.

Life-cycle assessment is more informative, and its evidence is mixed. A comparative assessment of silver routes located the dominant burden not in the reducing agent but in the metal precursor and in downstream heating, centrifugation and purification ⁴⁹; if that is where the burden sits, substituting leaf extract for borohydride modifies a small term. Against this, a cradle-to-gate assessment of green versus conventional titanium dioxide reported a climate-change impact roughly fourteen and a half times lower for the green route, at 92% yield against 74% ⁵⁰, with comparable advantages elsewhere ⁵¹. The reconciliation matters more than either result: the studies differ in system boundary and functional unit, since an assessment beginning at the precursor salt attributes burden differently from one including cultivation, extraction energy, calcination and washing water. Outcomes are therefore reported and contested, traceable to methodology rather than chemistry. Silver and zinc oxide nanomaterials also carry documented ecotoxicity regardless of how they were made ^{45, 52}.

Reproducibility has a shape usually described imprecisely. The complaint that one species gives different particles in different laboratories appears in most reviews, and the field has not measured it. Interlaboratory comparison is mature practice in nanoparticle metrology — ring trials for size and surface charge ⁵³ and for single-particle mass spectrometry ⁵⁴, with batch-to-batch variability quantified directly ⁵⁵ — yet no equivalent study for plant-mediated synthesis was located. The problem is not that reproducibility cannot be measured here, but that it has not been. If source variability is the dominant uncontrolled variable, as Section 4 argued from measured data, the minimum useful report must state species, plant part, harvest, extraction conditions and total phenolic content — an absence that also bounds predictive modelling, since models trained on published values inherit those inconsistencies ⁵⁶. Scale-up completes the picture: continuous-flow reactors give the residence-time control this chemistry needs and work with defined reagents ⁵⁷, but none was demonstrated with a crude extract, which is particulate, variable and prone to fouling.

RESEARCH GAPS

- Burst or continuous nucleation? Time-resolved scattering on one extract–precursor pair would settle it.
- For one species and plant part, how does total phenolic content map onto mean particle size, all else fixed?
- Which extract molecules are actually bound to the purified particle, by desorption mass spectrometry rather than infrared inference?
- Do phytosynthesised and chemically synthesised particles matched for size, shape and zeta potential differ in antibacterial activity at all?
- What fraction of reported bioactivity survives extract-only and equimolar-salt controls?

- Under one system boundary including cultivation, extraction and purification, does any plant route beat its chemical counterpart on process mass intensity and climate impact?

CONCLUSION

The evidence supports neither dismissal nor celebration. Isolated phytochemicals reduce and cap metal ions by demonstrated mechanisms, and the resulting materials degrade dyes, adsorb metal ions and inhibit bacteria measurably. Equally, the field's central claims outrun its evidence: the mechanism it draws has not been observed in the systems it draws it for; the sustainability it asserts is boundary-dependent rather than settled; the reproducibility it laments has never been measured; and the bioactivity it reports is frequently uncontrolled for the two most obvious confounders.

What unifies these is an unmeasured variable. The dominant determinant of the product is the composition of the extract, and it is almost never determined. A study varying only the plant source under a fixed protocol moved particle size by a factor of 2.8 and the band gap by 0.57 eV²⁸; the variable responsible was recorded as a species name. The route is not unpromising. It is unpredictable, and those is a condition with a remedy — measure the feedstock, run the controls, watch the reaction while it happens, and report enough that another laboratory can repeat it. metal-salt control.

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ABSTRACT

Alkaloids are naturally occurring organic compounds containing at least one basic nitrogen atom, primarily found in plants, which exert strong physiological effects on humans and animals. Recent advancements at the intersection of pharmacognosy and materials science have led to the development of novel Nano-drug delivery systems (NDDS) designed to encapsulate both plant-based natural alkaloids and lab-engineered synthetic variants. This review systematically categorizes and evaluates the formulation methodologies and therapeutic paradigms of natural versus synthetic alkaloid nanoparticles. Natural plant-based configurations heavily leverage green chemistry and biomimetic principles, utilizing crude or purified alkaloid extracts (e.g., berberine, morphine) alongside metallic precursors (Ag, Au) or biocompatible biopolymers (chitosan, alginate) to achieve synergistic therapeutic responses with minimal environmental toxicity. Ultimately, bridging the gap between traditional phytochemistry and advanced Nano medicine provides a highly scalable, targeted, and potent platform for next-generation oncology, antimicrobial, and pain management therapies.

KEYWORDS: Plant-Based Nanoparticles, Phyto Chemistry, Green Synthesis, Oncology.

INTRODUCTION

Alkaloids represent one of the most structurally diverse and pharmacologically potent classes of nitrogenous compounds, serving as the cornerstone for many modern lifesaving medicines. Both plant-derived and synthetic alkaloids frequently suffer from major biomedical limitations, including poor water solubility, low cellular uptake, rapid metabolic clearance, and severe systemic toxicity.

CHEMICAL (STRUCTURAL) CLASSIFICATION

This is the most widely accepted scientific system. It groups alkaloids based on the specific nitrogen-containing ring core present in their molecular architecture.

Heterocyclic Alkaloids (True Alkaloids): The nitrogen atom is integrated directly inside the cyclic ring system.

1. *Pyrrolidine*: Contains a 5-membered saturated ring. e.g., Hygrine.

2. *Pyridine & Piperidine*: Feature 6-membered rings. e.g., Nicotine, Coniine, Piperine.
3. *Tropane*: Characterized by a bicyclic azabicyclo core. e.g., Atropine, Scopolamine, Cocaine.
4. *Quinoline*: Formed by a benzene ring fused to a pyridine ring. e.g., Quinine.
5. *Isoquinoline*: The nitrogen is at position 2 instead of position. e.g., Morphine, Codeine, Berberine.
6. *Indole*: Contains a benzene ring fused to a pyrrole ring; one of the largest classes. e.g., Vincristine, Strychnine, Reserpine.
7. *Imidazole*: Features a 5-membered ring with two non-adjacent nitrogen atoms. e.g., Pilocarpine.

Non-Heterocyclic Alkaloids (Protoalkaloids): The nitrogen atom is attached to an aliphatic side chain, *outside* the ring structure. e.g., Capsaicin, Colchicine, Ephedrine, Mescaline.

BIOSYNTHETIC CLASSIFICATION

This approach groups alkaloids based on the amino acid precursors the plant uses to build the molecules.

True Alkaloids: Derived directly from amino acids and contain nitrogen within a heterocyclic ring.

1. *Precursors*: L-Tryptophan (leads to Indole alkaloids), L-Tyrosine (leads to Isoquinoline alkaloids), L-Ornithine (leads to Tropane alkaloids), and L-Lysine (leads to Piperidine alkaloids).
2. **Protoalkaloids**: Derived directly from amino acids (primarily L-Tyrosine or L-Tryptophan), but the final structure keeps the nitrogen atom outside the ring system.
3. **Pseudoalkaloids**: Do not originate from amino acids. Instead, nitrogen atoms are inserted into pre-existing carbon skeletons derived from other metabolic networks:
4. *Purine Pathway*: Formed from purine nucleotides e.g., Caffeine, Theobromine.
5. *Terpenoid/Steroid Pathway*: Formed via mevalonic acid routes e.g., Solanidine, Aconitine.

PHARMACOLOGICAL (THERAPEUTIC) CLASSIFICATION

This system bypasses chemical shapes and categorizes alkaloids according to their **physiological effects** on the human body or central nervous system.

1. **Analgesics** (Pain Relievers): Act on opioid receptors in the brain (e.g., Morphine, Codeine).
2. **Central Nervous System (CNS) Stimulants**: Increase alertness and metabolic activity (e.g., Caffeine, Nicotine, Strychnine).
3. **CNS Depressants / Sedatives**: Lower nervous activity (e.g., Reserpine, Scopolamine).
4. **Antimalarials**: Target bloodborne parasites (e.g., Quinine).
5. **Antineoplastics** (Cancer Chemotherapy): Arrest cellular division by disrupting microtubules (e.g., Vincristine, Vinblastine, Paclitaxel).
6. **Miotics / Mydriatics** (Ocular Drugs): Constrict or dilate the eye pupils (e.g., Pilocarpine constricts; Atropine dilates).

TAXONOMIC CLASSIFICATION

This botanical approach groups alkaloids based on the plant families or genera in which they are exclusively or primarily produced.

1. **Solanaceous Alkaloids:** Found in the nightshade family (*Solanaceae*), predominantly producing tropane variations (e.g., *Atropa*, *Datura*).
2. **Papaveraceous Alkaloids:** Found in the poppy family (*Papaveraceae*), rich in isoquinolines.
3. **Ranunculaceous Alkaloids:** Found in the buttercup family (*Ranunculaceae*), known for complex diterpene types (e.g., *Aconitum*).
4. **Rubiaceous Alkaloids:** Found in the coffee and cinchona family (*Rubiaceae*).

The comprehensive breakdown of how plant alkaloids are classified.

1. Antineoplastic & Cytotoxic Alkaloids (Cancer Therapy)

These alkaloids are among the most valuable assets in oncology, functioning primarily as mitotic inhibitors that halt the division of cancer cells.

Vincristine & Vinblastine (Indole Alkaloids): Isolated from the Madagascar Periwinkle (*Catharanthus roseus*). They bind to tubulin dimers, inhibiting assembly of the mitotic spindle and halting cell division in metaphase. They are frontline treatments for Hodgkin's lymphoma and acute lymphocytic leukemia.

Camptothecin (Quinoline-like Alkaloid): Sourced from the Chinese stem wood *Camptotheca acuminata*. It acts as a potent topoisomerase I inhibitor, preventing DNA replication. Its semi-synthetic derivatives (irinotecan and topotecan) are mainstream chemotherapies.

Paclitaxel / Taxol (Pseudoalkaloid): Extracted from the bark of the Pacific Yew (*Taxus brevifolia*). Unlike vinca alkaloids, it *stabilizes* microtubules, freezing the cell structure so it cannot divide.

ANALGESIC & NARCOTIC ALKALOIDS (PAIN MANAGEMENT)

These compounds interact directly with the central nervous system (CNS) to modulate pain pathways.

Morphine (Isoquinoline Alkaloid): The gold standard opioid analgesic, obtained from the crude latex of the Opium Poppy (*Papaver somniferum*). It selectively binds to μ -opioid receptors in the brain and spinal cord to block severe acute and chronic pain signaling.

