

An Encyclopedia
of the Applications
of Nanotechnology

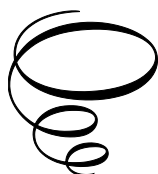
An Encyclopedia of the Applications of Nanotechnology:

*Bio-waste-derived
Nanomaterial Synthesis*

By

Aneesa Batool and Sajad Majeed Zargar

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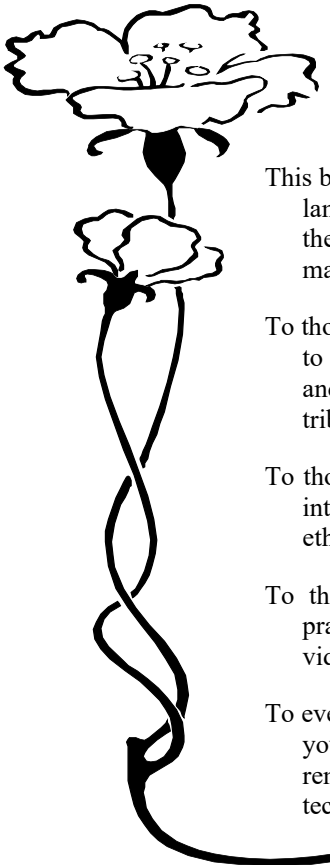
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By the grace of Almighty

This book is dedicated to the spirit of *Khudi*, which Dr Al-lama Iqbal wonderfully illuminated, as a reminder that the power to transform the world exists within the human soul.

To those who dare to dream beyond the visible, who strive to unveil the mysteries hidden in the smallest of forms and see the cosmos in a nanoparticle. This work is a tribute to their courage and curiosity.

To those who honour nature's gift by transforming waste into wonders and wielding knowledge with wisdom, ethics, and grace.

To those whose hands held our childhood and whose prayers cherished our future, whose quiet support provided us with wings to fly - **our cherished parents.**

To every reader who reads this book. May this book ignite your imagination towards sustainable solutions, and remind us all of our shared responsibility to harness technology ethically and for the greater good

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ABOUT THE BOOK

The application of nano-particles in agriculture has remained low at the ground level owing to the lacuna in representing its vast applications in sustainable agriculture. To bridge this gap, the authors believe that it is important at this point, particularly for agriculturists, to be aware of the potential of nano-materials derived from bio-wastes for environmental protection and long-term agricultural solutions. Significant research efforts are required to develop novel products that are competitive, environmentally friendly, and economically viable. It acted as a motivating factor for authors to study and create a framework for a long-term solution to a complex and multidimensional problem. Additionally, we found it difficult to gather study material for UG and PG courses that include Nanotechnology, as one of the subjects, which motivated us towards writing a book for a better understanding of nanotechnology to the UG/ PG students, as well as providing technical procedures in the book that may help researchers and academicians involved in Nanotechnology research and teaching.

Several barriers to the application of nanotechnology in agriculture appear to have hindered its progress compared to other fields. An analysis was conducted, which is presented in an article titled 'A critical evaluation of nano pesticides and nanofertilizers against their conventional analogues', the delay in development is due to constraints such as limited public funding and slow uptake of this innovation by agricultural research organizations. Agriculture is a low-profit industry, and/or public acceptance of technology, as well as the available knowledge about ecofriendly approach to crop development using nanoparticles, is very limited as it is still in its infancy and there is a lack of clarity. The book titled 'Encyclopedia of Application of Nanotechnology – Bio-waste Derived Nanomaterial Synthesis' gives immense awareness to the scientific community/researchers/agriculturists, and students about harnessing bio-wastes for the improvement of crops. The authors have also discussed the potential of nano-materials developed from bio-wastes and their use in protecting the environment and providing long-term solutions for improving the agricultural biome. As such, topics from the very basics to the upper hierarchy have been added, making it useful for researchers working in the field of nanotechnology. Some protocols about the

synthesis of nanoagrochemicals from bio-wastes have also been included for the guidance of researchers.

This book is an admix of solutions for environmental and economic sustainability as well as a guide for researchers, giving a unique aura to the book.

We strongly believe our book is unique in its theoretical background and technical approaches.

‘When atoms align with intention, even waste can whisper wonders!’

Anesa Batool and Sajad Majeed Zargar

CHAPTER 1

NANOTECHNOLOGY AND ITS APPLICATION IN VARIOUS FIELDS

Abstract

Nanotechnology is revolutionising a multitude of industries by leveraging the unique properties of materials at the nanoscale. This chapter explores the diverse applications of nanotechnology, encompassing enhancements to catalytic processes, improvements in energy efficiency, advancements in computing technologies, and improvements to consumer products. In the field of energy, nanotechnology holds promise for more sustainable and efficient methods of production and consumption. In computing and electronics, it supports the development of cutting-edge technologies like quantum computing and nanosensors. The chapter also highlights the role of nanotechnology in food safety, construction, textiles, and automotive industries, showcasing its potential to transform traditional practices. In cosmetics, nanoscale innovations offer improved performance and safety.

Keywords: Nanoscale materials, Nanocatalysis, Energy efficiency, Food safety, Quantum computing

1.1 Introduction

Nanotechnology is a multidisciplinary and promising technology that manipulates organic and inorganic materials at the atomic and molecular scale, resulting in materials with biological, chemical, and physical properties [Chellaram, 2014]. The foundation of nanoscience and nanotechnology was laid during a groundbreaking lecture titled ‘There’s Plenty of Room at the Bottom,’ delivered by physicist Richard Feynman at a meeting of the American Physical Society on December 29, 1959, at the California Institute of Technology [Bayda et al.,2020]. Specifically, when the structure of materials is altered, and particle size is reduced to 1–100 nm, they exhibit significant differences in physical and chemical

properties compared to the original materials, even though they contain the same base materials [Colica et al.,2018; Dera et al.,2020]. These properties result from a high surface area-to-volume ratio [Grumezescu and Holban,2018], which leads to a wide range of applications in sectors like engineering, materials science, chemistry, biology, and medicine, agriculture, molecular computing, energy production, food, cosmetics, and more [Batool et al.,2024a; Batool et al.,2024b; Batool et al.,2026c; Berekaa,2015; Chaudary et al.,2017; Duncan,2011; Nile et al.,2020]. In the food sector, nano capsules improve the bioavailability of nutraceuticals while nanoencapsulation improves flavour and texture. Nanotechnology has been used to manufacture nutritional supplements, antioxidants and preservatives [Berekaa,2015; Grumezescu and Holban,2018; Singh et al.,2017]. The high surface area-to-volume ratio enables the development of powerful nanocatalysts that improve chemical reaction efficiency while reducing waste [Nasrollahzadeh et al.,2019]. Nanoparticles are employed to create stronger, lighter-weight materials with better thermal properties. For instance, zinc oxide nanomaterials are put into sunscreen glasses to improve performance and durability [Nasrollahzadeh et al.,2019]. Nanomaterials are also used in industries such as construction, and aviation, where they contribute to the production of self-cleaning windows, solar panels, and corrosion-resistant coatings [Adachi,2000; Jain et al.,2009]. Nanotechnology has also brought significant advancements in the field of medicine, particularly in drug delivery. Certain nanoparticles can improve drug targeting and enhance the controlled release of therapeutic agents [Li et al., 2021; Occhiutto et al., 2020]. Clinicians use these technologies to detect and treat diseased cells more precisely, optimising treatment dosages and minimising side effects [Haleem et al., 2023; Occhiutto et al., 2020]. Nanoparticles are already being used in personalised medicine to treat spinal cord injuries and brain tumours. Researchers are developing intelligent nanoparticles for targeted drug delivery [Garimella and Eltorai,2017; Occhiutto et al.,2020].