Codeine (Isoquinoline Alkaloid): A methylated derivative of morphine found in the same plant, used in pharmacognosy for its mild analgesic profile and its potent antitussive (cough-suppressing) properties.

CARDIOVASCULAR & AUTONOMIC NERVOUS SYSTEM ALKALOIDS

These molecules are highly effective at regulating blood pressure, heart rate, and smooth muscle contractions.

Reserpine (Indole Alkaloid): Extracted from Indian Snakeroot (*Rauvolfia serpentina*). It depletes vesicular stores of catecholamines (like norepinephrine), effectively lowering blood pressure and serving historically as an antipsychotic.

Atropine & Scopolamine (Tropane Alkaloids): Sourced from Deadly Nightshade (*Atropa belladonna*) and Jimsonweed (*Datura stramonium*). They act as competitive antagonists at muscarinic acetylcholine receptors. Atropine increases heart rate during bradycardia and serves as an antidote to nerve gas poisoning, while scopolamine treats motion sickness.

Pilocarpine (Imidazole Alkaloid): Isolated from *Pilocarpus jaborandi* leaves. It is a cholinergic agonist used to reduce intraocular pressure in glaucoma patients.

ANTIMICROBIAL & ANTIPARASITIC ALKALOIDS

Plants synthesize these molecules as natural antibiotics, which pharmacognosists leverage against human pathogens.

Quinine (Quinoline Alkaloid): Harvested from the bark of the *Cinchona* tree. It interferes with the malaria parasite's (*Plasmodium falciparum*) ability to dissolve hemoglobin, making it a foundational antimalarial drug.

Berberine (Isoquinoline Alkaloid): Found in *Hydrastis canadensis* (Goldenseal) and *Berberis* species. It exhibits broad-spectrum antimicrobial, anti-inflammatory, and blood-glucose-lowering activity.

NANOPARTICLE ALKALOIDS & NANOMATERIALS

Integrating alkaloids with nanotechnology is a rapidly growing field in medicine to bypass natural limitations like low water solubility, poor absorption, and high toxicity.

Nanoparticle Alkaloids: The delivery of alkaloid molecules encapsulated inside nano-sized carriers (1-100 nm). This targets specific cells (like cancer tumors) without damaging healthy tissue.

Nano Materials of Alkaloids: Nanoparticles created or stabilised by using the alkaloids themselves.

Polymer Micelles & Liposomes: Spherical nano-vesicles used to pack hydrophobic alkaloids like Paclitaxel or Camptothecin to improve their travel through the bloodstream.

Green Synthesis Nanomaterials: Plant extracts rich in alkaloids act as reducing and capping agents to safely synthesise metallic nanoparticles (like Silver (Ag) or Gold (Au) nanoparticles) without toxic chemicals.

Magnetic Nanocarriers: Iron oxide nanoparticles bound with alkaloids, allowing doctors to use external magnetic fields to guide the drug directly to a target organ.

The intersection of nanotechnology and alkaloid chemistry has yielded advanced drug delivery systems and materials. Formulating alkaloids into nanoparticles overcomes clinical limitations like poor water solubility, high systemic toxicity, rapid metabolic clearance, and lack of cellular targeting. Nanoparticles involving alkaloids are categorised into two paradigms: Natural plant-based alkaloid nano-system and Synthetic/Semi-synthetic alkaloid nano-systems.

NANOPARTICLES OF NATURAL PLANT-BASED ALKALOIDS

Natural plant-based alkaloid nano-formulations typically utilize two distinct pathways: the alkaloid acts as the **therapeutic payload** inside a Nano carrier, or the alkaloid acts as a reducing agent to form a metallic nanoparticle via green synthesis.

A. GREEN-SYNTHESIZED METALLIC NANOPARTICLES (PHYTOSYNTHESIS)

Mechanism: Plant extracts rich in natural alkaloids (such as indole, tropane, or isoquinoline varieties) are mixed with metallic salt precursors (like silver nitrate or gold chloride). The alkaloids act as sustainable reducing and capping agents, converting metal ions into stable, non-agglomerated metallic nanoparticles without using toxic laboratory chemicals.

Nanoparticle Types:

Silver (AgNPs): Highly utilized for anti-bacterial and anti-cancer applications due to cell wall disruption properties.

Gold (AuNPs): Extremely biocompatible, used for diagnostics and deep tissue imaging.

Zinc Oxide (ZnONPs): Possess high semiconductor bandgaps and strong photocatalytic attributes.

B. NATURAL BIO-POLYMER NANO-ENCAPSULATION

- **Mechanism:** Hydrophobic natural alkaloids are trapped inside organic, biocompatible biopolymers extracted from nature.

Nanoparticle Types:

- **Chitosan Nanoparticles:** Positively charged (cationic) particles derived from shellfish chitin. They exhibit high mucoadhesiveness, making them ideal for nasal or oral delivery of natural alkaloids like **Berberine** to improve gut absorption.
- **Alginate/Cellulose Nanostructures:** Hydrophilic carbohydrate matrices used to achieve slow, time-controlled release of plant metabolites.

NANOPARTICLES OF SYNTHETIC & SEMI-SYNTHETIC ALKALOIDS

Synthetic and semi-synthetic alkaloids (either entirely lab-created or natural structures chemically modified for enhanced potency) rely on precisely engineered Synthetic Nano-Drug Delivery Systems (NDDS) to safely navigate the human bloodstream.

A. SYNTHETIC POLYMERIC NANOPARTICLES

Mechanism: Formulated as either nanospheres (matrix systems) or nanocapsules (core-shell structures) using entirely synthetic, FDA-approved biodegradable polymers.

Nanoparticle Types:

PLGA (Poly lactic-co-glycolic acid) Nanoparticles: The industry standard for encapsulating potent semi-synthetic chemotherapeutic alkaloids like Paclitaxel or Camptothecin derivatives. They break down safely into lactic and glycolic acids in the body while providing sustained drug release.

PLA-PVA Micelles: Amphiphilic block copolymers that self-assemble in water, creating a hydrophobic core to shield poorly soluble synthetic drugs.

B. LIPID-BASED NANOPARTICLES (LNPS) AND LIPOSOMES

Mechanism: Artificial spherical vesicles composed of a synthetic phospholipid bilayer enclosing either a liquid core or an oil droplet.

Nanoparticle Types:

PEGylated Liposomes: Liposomes coated with synthetic Polyethylene Glycol (PEG). The PEG coating hides the nanoparticle from the body's immune system ("stealth effect"), preventing rapid liver clearance.

Solid Lipid Nanoparticles (SLNs): Made from solid lipids rather than liquid oils, providing excellent physical stability and chemical protection for sensitive synthetic alkaloid payloads. The Enhanced Permeability and Retention (EPR) effect that allows these nanoparticles to target cancer tumors.

A specific synthesis recipe, such as how silver nanoparticles are reduced using leaf extracts.

PLANT BASED NATURAL ALKALOIDS BENEFICIAL IN PHARMACOGNOSY

The study of medicines derived from natural sources relies heavily on plant-based alkaloids due to their profound, highly specific interactions with human physiological systems. These compounds serve as structural blueprints for drug design, active pharmaceutical ingredients (APIs), and critical molecular tools in biochemical research.

Here is the classification of the most beneficial natural plant alkaloids utilized in modern pharmacognosy, organized by their therapeutic applications.

DIFFERENT TYPES OF PLANT ALKALOIDS

Plant alkaloids are categorized into distinct structural classes based on the chemical ring skeleton that forms their core and the specific amino acid pathways through which the plant synthesizes them. Structural types of plant alkaloids, categorized by their chemical backbones.

PYRIDINE AND PIPERIDINE ALKALOIDS

These alkaloids possess a simple six-membered ring containing a single nitrogen atom. They are derived from the amino acids lysine, nicotinic acid, or acetate.

Core Structure: Pyridine (unsaturated ring) or Piperidine (fully saturated ring).

Example: Nicotine: A powerful central nervous system stimulant and natural insecticide found in tobacco leaves (*Nicotiana tabacum*).

Coniine: A highly toxic neuromuscular blocker found in poison hemlock (*Conium maculatum*).

Piperine: The pungent compound responsible for the sharp heat in black pepper (*Piper nigrum*).

TROPANE ALKALOIDS

Characterized by a bicyclic azabicyclo system, these compounds are primarily synthesized by plants in the *Solanaceae* (nightshade) family.

Core Structure: Formed by the condensation of a pyrrolidine ring and a piperidine ring sharing two carbon atoms.

Example: Atropine & Scopolamine: Anticholinergic drugs derived from deadly nightshade (*Atropa belladonna*) used to dilate pupils and treat motion sickness.

Cocaine: A potent central nervous system stimulant and local anesthetic extracted from coca leaves (*Erythroxylum coca*).

QUINOLINE AND ISOQUINOLINE ALKALOIDS

These types feature dual-ring aromatic configurations and comprise some of the most pharmacologically potent natural products known.

Core Structure: A benzene ring fused to a pyridine ring. In quinolines, the nitrogen is at position 1; in isoquinolines, it is at position 2.

Example: Quinine (Quinoline): The classic antimalarial compound isolated from the bark of the Cinchona tree.

Morphine & Codeine (Isoquinoline): Powerful narcotic analgesics extracted from the latex of the opium poppy (*Papaver somniferum*).

Berberine (Isoquinoline): A bright yellow antimicrobial alkaloid found in goldenseal and barberry roots.

INDOLE ALKALOIDS

This is one of the largest classes of plant alkaloids. They are biosynthesized directly from the aromatic amino acids.

Core Structure: A six-membered benzene ring fused directly to a five-membered nitrogen-containing pyrrole ring.

Example: Reserpine: An antipsychotic and antihypertensive drug extracted from Indian snakeroot (*Rauvolfia serpentina*).

Vinblastine & Vincristine: Crucial microtubule-inhibiting chemotherapeutic agents found in the Madagascar periwinkle (*Catharanthus roseus*).

Strychnine: A highly toxic pesticide agent derived from *Strychnos nux-vomica* seeds.

PURINE ALKALOIDS (PSEUDOALKALOIDS)

Unlike true alkaloids, purine variants do not originate from amino acids. They are derived directly from nucleotide pathways, specifically xanthosine.

Core Structure: A pyrimidine ring fused to an imidazole ring.

Example: Caffeine: The world's most widely consumed psychoactive substance, found in coffee beans, tea leaves, and cacao.

Theobromine: A mild cardiac stimulant found in high concentrations within dark chocolate and cocoa products.

CONCLUSION

Nanomaterials serve as the critical bridge that transforms both plant-based and synthetic alkaloids into highly viable, next-generation medical therapeutics. While plant-derived alkaloids offer unparalleled natural complexity and synthetic variants provide manufacturing scalability, both are historically bottlenecked by poor solubility, rapid clearance, and systemic toxicity. Nanotechnology fundamentally redefines these limits by acting as smart delivery vehicles that protect the compounds, boost their bioavailability, and target diseased cells with pinpoint accuracy. Ultimately, merging alkaloid chemistry with Nano medicine shifts the paradigm from simply discovering potent compounds to safely and effectively deploying them in patient care.

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Chapter

16

**NANO-FORMULATION IN HERBAL MEDICINES AND
NUTRACEUTICALS**

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ABSTRACT

Nanotechnology has emerged as a transformative approach in the field of herbal medicine and nutraceuticals, offering solutions to long-standing challenges such as poor solubility, instability, and low bioavailability of phytochemicals. This chapter explores the historical evolution of nanotechnology and its integration into herbal formulations, highlighting how traditional remedies are being redefined through modern science. The nano-formulation process is outlined step-by-step, including extraction of herbal actives, phytochemical characterization, nanocarrier selection, formulation development, nanoparticle characterization, and biological evaluation. Case studies such as nano-curcumin, silymarin phytosomes, resveratrol nanocarriers, and quercetin liposomes demonstrate the enhanced therapeutic efficacy achieved through nanotechnology. Comparative analysis with traditional delivery systems underscores the advantages of nano-formulations in terms of solubility, stability, and reproducibility. Recent research trends emphasize stimuli-responsive nanocarriers, green synthesis methods, hybrid systems, and clinical trials, while future perspectives point toward personalized nutrition, AI-driven design, and global commercialization. Collectively, this chapter establishes nanotechnology as a pivotal innovation that bridges traditional herbal medicine with contemporary healthcare, paving the way for scientifically validated and consumer-friendly nutraceutical solutions.

KEYWORDS: Nanotechnology, Herbal Medicine, Nutraceuticals, Nano-Formulation, Phytochemical Characterization, Nanocarriers, Bioavailability, Functional Foods, Personalized Nutrition.

INTRODUCTION

Herbal medicine has been a cornerstone of healthcare across civilizations, from Ayurveda in India to Traditional Chinese Medicine and indigenous practices worldwide. Despite their therapeutic potential, many herbal compounds suffer from poor solubility, instability, and low bioavailability, limiting their clinical efficacy. Nanotechnology, a revolutionary field that manipulates matter at the nanoscale, has emerged as a powerful solution to these challenges. By integrating herbal actives into nanocarriers, researchers have developed formulations that enhance absorption, stability, and therapeutic outcomes, transforming traditional remedies into modern nutraceuticals.

HISTORICAL CONTEXT OF NANOTECHNOLOGY IN HERBAL MEDICINES

Nanotechnology was first conceptualized by Richard Feynman in 1959, with practical advances emerging in the 1980s through tools like scanning tunneling microscopy. Initially applied in electronics and materials science, nanotechnology entered biomedical research in the early 2000s, focusing on drug delivery systems. Herbal medicine, practiced for centuries, faced persistent limitations in delivering bioactive compounds effectively. The convergence of nanotechnology and herbal medicine marked a paradigm shift, enabling encapsulation, targeted delivery, and controlled release of phytochemicals. This evolution bridged traditional knowledge with modern science, laying the foundation for nutraceutical innovation.

NANO-FORMULATION PROCESS

The development of nano-herbal formulations involves a systematic sequence of steps:

Extraction of Herbal Actives

Bioactive compounds are isolated from plant materials using methods such as solvent extraction, supercritical CO₂ extraction, or green techniques like microwave-assisted and ultrasound-assisted extraction. These approaches aim to maximize yield while preserving sensitive phytochemicals.

Phytochemical Characterization

Analytical techniques such as High-Performance Liquid Chromatography (HPLC), Liquid Chromatography–Mass Spectrometry (LC-MS), and Nuclear Magnetic Resonance (NMR) confirm the identity, purity, and concentration of active molecules, ensuring reproducibility and safety.

Nanocarrier Selection

Carriers are chosen based on compound properties. Liposomes are ideal for hydrophilic actives, phytosomes enhance flavonoid absorption, and Solid Lipid Nanoparticles (SLNs) stabilize lipophilic compounds. The choice of carrier directly influences bioavailability and therapeutic efficacy.

Nano-Formulation Development

Techniques such as thin-film hydration, emulsification, nanoprecipitation, and spray drying are employed to encapsulate phytochemicals into nanocarriers. Each method is selected according to the physicochemical nature of the compound and desired product characteristics.

Characterization of Nanoparticles

Parameters such as particle size, zeta potential, encapsulation efficiency, and release profile are measured using Dynamic Light Scattering (DLS), Transmission Electron Microscopy (TEM), and Fourier Transform Infrared Spectroscopy (FTIR). These evaluations ensure stability and performance.

In-vitro and In-vivo Evaluation

Biological performance is assessed through cell culture assays and animal models to evaluate bioavailability, therapeutic efficacy, and toxicity. These studies provide evidence that nano-formulations outperform raw herbal extracts.

Application in Nutraceuticals and Herbal Medicine

Nano-formulations are incorporated into supplements, functional foods, and topical products. Examples include nano-curcumin capsules, green tea catechin beverages, and nano-aloe vera gels for skincare. Refer table 1.

Table 1: Nano-Formulation Process

The development of nano-herbal formulations follows a systematic sequence of steps:

Step	Description
Extraction of Herbal Actives	Isolation of bioactive compounds using solvent extraction, supercritical CO ₂ , or green methods.
Phytochemical Characterization	Analytical confirmation of purity and concentration using HPLC, LC-MS, and NMR.
Nanocarrier Selection	Choice of delivery system (liposomes, phytosomes, SLNs) based on compound properties.
Nano-Formulation Development	Techniques such as thin-film hydration, emulsification, nanoprecipitation, and spray drying.
Characterization of Nanoparticles	Evaluation of particle size, zeta potential, encapsulation efficiency, and release profile using DLS, TEM, FTIR.
In-vitro and In-vivo Evaluation	Biological testing for bioavailability, efficacy, and toxicity in cell cultures and animal models.
Application in Nutraceuticals	Incorporation into supplements, functional foods, and topical herbal products.

CASE STUDY EXAMPLES

Curcumin nanoparticles – Enhanced oral bioavailability and anti-inflammatory activity compared to raw turmeric.

Silymarin phytosomes – Improved hepatoprotective efficacy in nutraceutical supplements.

Resveratrol nanocarriers – Increased stability and antioxidant activity in functional foods.

Quercetin liposomes – Better absorption and anticancer potential in experimental models.

These case studies illustrate how nanotechnology addresses the limitations of traditional herbal formulations.

COMPARISON WITH TRADITIONAL TECHNOLOGIES

Traditional herbal formulations, such as decoctions, powders, and tinctures, often suffered from poor absorption and inconsistent therapeutic outcomes. For instance, curcumin in turmeric has strong medicinal properties but extremely low oral bioavailability in its natural form. Conventional tablets or capsules could not overcome these limitations. Nanotechnology, however, allows encapsulation of curcumin into nanoparticles, dramatically improving solubility and systemic availability. Similarly, phytosomes outperform herbal teas by ensuring flavonoids bind to phospholipids, enhancing absorption. Thus, nanotechnology represents a significant advancement over traditional delivery systems, offering precision, stability, and reproducibility. Refer table 2

Table 2: Comparison with Traditional Technologies

Aspect	Traditional Formulations (Extracts, Powders, Decoctions)	Nano-Formulations (Liposomes, Phytosomes, SLNs)
Solubility	Often poor, limiting absorption.	Enhanced solubility through encapsulation.
Bioavailability	Low and inconsistent.	High, reproducible, and targeted.
Stability	Susceptible to degradation.	Improved stability and controlled release.
Therapeutic Efficacy	Variable outcomes.	Consistent, enhanced efficacy.
Consumer Acceptability	Traditional appeal but limited effectiveness.	Modern, scientifically validated nutraceuticals.

RECENT RESEARCH TRENDS

Recent research highlights several innovative directions in herbal nanotechnology. Stimuli-responsive nanocarriers are being developed to release phytochemicals in response to pH, temperature, or enzymatic activity, enabling site-specific targeting. Green synthesis methods using plant extracts for nanoparticle production are gaining traction as sustainable alternatives. Hybrid nanocarriers combining lipids and polymers are being explored for improved stability. Clinical trials are underway to evaluate nano-curcumin, nano-resveratrol, and nano-silymarin in chronic disease management. Functional food innovations are incorporating nano-encapsulated herbal actives into beverages, dairy products, and nutraceutical supplements, making them more accessible to consumers.

FUTURE PERSPECTIVES

The future of nanotechnology in herbal medicine and nutraceuticals lies in personalized nutrition and precision medicine. Nano-formulations could be tailored to individual metabolic profiles, ensuring optimal therapeutic outcomes. Regulatory frameworks will need to evolve to address safety, toxicity, and quality control of herbal nano-products. Advances in artificial intelligence and machine learning may further optimize nanocarrier design and predict therapeutic efficacy. Commercialization will expand as costs decrease and consumer demand for natural yet effective remedies grows. Ultimately, nanotechnology has the potential to transform herbal medicine from traditional practice into scientifically validated, globally accepted healthcare solutions.

CONCLUSION

Nanotechnology has revolutionized the field of herbal medicine and nutraceuticals by overcoming the limitations of traditional formulations. Through systematic processes of extraction, characterization, nanocarrier selection, formulation, and evaluation, researchers have developed products with enhanced bioavailability, stability, and therapeutic efficacy. Case studies demonstrate the success of nano-curcumin, nano-silymarin, and other formulations, while recent research trends point toward sustainable synthesis and personalized applications.

With future advancements in AI, regulatory frameworks, and commercialization, nano-formulations are poised to redefine the role of herbal medicine in modern healthcare.