Across the globe, billions of dollars are being invested in nanotechnology, particularly in developed regions like Europe, China, and the USA, to harness its potential [Schulte,2005]. However, developing countries lag due to economic challenges and slower industrial growth [Lemley, 2005]. Both developed and developing nations agree that nanotechnology will be pivotal for future technological advancements and will drive industrial upgrades and investments in the years ahead [Salamanca-Buentello et al.,2005]. The European Commission has recognised nanotechnology as a key enabling technology for sustainable growth in multiple fields, including agriculture [Pramanik et al.,2020].

Agricultural scientists are realising that technologies like nanotechnology are vital in addressing global concerns, such as food security and climate change [Kuzma and Verhage 2006]. The use of nanomaterials can improve fertiliser efficiency, reduce pesticide use, and enable early detection of pathogens in food [Pramanik et al.,2020]. Nanotechnology is also applied to smart systems for pesticide delivery, food packaging, and processing, making it a path-finder in modern agriculture [Pramanik et al.,2020]. In this chapter, we have highlighted various properties of nanoparticles and have discussed the usage of nanomaterials in various fields.

1.2 The distinct properties of nanoparticles: why we choose nanoscale solutions

At the nanoscale, materials exhibit unique and altered properties that differ significantly from those observed at the macroscopic level. These changes in properties arise from the smaller molecular size and modified interactions between molecules. Some of these distinctive properties are given below.

i) Increased surface area to volume ratio

At the nanoscale, the surface area to volume ratio of nanoparticles is substantially higher. This means that more of the material is exposed to the environment, increasing its reactivity. This attribute makes nanomaterials efficient catalysts because the maximum amount of material is available for reactions. Nanomaterials are already used in one-third of the U.S. and global catalytic markets [Wu et al.,2020].

ii) Shift in optical absorbance and fluorescence

Nanoparticles of noble metals have size-dependent optical properties. They show a strong UV-visible extinction band, which is not seen in bulk materials. One example is gold nanoparticles, which give the rusty colours visible in stained glass windows [Joudeh and Linke,2022].

iii) Improved mechanical properties

Nanomaterials have unique mechanical properties due to surface and quantum phenomena. At the nanoscale, metals and alloys show increased hardness and toughness. Nanomaterials, such as ultrafine FeAl powder, have higher strength and ductility compared to their bulk equivalents [Joudeh and Linke,2022]. These properties result from changes in

interaction forces at the nanoscale, such as van der Waals forces [Joudeh and Linke,2022] and hydration forces, which differ from bulk materials [Qiu et al.,2020; Shima et al.,2009], influencing the strength, elasticity, and ductility of nanomaterials and enhancing their overall mechanical performance [Sham and Sharma,2008].

iv) Increased permeability and electrical conductivity

Due to their small size, nanoparticles can more easily penetrate biological membranes. This makes them useful in drug delivery systems. Moreover, their electrical conductivity increases at the nanoscale, which improves their application in various electrical and electronic devices [Guo et al.,2013].

v) Enhanced solubility

Nanoparticles increase the solubility of hydrophobic drugs. These drugs can be transformed into nanosuspensions, improving their delivery to targeted sites within the body [Joudeh and Linke,2022; Missana et al.,2000].

vi) Faster diffusion

Nanoparticles, with their high surface area and small size, allow molecules and ions to diffuse at faster rates. This property accelerates processes like catalysis, lowering the reaction time [Brant et al.,2005].

vii) Strong adhesive properties

Materials cling together at the nanoscale due to strong van der Waals forces, making materials sticky. Nanofibers are ideal for filtration due to their ability to capture and trap small particles [Tan et al.,2004].

viii) Reduced energy and material consumption

Nanotechnology products are smaller, lighter, and more functional. They use less energy and raw materials, making industrial processes more efficient and cost-effective [Armini et al.,2007].