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Chapter

17

**THE RISE OF MXENES: HOW LAYERED NANOMATERIALS ARE
REWRITING MATERIAL SCIENCE**

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INTRODUCTION

MXenes represents a rapidly expanding class of two-dimensional (2D) inorganic nanomaterials discovered in 2011 by researchers at Drexel University which have completely change physics, chemistry, and material science. MXenes are first isolated a single layer of graphene in 2004, While graphenes have incredible standards for strength and electrical conductivity, but also has major practical challenges. Specifically, lacks natural electronic off-switch and are hydrophobic, which makes it difficult to process and use in many real-world applications. But MXene combine metallic-grade electrical conductivity, high physical strength, hydrophilicity, and a reactive chemical surface, making them uniquely versatile for advanced materials science applications.

Graphene is made entirely of carbon atoms arranged in a flat, honeycomb-like sheet, MXenes are made from combinations of transition metals with carbon, nitrogen, or both. Researchers make these materials by starting with layered ceramic compounds-known as MAX phase- and chemically stripping away specific inner metal layers. This process leaves behind the distinct, ultrathin 2D sheets that give MXenes their unique abilities.

MXenes are major turning points in materials science by bridging the traditional gap between metals a ceramic. They combine the fast electrical conductivity of conventional metals with a natural attraction to water, making them remarkably easy to process in liquids like water-soluble polymers.

Over the past decade, MXene research has grown at remarkable pace. Scientists have mapped out more than 100 possible chemical combinations on paper and have successfully created dozens of them in lab. Today, MXenes sit at the cutting edge of modern technology. They are widely used to build advanced energy storage devices, block harmful electromagnetic signals, clean up environmental pollutants, speed up chemical reactions, and power flexible electronics.

CHEMICAL FORMULA AND STRUCTURAL COMPOSITION

MXenes are synthesized by selectively removing the reactive element from layered parent compounds known as MAX phases.

General formula: $M_{n+1} X_n T_x$

M- early transition metals (e.g., Titanium, Molybdenum, Vanadium, Niobium, Chromium).

X- Carbon and/ or Nitrogen (forming carbides, nitrides, or carbonitrides).

n- typically ranges from 1 to 4, representing the atomic layers of transition metal.

T_x- surface termination function all groups (e.g., O, OH, F, Cl) attached during chemical synthesis.

MXenes get their inner structure straight from their starting materials, known as MAX phases. These parent materials follow a specific chemical pattern made of three main components: transition metals, main-group elements (usually aluminium or silicon), and carbon or nitrogen. Within this structure, the bonds holding the metal and carbon/nitrogen together are extremely strong. However, the bonds holding the aluminium or silicon layers are much weaker. Because of this difference in bond strength, scientists can selectively etch away the weaker layer using chemicals while keeping the strong core structure intact to form thin MXene sheets.

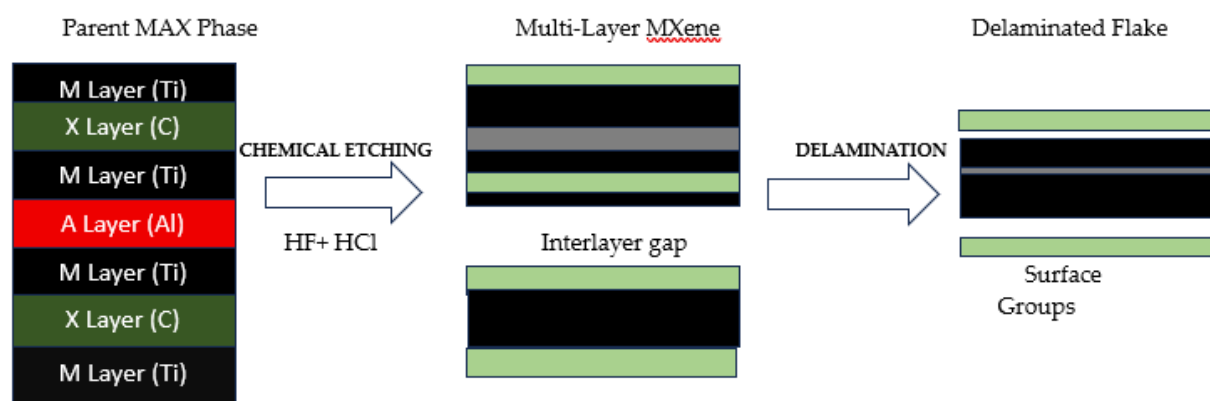
GENERAL MXENE STIOCHIOMETRIC VARIATIONS

M₂XT_x- Ti₂XT_x, V₂CT_x, Nb₂CT_x

M₃X₂T_x- Ti₃C₂T_x, Zr₃C₂T_x

M₄X₃T_x-Nb₄C₃T_x, Ta₄C₃T_x

M₅X₄T_x- Mo₄VC₄T_x



How MAX phases are turned into ultra-thin MXene sheets:

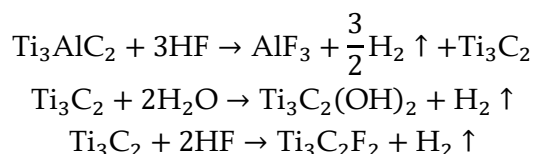
- Etch- Wash away the middle A-layer from the starting material using chemicals.
- Expand- The remaining layers puff out like an accordion.
- Separate- Peel the stack into single, water-friendly sheets.

SYNTHESIS ROUTE AND ETCHING CHEMISTRY

The strong chemical bonds connecting the transition metals to carbon or nitrogen are much tougher than the metallic bonds securing the middle element (like aluminium) inside the crystal. Because of these tight internal connections, simple mechanical peeling—like the famous Scotch-tape method needed to break down those specific metal layers and create isolated MXene sheets.

AQUEOUS HYDROFLUORIC ACID (HF) ETCHING

The original method for creating Ti₃C₂T_x MXenes uses concentrated hydrofluoric acid (HF) mixed with titanium aluminium carbide (Ti₃AlC₂) at room temperature. The process follows three main chemical steps:



This process releases hydrogen gas and produces soluble aluminium fluoride salts. As the aluminium layer dissolves, it leaves behind an accordion like-like stack of multi-layered MXene sheets, loosely held together by hydrogen bonds and weak van der Waals forces.

IN-SITU FLUORIDE-BASED METHODS (MILD METHOD)

To avoid working with dangerous concentrated hydrofluoric acid and to produce larger, higher-quality MXene flakes, researcher developed the MILD (Minimally Intensive Layer Delamination) method.

This process replaces direct HF with a safer blend of lithium fluoride (LiF) and hydrochloric acid (HCl), which generates HF directly inside the reaction mixture.

- On-Demand Etching: Combining LiF and HCl produces gentle amounts of acid as needed, carving out the aluminium layers without harsh chemical handling.
- Simultaneous Layer Wedging: As etching takes place, free lithium ions (Li⁺) naturally slip between the MXene layers.
- Effortless Sheet Separation: The inserted lithium ions force the sheets apart and weaken the force holding them together. This allows the material to separate cleanly into individual 2D nanosheets with light shaking or mild ultrasound –no harsh mechanical grinding required.

FLUORIDE-FREE AND GREEN SYNTHESIS ROUTES

To improve safety and meet commercial manufacturing standards, scientists have developed several fluoride-free etching methods:

- Molten Salt Etching: High-temperature Lewis's acid salts (such as ZnCl₂ or CuCl₂) react with the MAX phase at around 500° C to replace the middle element. This technique produces chlorine-terminated MXenes (M_{n+1} X_n Cl_x) with enhanced thermal stability.
- Electrochemical Etching: applying electric currents in liquid electrolyte solutions (like a mixture of NH₄Cl and TMAOH) selectively dissolves the aluminium layer without introducing fluorine chemical groups.
- Alkali Etching: High concentrations of sodium hydroxide (NaOH) under pressurized, hot water conditions (around 270° C) pull out the aluminium layers by turning them into soluble aluminate compounds.

PHYSICAL, ELECTRICAL, AND SURFACE PROPERTIES

MXenes possess amazing combination of physical and chemical properties that differentiate them from other 2D materials like graphene, transition metal dichalcogenides (TMDs), and hexagonal boron nitride (h-BN).

Electrical Conductivity- The high density of free electrons originating from the d-orbitals of early transition metals grants individual MXene nanosheets their exceptional metallic conductivity. this electron-rich structure allows electrical charges to move effortlessly across the

2D plane, reinforcing their performance in ultra-fast energy storage, electrocatalysis, high-frequency wave absorption.

Hydrophilicity- An abundance of surface termination groups ($-O$, $-OH$, $-F$) enables MXenes to form strong hydrogen bonds with water molecules. This naturally water-attracting nature allows raw MXene powder to disperse evenly in aqueous solutions without needing additional chemical surfactants, simplifying eco-friendly manufacturing processes like ink printing, spray-coating, and vacuum filtration into flexible sheets.

Optical Transparency and High Conductivity- At just few atomic layers thick, MXene films let visible light pass through easily while preserving clear paths for electrical charges. This combination of high light transmittance and metallic conductivity makes ultra-thin MXene coatings ideal for flexible touchscreens, smart windows, and transparent electrodes.

Fast Surface Redox and Ion Intercalation- MXenes store energy through rapid surface redox reactions paired with fast movement of ions between their water-attracting layers. This process gives supercapacitors and hybrid batteries high energy storage capacity along with fast charging speeds.

TECHNOLOGICAL APPLICATIONS

The broad range of unique capabilities that MXenes offer has created exciting new possibilities across many advanced engineering fields.