ix) Minimal labour and maintenance

Nanotechnology is highly productive, affordable, and requires minimal labour, land, and maintenance. It requires only a small amount of materials and energy to function efficiently [Savage and Rao,2004].

x) Drug encapsulation for targeted delivery

Nanotechnology allows drugs to be encapsulated in nanocoatings. These coatings shield drugs from degradation and release them slowly to targeted sites over time. This ensures long-term therapeutic effects and controlled release [Andrievski,2014].

xi) Thermal properties

Nanoparticles have higher thermal conductivity due to their high surface-to-volume ratio. For example, adding copper nanoparticles to a fluid like ethylene glycol can increase thermal conductivity by up to 40% [Eastman et al.,2001]. Nanoparticles have larger heat capacity than bulk materials, and their melting temperatures decrease as particle size reduces [Zebarjadi et al.,2009].

xii) Magnetic properties

Nanoparticles of magnetic elements exhibit new magnetic behaviours, such as superparamagnetism. This phenomenon occurs when the magnetic anisotropy energy decreases with nanoparticle size, causing random flipping of the magnetic moment [Zeng et al.,2007]. Nanoparticles have unique magnetic characteristics that are not found in bulk materials [Kim et al.,2006].

xiii) Optical properties and plasmon resonance

Metallic nanoparticles have intriguing optical properties due to localised surface plasmon resonance. This happens when the frequency of incoming light matches the frequency of electron oscillations in the nanoparticles. Noble metals, such as gold, exhibit strong size-dependent UV-visible extinction that is absent in bulk metals [Likhachev et al.,2006].

1.3 From concept to application: The reach of nanotechnology

Nanotechnology has exerted its influence in various fields, as briefly shown in **Fig. 1.1**

1.3.1 Application of nanotechnology in diagnostics

Nanotechnology is increasingly being used in diagnostic sciences for early and rapid disease detection, allowing for more accurate medical treatments. It can detect disorders at the cellular and molecular levels, providing information on potential treatments [Dessale et al.,2022]. Nanotechnology holds great potential to transform healthcare diagnostics by improving accuracy, sensitivity, and speed of medical tests [Fox et al.,2019]. One important application of nanotechnology is nanoparticle-based diagnostic imaging. This method involves attaching nanoparticles to specific biomarkers, which improves imaging techniques such as magnetic

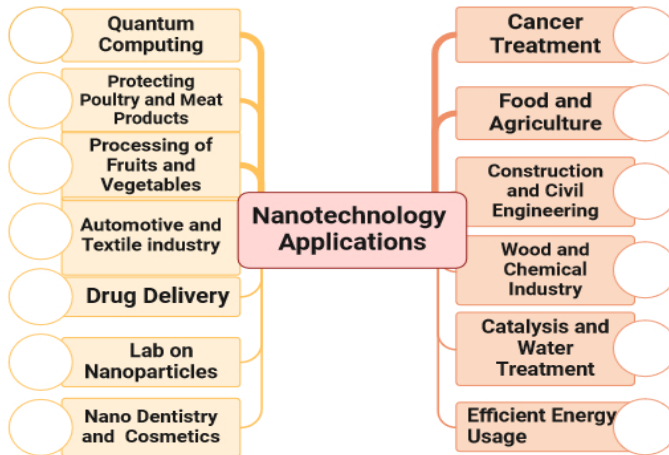


Fig. 1-1 Application of nanotechnology in various fields

resonance imaging (MRI), computerised tomography (CT) scans, and positron emission tomography (PET) scans. This improves the imaging sensitivity, accuracy, and specificity [Singh and Amjii,2022]. Nanotechnology has facilitated the development of highly sensitive biosensors capable of detecting tiny amounts of biomolecules in body fluids like blood and urine. This early detection can significantly improve disease

management [Xu et al.,2022; Sadeghi et al.,2023]. Similarly, microfluidic devices that use nanomaterials can isolate and examine cells, proteins, and genetic material, allowing for quick and exact diagnosis [Rajput et al.,2023; Singh et al.,2022]

Nanopore sequencing, a technique that uses nanopores to sequence DNA or RNA molecules, enables the rapid and precise detection of genetic disorders, including cancers and hereditary diseases [Wang et al.,2021]. Recent advances suggest that nanomedicine can increase the reliability of disease detection under in vitro diagnostics by using nanodevices to analyse samples from human tissues, cell cultures, or body fluids [Dang and Guan,2020; Malik et al.,2023b; Singh et al., 2022; Welch et al.,2021]. In in vivo diagnostics, nanomedicine is being used to create devices that can function inside the body to detect early signs of diseases, such as toxicity or tumours [Rajput et al.,2023]

1.3.1.1 Nanotechnology and lab-on-chip technology in healthcare

Nanotechnology and lab-on-chip technologies have transformed healthcare by enabling novel methods of diagnosing diseases, offering personalised treatments, and delivering drugs [Vaishampayan et al.,2023]. The integration of these two technologies has resulted in diagnostic tools that are faster, more precise, and cost-efficient than traditional methods [Thwala et al.,2023]. Lab-on-nanoparticles are microscopic devices that can perform multiple tasks such as diagnostics, drug delivery, and monitoring of health conditions [Kumari et al.,2022]. These devices are made up of nanoscale materials that detect and respond to changes in the body, allowing for real-time health monitoring and personalised treatment [Welch et al.,2021]. Nanoparticles can target cancer cells for early identification and treatment, making cancer diagnostics one of their most important applications [Sadeghi et al.,2023; Xu et al.,2022].

1.3.2 Nanotechnology in drug delivery

Nanotechnology has significantly improved drug delivery systems by providing targeted and efficient delivery, minimising side effects, and enhancing drug effectiveness [Kumari et al.,2022]. Nanotechnology-based systems, such as nanoliposomes, can deliver drugs directly to specific cells or tissues, improving drug efficacy while reducing unwanted side effects [Crommelin et al.,2020; Wang et al.,2021a]. In future, nanoscale devices are expected to detect viral infections and monitor the release of medications within organs, providing more accurate treatment assessments [Kang et al.,2021]. Nanotechnology aims to improve the pharmacokinetics

and pharmacodynamics of drugs, allowing them to stay in the body for a longer time, act more effectively, and target specific areas [Park,2013]. Nanoparticles enhance drug solubility, stability, and bioavailability, enabling lower doses and reducing toxicity [Malik et al.,2023b; Mazayen et al.,2022]. Researchers are also exploring nanosponges that can absorb excess toxic drugs in the bloodstream, potentially offering a solution to drug overdoses [Irvani and Varma,2022]. These nanoassemblies are being studied as promising anticancer agents [Baroud et al.,2021; Dong et al.,2019].

1.3.3 DNA nanotechnology in drug delivery

Recent advances in DNA nanotechnology have offered new methods for drug delivery, such as DNA vaccines and DNA guns, with the potential to improve drug targeting and reduce toxicity [Dang et al.,2020; Liu et al.,2023]. This new field uses DNA-based nanostructures that self-assemble to improve drug efficacy and minimise side effects, particularly in cancer treatment [Liu et al.,2023]. Researchers are also using contemporary computational approaches to design precise DNA nanostructures with specific properties for treating diseases [Chouhan and Rangi,2023; Rajput et al.,2023]. The future of this field may involve RNA-based drugs, which offer new opportunities for personalised treatments [Kim and Franco,2020].

1.3.4 Nanobiotechnology and gene therapy

Nanobiotechnology and gene therapy are collaborating to develop new treatments for various diseases. Gene therapy includes inserting DNA into a patient's cells to replace damaged genes, and nanotechnology plays a key role in delivering these therapeutic genes to the target cells [Hu et al.,2018; Jiang et al.,2022; Yu et al.,2021]. Nanocarriers protect the DNA and improve its ability to enter cells, increasing the safety and efficacy of gene therapy [Deluca et al.,2020; Jiang et al.,2022].