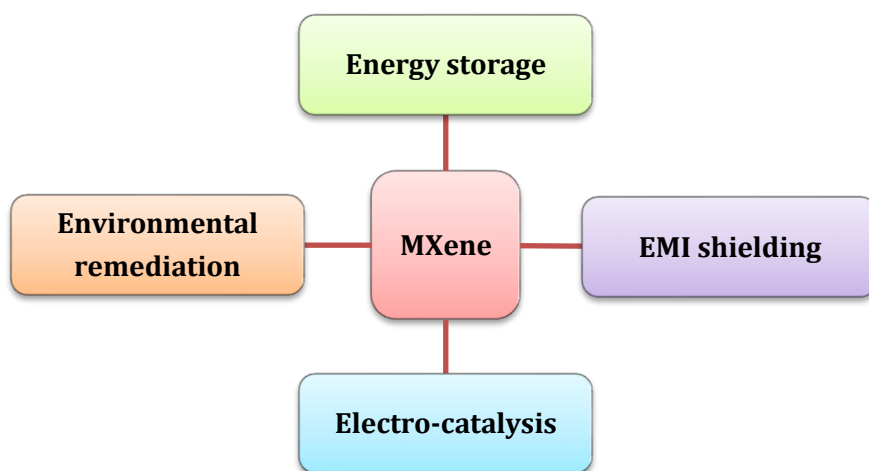


Figure 1: MXene

ELECTROCHEMICAL ENERGY STORAGE

MXenes are top contenders for high power energy storage systems because of how they store electrical charge. Rather than relying only on static surface charges like standard capacitors do, MXenes undergo fast, reversible chemical reactions right on the metal surface and at the same time, tiny charged particles like lithium, sodium, potassium, magnesium, and aluminium easily slide between the flat 2D layers. This makes an open highway for ions to move quickly alongside fast electrical currents, allowing MXene-based batteries and supercapacitors to charge rapidly while holding a large amount of energy.

ELECTROMAGNETIC INTERFERENCE (EMI) SHEILDING

As wearable devices, wireless networks, and radar technologies spread, blocking unwanted electromagnetic noise has become a major technical challenge. MXene absorb the energy instead. When electromagnetic 2D layers, quickly losing energy as heat and electrical charge. Because of this trapped-bounce design, even ultra-thin MXene coatings-just a fraction of a millimetre thick-block signals far better than carbon nanotubes or graphene at the same thickness

ENVIRONMENTAL REMEDIATION AND WAER TREATMENT

MXene excel at cleaning up the environment because of their large surface area, negative charge, and adjustable spacing between layers:

Heavy metal removal: surface chemistry rick in hydroxyl and fluorine groups acts like a magnet, capturing toxic heavy matels such as lead, chromium, mercury, and radioactive waste.

Desalination and water filtration: specially linked MXene membranes work like ultra-fine sieves. They block tiny salt ions while allowing water molecules to flow through rapidly.

ELECTROCATALYSIS AND GREEN ENERGY CONSERVATION

MXenes are strong tools for driving clean energy reactions, working both as stable bases for catalysts and as active catalyst themselves. The exposed metal spots along the edge of their flat sheets lower the energy needed to split water into hydrogen and oxygen. They also help convert nitrogen into green ammonia, making clean fuel production more efficient.

CHALLENGES AND FUTURE

Even though MXenes have a lot of potential, scientists still need to solve a few major problems before these materials can be made and sold on large scale:

Environmental stability and oxidation: Water-based MXene mixture naturally break down over time when exposed to air, turning into basic metal oxides (TiO_2) AND carbon within a few weeks. Because of this, scientists are actively searching for ways to slow down rust-like decay, protect sheet surfaces, and create better storage methods to keep MXenes stable over long period.

Safe and scalable manufacturing: creating MXenes on a commercial scale requires replacing dangerous hydrofluoric acid chemicals with safer, eco-friendly methods. Switching to cleaner techniques, such as molten salt processes, is essential to produce these materials safely, cheaply, and on large quantities.

Control over surface terminations: Synthesizing MXenes and related two-dimensional materials with tailored surface terminations require precise chemical control during etching and post-treatment.

Etchant Chemical selection: Using targeted acid blends dictates initial functionalization. High HF concentrations increase $-F$ terminations, while molten salt etchants (Lewis acid salts like ZnCl_2) selectively introduce $-Cl$ groups.

Post-Synthesis Chemical washing: Rinsing with specific alkaline solutions (such as NaOH or KOH) systematically replaces halogens terminations with hydroxyl groups ($-OH$).

Thermal Annealing: Vacuum or inert gas annealing at high temperatures (400-800°C) desorbs temperature-sensitive $-OH$ and $-F$ groups, converting them into stable oxygen terminations ($-O$).

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Chapter

18

**A REVIEW OF EMERGING NANOTECHNOLOGY-BASED
DELIVERY PLATFORMS FOR GENETIC ENGINEERING,
GENOME EDITING, AND RNA-BASED CROP PROTECTION**

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ABSTRACT

For most of the history of plant biotechnology, introducing a gene, protein, or strand of RNA into a plant cell has meant overcoming the plant's natural barriers, using gold particles to bombard cells, coaxing soil bacteria to deliver genetic material, stripping away the cell wall entirely, or working with fragile protoplasts. Each of these routes works, but each also carries a cost such as tissue damage, narrow host range, unpredictable transgene integration, or a total dependence on tissue culture and regeneration. Across the past fifteen years, a different strategy has tailored including engineering the size, shape, and surface chemistry of nanoscale materials so that they simply walk biomolecules through the cell wall on their own, without mechanical force and, in many cases, without leaving any foreign DNA behind. This review surveys the major classes of nanocarriers now used in plant genetic and molecular biology, in particular carbon nanotubes, mesoporous silica nanoparticles, DNA-based nanostructures, layered double hydroxides, gold nanoparticles, and chitosan-based polymers and traces their applications across transient gene expression, stable transformation, organelle-targeted delivery, CRISPR/Cas ribonucleoprotein editing, and RNA interference for pest and pathogen control. The review concludes by highlighting the challenges that must be overcome to translate laboratory findings into practical field applications. These challenges include cytotoxicity, genotype dependence, manufacturing scale-up, and an evolving regulatory landscape. The review also examines emerging directions in the field, including stimulus-responsive carriers and transgene-free precision breeding.

KEYWORDS: Nanocarriers, Nanobiotechnology, CRISPR/Cas9, RNA Interference, Carbon Nanotubes, Mesoporous Silica Nanoparticles, DNA Nanostructures.

INTRODUCTION

Plant genetic engineering has always had a plumbing problem. The trait you want to introduce such as drought tolerance, disease resistance, a nutritional upgrade, is seldom what trips researchers up. The hard part is physically getting the DNA, RNA, or protein that encodes that trait across a barrier that plant cells, unlike animal cells, are uniquely equipped to resist: a rigid, multilayered wall of cellulose, hemicellulose, pectin, and in some tissues lignin, sitting just

outside the plasma membrane. This wall has a size-exclusion limit generally estimated at somewhere between 5 and 20 nanometers, far smaller than the plasmid DNA, ribonucleoprotein complexes, or viral vectors that plant biologists want to deliver (Zhang *et al.*, 2019; Cunningham *et al.*, 2018).

Agrobacterium tumefaciens-mediated transformation hijacks a soil bacterium's natural gene-transfer machinery, but it is species- and genotype-limited and its Ti-plasmid insertions land in essentially random, uncontrollable genomic locations. Biolistic ("gene gun") delivery physically fires DNA-coated tungsten or gold micro particles into cells at high velocity, which works across a far broader range of species but causes considerable tissue trauma, low transformation efficiency, and the same unpredictable integration problem (Russell, Roy, & Sanford, 1992). Both methods, in addition, are usually tied to lengthy tissue-culture and regeneration protocols, and both are notoriously difficult to apply to recalcitrant, elite, or vegetatively propagated crop varieties.

Nanotechnology has entered this picture not as a replacement philosophy but as an engineering solution to the same old transport problem. A nanocarrier, broadly defined, is any engineered nanoscale material, typically between 1 and 200 nanometers. Its surface chemistry, charge, shape, and aspect ratio can be tuned so that it either diffuses passively through the cell wall's nanopores or is actively taken up through wall-remodelling and endocytic pathways, carrying its cargo along with it (Cunningham *et al.*, 2018). Because the delivery mechanism depends on the physical and chemical properties of the material rather than on species-specific biological recognition (as *Agrobacterium* infection does), nanocarrier-based delivery has repeatedly been demonstrated across a strikingly broad host range from model species such as *Nicotiana benthamiana* and *Arabidopsis thaliana* to genuinely difficult agronomic targets such as cotton, wheat, and grapevine (Demirer *et al.*, 2019).

THE BARRIER PROBLEM: WHY PLANTS NEED THEIR OWN DELIVERY SCIENCE

It is worth dwelling briefly on why plant nanocarrier design cannot simply borrow wholesale from the mammalian nanomedicine playbook, where lipid nanoparticles and polymeric micelles have already been clinically validated (most visibly in mRNA vaccine delivery). Mammalian cells present a lipid bilayer as their outermost barrier whereas plant cells present that same bilayer, but behind a second, much more restrictive gatekeeper, the cell wall. A nanoparticle designed purely to fuse with or be endocytosed by a lipid membrane may never even reach that membrane in a plant cell, because it cannot get past the wall's pore network in the first place.

This has pushed plant-focused nanocarrier design toward materials with two properties that are less emphasized in mammalian nanomedicine: high aspect ratio (long, thin shapes that can needle through wall pores more readily than spheres of an equivalent volume) and robust, often covalent or highly stable, cargo attachment chemistries (because plant delivery frequently relies on passive diffusion through an intact wall rather than active cellular machinery, cargo needs to survive extracellular transit through a comparatively hostile apoplastic space)

(Demirer *et al.*, 2019; Zhang *et al.*, 2019, Hubbard *et al.*, 2025). Studies from the Landry laboratory at UC Berkeley showed that the stiffness and shape of nanostructures can independently affect their uptake by plant cells and their gene-silencing efficiency in *N. benthamiana* leaves. The results also showed that longer and thinner nanostructures are not always more effective. A rigid, high-aspect-ratio DNA “nanosttring” showed lower uptake than expected when used alone, whereas attaching it to a stiffer carbon nanotube scaffold improved cellular uptake (Zhang *et al.*, 2019; Hubbard *et al.*, 2025). These kinds of structure-function findings are foundational to the field and explain why so much of the primary literature reads as careful materials-engineering work rather than pure molecular biology.

CLASSES OF NANOCARRIERS USED IN PLANT MOLECULAR BIOLOGY

CARBON NANOTUBES (CNTS)

Carbon nanotubes rolled sheets of graphene, either single-walled (SWCNTs) or multi-walled (MWCNTs) were among the earliest nanomaterials shown to cross plant cell walls without mechanical assistance, and they remain the most extensively characterized nanocarrier platform in the field. An early study demonstrated that both SWCNTs and MWCNTs could deliver a plasmid encoding yellow fluorescent protein into tobacco callus cells, mesophyll protoplasts, and leaf explants, though only SWCNT-delivered constructs produced stable transgene expression in regenerated plants (Liu *et al.*, 2009; Serag *et al.*, 2011).