Nanotechnology also supports gene editing techniques and real-time monitoring of gene expression, which could lead to advancements in personalised medicine [Chen et al.,2020]. The incorporation of nanotechnology into gene therapy is opening doors for more precise genetic treatments for diseases like cancer and genetic disorders [Idrees et al.,2020; Javaid et al.,2021].

1.4 Nanotechnology in bone regeneration

Nanotechnology is also making strides in bone regeneration by enabling the development of materials that promote bone growth [Wang et al.,2021b]. Researchers are developing nanoparticles that can deliver drugs directly to the bone healing sites, improving treatment outcomes [Pardi et al.,2015]. Nanotechnology is also being used to produce scaffolds that imitate the structure of bone, guiding new bone formation and speeding up the healing process [Pardi et al.,2015; Wang et al.,2021b]. Advances in 3D printing with nanoscale materials are allowing for the production of highly customised bone implants [Wang et al.,2021b]. Studies are ongoing to develop nanostructured bone grafts with properties that allow them to be easily accepted by body tissues [Hajjali et al.,2021]. Biomineralisation research aims to reduce the size of bone particles to improve their incorporation into damaged bone areas, potentially revolutionising osteology and bone tissue engineering [Gu et al.,2013; Pardi et al.,2015].

1.5 Nanotechnology and anaesthesia induction

Anaesthesia induction is crucial for dentistry and medical treatments, including brain surgeries. Researchers are developing nanorobotic suspensions containing millions of nanoscale analgesic nanoparticles for anaesthesia induction. These nanoparticles use chemical and thermal gradients to penetrate deep into sensitive tissues like gums. Nanocomputers regulate the process to ensure even distribution and effectiveness. This enables precise anaesthesia targeting, which is very useful for dental surgeries. Following the procedure, nanorobots can restore normal tooth sensitivity with the same nanocomputer control [Bhansali et al.,2021; Naaz and Asghar,2022; Zhang et al.,2023].

1.5.1 Applications of nanotechnology in dentistry

Nanodentistry is a specialised field of nanomedicine that focuses on the diagnosis, treatment, and maintenance of oral health using nanomaterials. These nanomaterials, developed through tissue engineering and dental nanorobotics, can cure various oral health problems such as anaesthesia, orthodontic realignment, and hypersensitivity. Mechanical dental robots can regulate tooth tissue and maintain its normal function. Programmed nanocomputers control the action of these robots, enabling them to respond to internal and external inputs. This technology helps dental surgeons to give

precise treatments in real time [Agnihotri et al.,2020; Haridas et al.,2015; Jandt and Watts,2020; Vasiliu et al.,2021; Wang et al.,2022]

1.5.2 Nanotechnologies in tooth repair and hypersensitivity treatment

Researchers are using nanotechnology to improve dental treatments through natural biomineralisation and creating artificial teeth. Calcium hydroxyapatite nanorods are produced using nanoscale manufacturing techniques, which help to reinforce tooth enamel and aid in reconstructive dentistry. These dental nanoparticles also benefit patients by offering a quick and long-lasting treatment for hypersensitivity [Kasimoglu et al.,2020; Kochan et al.,2022; Wang et al.,2022].

1.5.3 Tooth repositioning

Orthodontic nanorobots can perform painless tooth repositioning and rotation, improving dental health. Nanotechnology also plays a role in dental aesthetics, enabling procedures like removing dental amalgams or developing fillings and crowns. This provides patients with a diverse choice of options for both dental treatment and cosmetic improvements [Foong et al.,2020; Moradpoor et al.,2021].