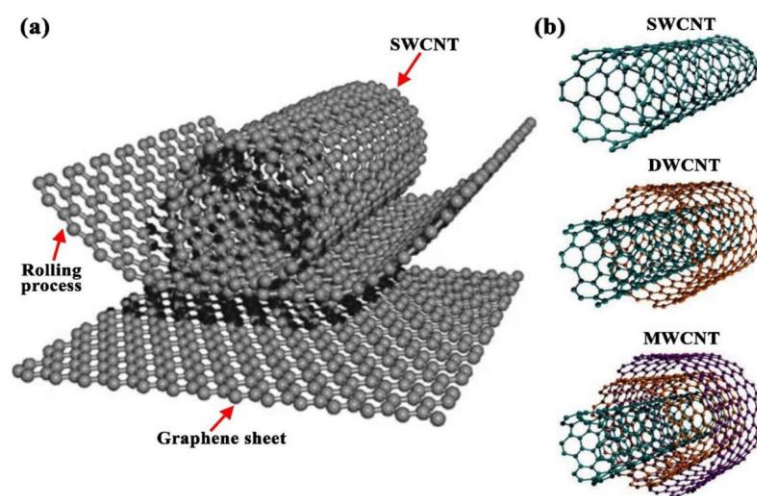


Figure 1: a) Graphene b) SWCNT, DWCNT & MWCNT

The platform reached a landmark moment when Demirer and colleagues showed that polyethylenimine-functionalized SWCNTs could deliver plasmid DNA into fully intact, mature leaves of several agriculturally relevant species, for example *N. benthamiana*, arugula, wheat, and cotton via simple leaf infiltration, achieving strong transient protein expression without any detectable integration of the transgene into the plant genome (Demirer *et al.*, 2019). Because the DNA never becomes chromosomally integrated, plants produced this way sidestep the regulatory category of “transgenic,” a point with significant downstream implications for how nanocarrier-edited crops might eventually be classified and approved. The same group subsequently published a detailed step-by-step protocol for functionalizing SWCNTs and using

them for DNA delivery, intended to make the method broadly reproducible across plant biology laboratories (Demirer *et al.*, 2019).

CNTs have since been extended well beyond simple transient DNA delivery. Chitosan-complexed SWCNTs, designed around a "lipid-exchange envelope penetration" mechanism, have been used to selectively deliver plasmid DNA to chloroplasts rather than the nucleus in species including arugula, watercress, tobacco, and spinach, exploiting the fact that the plastid genome is maternally inherited in most crops and therefore offers a route to genetic modification with reduced risk of transgene escape via pollen (Kwak *et al.*, 2019).

A more recent extension used polymer-coated CNTs functionalized with targeting peptides to reach even harder target plant mitochondria, achieving roughly thirty-fold higher delivery efficiency than prior methods and enabling stable genetic integration of a folate-pathway gene into the mitochondrial genome, with measurable downstream effects on plant growth rate (Nature Communications, 2022). CNTs have also proven effective as RNA carriers: SWCNTs can deliver small interfering RNA (siRNA) into mature *N. benthamiana* leaves while protecting it from nuclease degradation, achieving gene-silencing efficiencies reported as high as 95% in some constructs (Landry Lab, UC Berkeley research summaries; Zhang *et al.*, 2019), and arginine-functionalized SWCNTs have been separately evaluated for their efficiency in nucleic acid delivery across plant systems (Golestanipour *et al.*, 2018).

MESOPOROUS SILICA NANOPARTICLES (MSNS)

Mesoporous silica nanoparticles were the first engineered nanomaterial shown, in a widely cited *Nature Nanotechnology* paper, to deliver both DNA and small chemicals into plant cells and intact leaves (Torney, *et al.*, 2007). The original design used a honeycomb-structured MSN with roughly 3-nanometer pores, loaded with a gene construct and its chemical inducer, and capped with gold nanoparticles that physically blocked the pores until they were deliberately uncapped, allowing controlled-release, inducible gene expression rather than constitutive expression from the moment of delivery. This capped-and-triggered design remains one of the clearest early demonstrations that nanocarriers can do more than simply ferry cargo across a barrier; they can also impose temporal control over when a delivered gene becomes active.

Follow-up work simplified the MSN gene-delivery platform for broader use as a carrier system (Chang *et al.*, 2013; Ghosh *et al.*, 2026), while more recent studies have pushed MSNs toward RNA interference applications. Cai and colleagues reported an MSN-based platform capable of delivering siRNA into mature, intact plant leaves through simple topical spraying with no mechanical aid required, achieving up to 98% silencing efficiency at the molecular level and, notably, low enough phytotoxicity to allow repeated dosing for durable, long-term multi-gene knockdown (Cai, *et al.*, 2023). Their study visualized this functionally: spraying MSN-siRNA complexes targeted at phytoene desaturase and magnesium chelatase genes produced visible white-spot and yellowing phenotypes on treated leaves, a straightforward and elegant readout of delivery success.

Beyond genetic cargo, MSNs have also been explored more broadly as agrochemical carriers, for example, improving seedling growth and photosynthetic activity in wheat and lupin following root uptake, apparently by localizing within chloroplasts without inducing oxidative stress or membrane damage (Ghosh *et al.*, 2026) underscoring that the same physicochemical properties that make MSNs good gene carriers (tunable pore size, high surface area, ready functionalization, biodegradability) also make them useful for the broader category of "nano-agrochemicals."

MSNs have additionally supported protein delivery relevant to precision genome editing: gold-nanoparticle-capped MSNs were used to deliver Cre recombinase protein directly into maize cells, achieving loxP-site excision for genome editing without requiring the plant to express the recombinase transgene itself (Martin-Ortigosa *et al.*, 2014).

DNA-BASED NANOSTRUCTURES

A structurally elegant approach uses DNA itself folded into defined nanoscale shapes via DNA-origami-like design principles (Rothemund, 2006), as the delivery vehicle for other nucleic acid cargo. Zhang and colleagues systematically compared three programmed DNA nanostructure geometries (a three-dimensional tetrahedron, a one-dimensional "hairpin-tile" monomer, and a high-aspect-ratio "nanosttring") for their ability to internalize into intact *N. benthamiana* leaf cells and deliver siRNA for gene silencing (Zhang *et al.*, 2019).

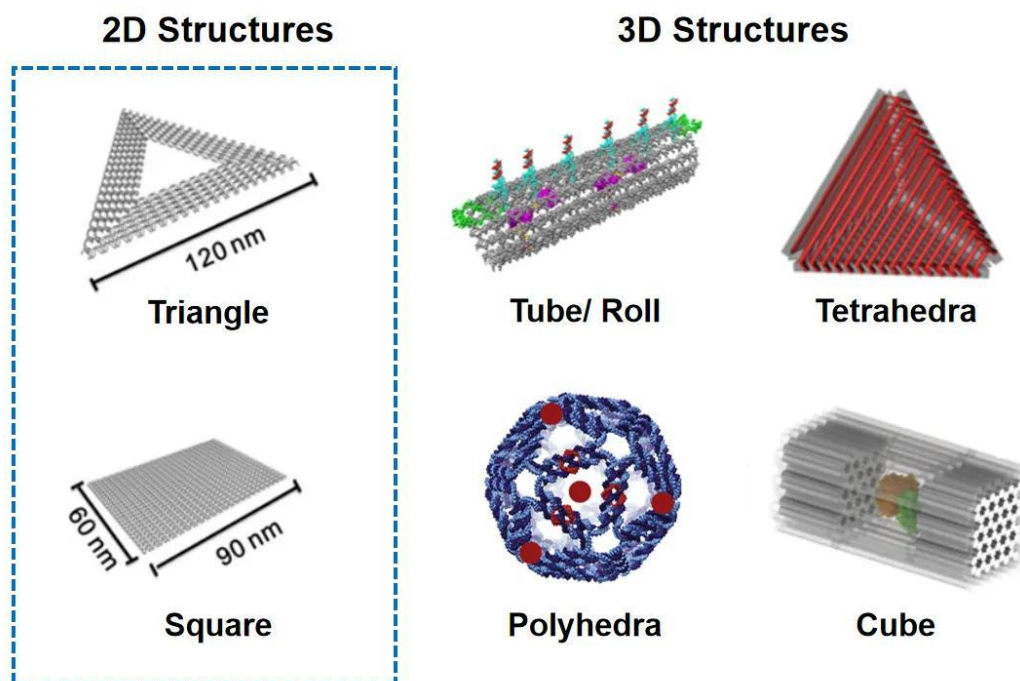


Figure 2: 2D and 3D Structures

The results were genuinely counterintuitive in places: while higher-aspect-ratio nanostructures generally facilitated better cellular entry, the very highest-aspect-ratio nanosttring construct actually showed the lowest internalization and silencing efficiency of the three shapes when used alone, revealing that shape is not a simple monotonic predictor of delivery success and that nanostructure rigidity, not just geometry, plays an independent role. The same body of

work found that the specific locus at which siRNA is chemically attached to the DNA nanostructure can shift the balance between transcriptional and post-transcriptional gene-silencing pathways in the plant, an unexpected mechanistic finding that connects nanocarrier design directly to plant epigenetic regulation.

A companion study from the same group asked a more fundamental question, does a nanocarrier actually need to be internalized by the plant cell at all in order to deliver functional RNA? Using gold nanospheres and nanorods, the researchers found that spherical gold nanoparticles functionalized with siRNA achieved efficient gene silencing in mature plant leaves even without measurable cellular internalization, while rod-shaped gold nanoparticles were internalized but were comparatively less effective, an inversion of the usual assumption that internalization is a prerequisite for nanocarrier efficacy (Zhang *et al.*, 2021). This finding has practical implications: it suggests that some nanocarrier platforms may be able to act at or near the plant cell surface, releasing cargo locally rather than requiring it to be trafficked deep inside the cell, which could simplify future carrier design.

LAYERED DOUBLE HYDROXIDES (LDH) AND CLAY NANOSHEETS — "BIOCLAY"

Where CNTs, MSNs, and DNA nanostructures have mostly been developed for delivering genetic cargo *into* plant cells for transformation or editing purposes, layered double hydroxide (LDH) clay nanosheets have been developed for a related but distinct molecular application: stabilizing double-stranded RNA (dsRNA) sprayed onto the outside of plants for pathogen and pest control, a strategy known as spray-induced gene silencing (Chen *et al.*, 2025; Manna *et al.*, 2026).

Naked dsRNA sprayed onto a leaf surface degrades within days under field conditions, severely limiting its practical use as a crop-protection tool. Mitter and colleagues addressed this by loading dsRNA onto degradable, non-toxic LDH clay nanosheets, a formulation they named "BioClay" and showed that a single spray application could protect plants against viral infection for at least twenty days, both on the sprayed leaves themselves and on newly emerged, unsprayed foliage, compared with only a few days of protection from naked dsRNA (Mitter *et al.*, 2017). The mechanism, as later work clarified, is essentially a slow-release "depot": the positively charged mineral layers of the LDH electrostatically bind and physically shield the negatively charged RNA, releasing it gradually as the clay itself degrades under ambient moisture, keeping a pool of bioactive dsRNA available for pathogen uptake over an extended window (Ladewig, Xu, & Lu, 2009).

Since that founding demonstration, the BioClay concept has been extended from antiviral protection to antifungal applications. A follow-up study found that BioClay formulations extended dsRNA-mediated protection against *Botrytis cinerea*, a major fungal pathogen, from roughly one week to three weeks on tomato leaves, and from five to ten days on harvested tomato fruit, with protection on flowering chickpea plants lasting up to four weeks long enough to cover the critical podding period when infection risk is highest (Niño-Sánchez *et al.*, 2022). Related nanocarrier chemistries, chitosan, polyethyleneimine, and star polycations, among

others have since been explored in the same SIGS space, generally aiming to improve dsRNA stability, cellular uptake by insect pests or fungal pathogens, and overall silencing efficacy. The commercial significance of this line of work was underscored in late 2023, when Ledprona became the first sprayable dsRNA biopesticide to receive U.S. Environmental Protection Agency approval, a milestone widely cited as validating the broader RNA-based, nanocarrier-assisted approach to crop protection (Chen *et al.*, 2025).

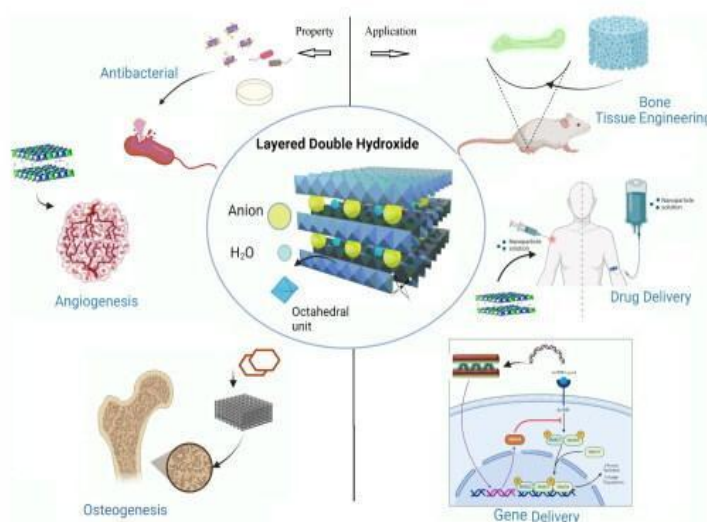


Figure 3: Layered Double Hydroxide

GOLD NANOPARTICLES AND QUANTUM DOTS

Gold nanoparticles have a long history in plant biolistics, DNA-coated gold micro particles are the classical payload for gene-gun transformation — but at the true nanoscale, gold particles have taken on a second role as nucleic-acid carriers in their own right. As already noted, spherical gold nanoparticles conjugated to siRNA have achieved effective gene silencing in mature plant leaves even without cellular internalization (Zhang *et al.*, 2021), and gold-nanoparticle constructs have been used to silence the defense-regulatory gene *NPR1* in *Arabidopsis thaliana* with reportedly fast kinetics (Lei *et al.*, 2020), as well as to achieve efficient gene knockdown via gold-nanocluster-mediated siRNA delivery into intact plant cells (Zhang *et al.*, 2021).

Quantum dots occupy a related niche, valued less for bulk gene delivery and more for precision, organelle-targeted delivery combined with built-in optical tracking. Santana and colleagues designed quantum dots coated with a rationally engineered chloroplast-targeting peptide, based on the conserved transit-peptide sequence of the Rubisco small subunit, together with a β -cyclodextrin "molecular basket" capable of loading and releasing small chemical cargoes. The resulting platform achieved chloroplast-targeted delivery efficiencies of roughly 75% in planta and allowed the researchers to tune chloroplast redox status more specifically than delivering the same chemicals in free form (Santana, *et al.*, 2020). Because quantum dots fluoresce in a spectral window with low plant tissue auto fluorescence background, this platform doubles as a diagnostic tool, letting researchers directly visualize where their cargo

has gone by confocal microscopy, an advantage not shared by most DNA- or RNA-based carriers, which typically require indirect reporter assays to confirm successful delivery.

CHITOSAN AND OTHER POLYMERIC NANOCARRIERS

Chitosan, a biopolymer derived from deacetylated chitin, has attracted particular attention as a plant nanocarrier because it is cationic (and therefore binds negatively charged nucleic acids electrostatically without further chemical modification), biodegradable, inexpensive to produce, and already established in agriculture as a biostimulant with independent effects on plant stress tolerance (boa.unimib.it review; Akashpriya, Gopishankar, Praveen, & Vasantha, review chapter). These properties have made chitosan nanoparticles an attractive low-cost entry point for genetic transformation works in laboratories without access to more specialized nanomaterial synthesis.

Chitosan-nanoparticle-plasmid complexes have been used to transform reporter genes (such as *uidA*, encoding the GUS enzyme) into explants of both an herbaceous crop, potato, and a woody species, *Paulownia tomentosa*, with transformation confirmed both visually (by the characteristic blue GUS staining reaction) and molecularly by PCR (Tawfik & Ahmed, 2022). A related study used chitosan nanoparticles to deliver plasmids carrying antimicrobial thionin genes into *P. tomentosa*, producing transgenic lines with measurably improved resistance to the bacterial pathogens *Erwinia carotovora* and *Pseudomonas aeruginosa* relative to non-transformed controls (Hussien, 2020).

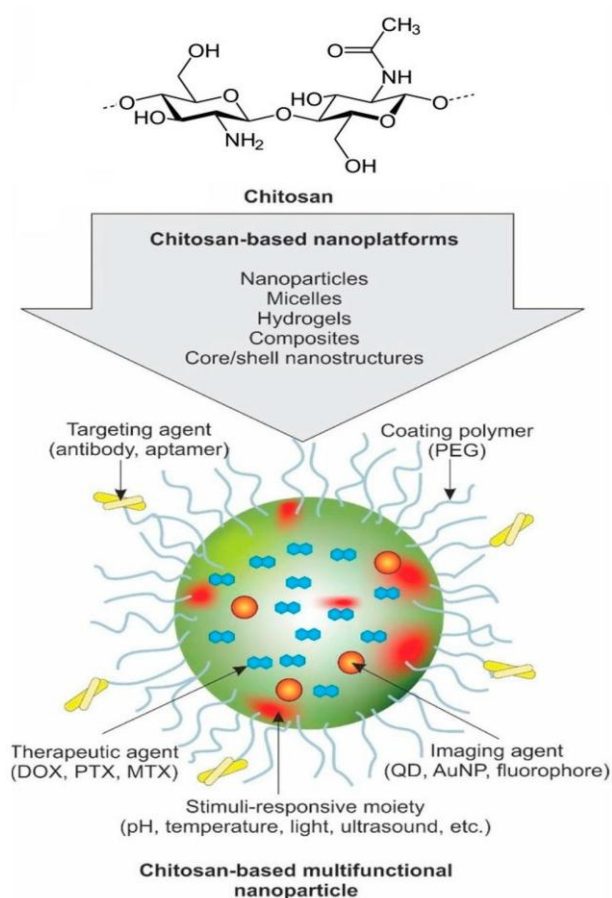


Figure 4: Chitosan-based Nanoplatforms

Reported transformation efficiencies for chitosan-nanoparticle-mediated delivery into plant cells have varied considerably by molecular weight and target tissue, with one study reporting roughly 32% transformation efficiency using medium-molecular-weight chitosan nanoparticles compared with about 15% for higher-molecular-weight formulations (research.asu.edu.eg report). As with any cationic polymer carrier, chitosan's charge density is also its chief liability: excessive positive surface charge is associated with cytotoxicity in cell-based assays, meaning formulation optimization has to balance nucleic-acid binding affinity against biocompatibility (openaccess.iyte.edu.tr, cytotoxicity study).

MOLECULAR AND GENETIC APPLICATIONS

TRANSIENT AND STABLE GENE EXPRESSION

The most direct application of plant nanocarriers is also the oldest: getting a reporter or trait gene expressed, either transiently (for rapid functional assays) or stably (for durable trait introduction). CNT- and MSN-based platforms have both demonstrated transient expression of fluorescent reporters such as GFP and YFP within hours to days of delivery, offering a much faster readout than waiting for stable transformant regeneration through tissue culture (Demirer *et al.*, 2019; Torney *et al.*, 2007). Stable transformation with the transgene passed on to progeny has proven harder to achieve consistently across nanocarrier platforms and tends to require either regeneration from transformed callus or protoplasts (as with early SWCNT work in tobacco) or specific organelle targeting strategies, such as the mitochondrial delivery system that achieved stable integration via homologous recombination in the mitochondrial genome (Nature Communications, 2022).

ORGANELLE-TARGETED DELIVERY

A recurring theme across the nanocarrier literature is the ability to direct cargo to a specific subcellular compartment such as nucleus, chloroplast, or mitochondrion rather than simply flooding the cytoplasm. Chloroplast targeting is of particular practical interest because the plastid genome is maternally inherited in the large majority of crop species, meaning that chloroplast-integrated transgenes are far less likely to spread via pollen than nuclear transgenes, a feature directly relevant to biocontainment and to public and regulatory acceptance of engineered crops (Kwak *et al.*, 2017). Chitosan-complexed SWCNTs, quantum dots bearing Rubisco-derived transit peptides, and MSNs that localize to chloroplasts after root uptake have all been used to achieve some degree of chloroplast-selective delivery (Kwak *et al.* 2017; Santana *et al.*, 2020). Mitochondrial targeting, historically the most technically difficult of the three compartments to reach, was achieved using peptide-functionalized, polymer-coated CNTs, with the resulting platform reported to outperform prior mitochondrial delivery methods by close to thirtyfold, a reminder that organelle-specific nanocarrier engineering is still a comparatively young and rapidly improving subfield.

CRISPR/CAS GENOME EDITING AND DNA-FREE DELIVERY

Perhaps the application with the greatest near-term translational significance is nanocarrier-assisted delivery of CRISPR/Cas genome-editing machinery, particularly as preassembled

ribonucleoprotein (RNP) complexes rather than as DNA-encoded constructs. Delivering Cas9 or Cas12a protein pre-bound to its guide RNA, instead of a plasmid that must be transcribed and translated inside the cell, offers several practical advantages: it eliminates the risk of the editing machinery's own DNA becoming randomly integrated into the plant genome, it shortens the window during which the nuclease is active (reducing off-target editing), and critically for regulatory purposes and it can produce edited plants that contain no foreign DNA at all, sometimes described as "transgene-free" genome editing (Gao *et al.*, 2026).

RNP delivery has been demonstrated across an increasingly wide range of protoplast systems using polyethylene-glycol-mediated transfection, including in maize, soybean, chickpea, grapevine, hexaploid sweet potato, and multiple *Brassica* species, with reported mutagenesis frequencies ranging broadly from roughly 4% to over 85% depending on species, target locus, and delivery conditions (references spanning maize, soybean, chickpea, grapevine, sweet potato, and *Brassica* protoplast studies, 2018–2025).

A systematic comparison of six different Cas9 and Cas12a RNP formulations across several species, including *N. benthamiana*, pennycress, soybean, and *Setaria viridis* found genome-editing frequencies in transfected protoplasts of 8.7% to 41.2%, rising to 34.0–85.2% in protoplast-regenerated calli and plants, with heritable mutations recovered in subsequent generations and, notably, little sensitivity to the temperature at which delivery was performed. True nanocarrier chemistry enters this picture through work using anionic polymers to stabilize Cas9 RNP nanoparticles, improving both delivery efficiency and downstream editing outcomes in plant protoplasts, in some cases building on amphiphilic, cell-penetrating peptides (such as the peptide "A5K," used in the peptide-enabled RNP delivery or "PERC" method originally developed for mammalian systems) (Hubbard *et al.*, 2025).

Calcium phosphate nanoparticle mineralization of Cas9 RNP complexes represents a parallel strategy, shown to improve RNP stability and cellular uptake while preserving nuclease activity reported at 20% editing efficiency in a fungal plant-pathogen protoplast model, pointing toward inorganic mineral-based carriers as a further avenue for RNP delivery (Zhang *et al.*, 2021).

A comprehensive 2026 review published in *Frontiers in Plant Science* frames this convergence explicitly: nanocarriers spanning lipid, polymeric, mesoporous silica, carbon-based, layered double hydroxide, and DNA-based materials are now being systematically evaluated for their ability to modulate cellular uptake, cargo stability, and tissue-specific targeting of CRISPR/Cas RNPs, DNA, and RNA with the explicit goal of achieving transgene-free, tissue-culture-independent genetic improvement that can be applied directly to elite, commercially relevant germplasm rather than only to easily regenerated model lines (Programmable Nanocarriers for Singh, *et al.*, 2026). Because nanocarrier-delivered, DNA-free editing can, in principle, bypass the callus-induction and regeneration phases that classical transformation requires, the same review argues it may also reduce the somaclonal variation, the unwanted, tissue-culture-induced genetic and epigenetic changes that have long complicated efforts to move gene-editing technology into elite breeding lines (Quiroz *et al.*, 2025).

RNA INTERFERENCE FOR CROP PROTECTION AND FUNCTIONAL GENOMICS

Beyond the BioClay/LDH platform already discussed in Section 3.4, RNA interference delivered by nanocarriers has become one of the most actively developed molecular applications in the field, serving two related but distinct purposes: functional genomics (silencing an endogenous plant gene to study its function) and crop protection (silencing an essential gene in an invading pest or pathogen via "cross-kingdom" RNAi).

For functional genomics, MSN-mediated siRNA spraying achieving up to 98% silencing of target plant genes (Cai *et al.*, 2023) and DNA-nanostructure-delivered siRNA achieving robust, shape-dependent gene knockdown in *N. benthamiana* (Zhang *et al.*, 2019) both offer researchers a much faster route to loss-of-function phenotypes than generating stable RNAi transgenic lines, which can take months.

For crop protection, the SIGS strategy applying dsRNA topically, stabilized by a nanocarrier, to silence essential genes in an insect pest, fungal pathogen, or virus rather than in the plant itself has moved furthest toward real-world deployment, culminating in the 2023 EPA approval of the first sprayable dsRNA biopesticide.

Nanocarrier chemistry is central to SIGS because naked dsRNA is both environmentally unstable (degrading within days under field UV exposure and moisture) and poorly taken up by target organisms on its own; LDH, chitosan, polyethyleneimine, and star-polycations carriers have each been shown to extend dsRNA persistence and/or improve its uptake by target pests, including reported effects against oriental fruit fly, green pea aphid, and lepidopteran crop pests.

PLANT NANOBIOTICS AND MOLECULAR SENSING

A related but distinct application worth noting briefly is the use of nanocarriers not to deliver genetic material but to embed functional nanosensors within living plant tissue, an approach sometimes called "plant nanobionics." Carbon-nanotube-based sensors have been used, for example, to detect nitro aromatic compounds and relay that detection as an infrared signal readable by a standard camera, effectively turning an intact, wild-type plant into an environmental sensor without any genetic modification at all (Wong *et al.*, 2019). While this review's primary focus is genetic and molecular delivery rather than sensing, the two applications share the same underlying materials science, high-aspect-ratio, surface-functionalized nanomaterials capable of penetrating or associating closely with plant tissue and nanosensors work is frequently published alongside gene-delivery work by the same research groups (Kwak *et al.* 2019).

COMPARATIVE PERSPECTIVE: NANOCARRIERS VERSUS CLASSICAL DELIVERY METHODS

It is worth stepping back to compare, in general terms, how nanocarrier-based delivery stacks up against the classical toolkit it is gradually supplementing. *Agrobacterium*-mediated transformation remains unmatched for stable, single-copy transgene integration in species it infects efficiently, but it is essentially unusable in many monocots and recalcitrant dicots

without extensive protocol optimization, and it always risks T-DNA integration into functionally important genomic regions. Biolistic delivery is close to species-agnostic but causes substantial physical tissue damage and, again, uncontrolled integration (Russell, Roy, & Sanford, 1992). Protoplast-based PEG transfection, widely used for RNP delivery, offers precise, DNA-free editing with excellent control over delivery conditions, but it is entirely dependent on the ability to isolate viable protoplasts and, more restrictively, to regenerate whole plants from them, a step that fails outright in a meaningful fraction of important crop species and even elite varieties within species that otherwise regenerate well.

Nanocarrier-based delivery, across the platforms reviewed above, offers a genuinely different tradeoff: broad host-range applicability that does not depend on species-specific infection biology (Demirer *et al.*, 2019); the possibility of delivering functional cargo directly into intact, mature tissue without requiring protoplast isolation or extensive tissue culture (Demirer *et al.*, 2019; Cai *et al.*, 2023); and, for several platforms, transgene-free outcomes that may simplify eventual regulatory classification. Against this, nanocarrier methods are generally newer, less standardized across laboratories, and with some notable exceptions such as SIGS-based biopesticides has not yet been deployed at commercial or field scale to the degree that classical transformation has.

FUTURE PERSPECTIVES

First, stimulus-responsive nanocarriers materials engineered to release their cargo only in response to a specific trigger, such as pH change, light exposure, or a particular enzymatic environment are increasingly discussed as a way to gain temporal and spatial control over gene expression or genome editing, building on the basic capped-and-triggered logic first demonstrated with gold-capped MSNs (Torney *et al.*, 2007)

Second, the field is moving toward integration with speed-breeding and multiplexed editing pipelines, aiming to combine nanocarrier-delivered, DNA-free CRISPR editing with accelerated generation-advancement protocols and simultaneous editing of multiple loci, explicitly targeting elite germplasm rather than only easily transformed model lines (Gao *et al.*, 2026).

Third, there is growing interest in meristem-targeted delivery, which would allow nanocarrier-mediated editing to be applied directly to the actively dividing stem-cell population of an intact plant, potentially producing heritable edits without any protoplast isolation or tissue-culture regeneration step at all, a long-standing goal that would remove one of the field's most persistent bottlenecks if achieved reliably (Gao *et al.*, 2026).

Fourth, on the crop-protection side, the regulatory approval of the first sprayable dsRNA biopesticide is likely to accelerate commercial investment in nanocarrier-stabilized RNAi products, extending the BioClay concept toward a broader range of pathogens, pests, and formulation chemistries.

Finally, a quieter but important trend is the increasing use of nanocarriers as combined delivery-and-diagnostic tools, as in the quantum-dot chloroplast-targeting platform, where the same nanoparticle both delivers a chemical cargo and reports, via its own fluorescence, exactly

where that cargo ended up (Santana *et al.*, 2020). As more nanocarrier platforms incorporate this kind of built-in traceability, researchers should be able to more quickly and rigorously validate delivery claims across new species and tissue types, addressing one of the reproducibility concerns noted above.

CONCLUSION

Nanocarriers have developed rapidly from a new research concept into an important delivery platform for plant genetic and molecular engineering. They can overcome the plant cell wall barrier and efficiently deliver different types of cargo, including DNA, siRNA, dsRNA, Cas9/Cas12a RNPs, and small molecules, into various plant species such as cotton, wheat, maize, soybean, and grapevine. Spray-induced RNA interference (RNAi) has emerged as a promising application for crop protection, while nanocarrier-mediated CRISPR/Cas RNP delivery is being explored for transgene-free and precise plant genome editing. However, challenges such as toxicity, genotype dependence, regeneration difficulties, environmental effects, and regulatory issues still need to be addressed. Overall, research over the past decade indicates that nanotechnology-based delivery systems are likely to become an increasingly useful tool for modern plant genetic engineering.

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