1.6 Nanotechnology in cancer treatment

Nanotechnology is transforming cancer treatment by developing nanoparticles and nanomedicine that can diagnose and treat cancer with higher precision [Fig. 1.2]. Scientists are exploring nanoparticle drug delivery systems that can improve specificity and reduce the side effects of traditional cancer treatments. These nanoparticles can carry anticancer drugs directly to the tumour site, improving drug targeting while minimising damage to healthy cells. Nanotechnology is also applied in immunotherapy, tumour imaging, and gene therapy [Chouhan and Rangi,2023; Dessale et al.,2022; Koyande et al.,2022; Ou et al.,2023; Raj et al.,2021; Souri et al.,2022].

1.6.1 Targeted nano drug delivery technology for cancer therapy

Targeted nano drug delivery systems are designed to selectively transport cancer drugs to tumour sites, thereby decreasing systemic toxicity and increasing treatment outcomes. These systems, which include liposomes, polymeric nanoparticles, and dendrimers, are specifically designed to bind to cancer cells. This results in a higher drug concentration at the tumour site while minimising harm to healthy tissues. Furthermore, targeted delivery can be monitored using imaging agents, which allows real-time tracking of drug distribution and treatment success [Dang et al.,2020; Hani et al.,2022; Ho et al.,2017; Huda et al.,2020; Talukdar et al.,2022].

1.6.2 Nanotech-based magnetic drug delivery in cancer therapy

Magnetic drug delivery technology uses externally applied magnetic fields to direct drug-loaded nanoparticles to targeted tumour sites. Magnetic nanoparticles improve drug concentration in tumours while reducing exposure to healthy tissues. This technology is also used for treating neurological disorders by directing drugs to specific brain regions. Nanoparticles protect drugs from degradation, offering improved stability and prolonged release, making them a promising approach for cancer and other disorders. [Adir et al.,2020; Chavda,2019; Edis et al.,2021; Pusta et al.,2023; Sim and Wong,2021]

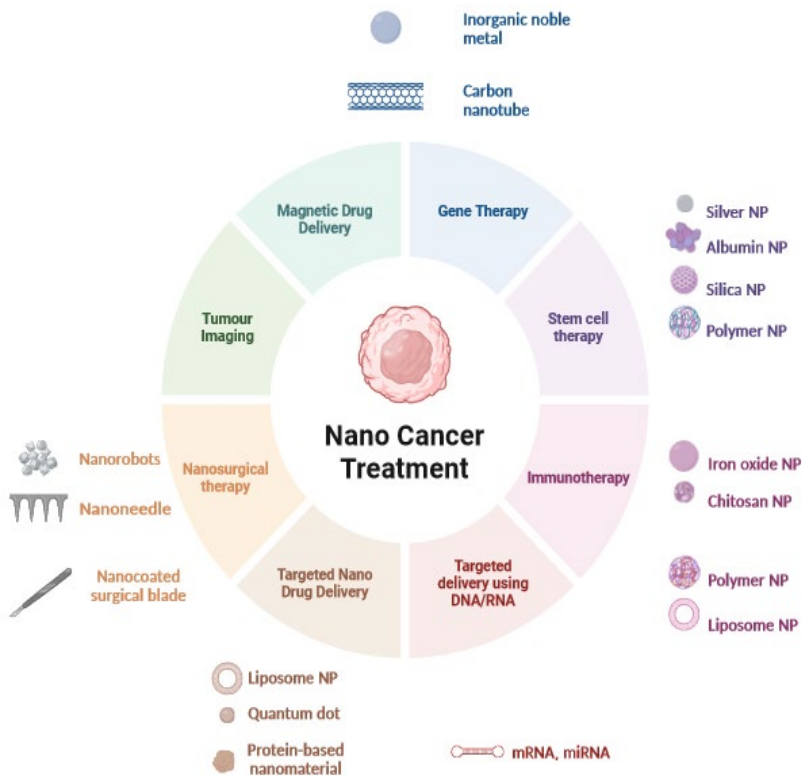


Fig. 1-2 Figure showing nano cancer treatment using different nanomaterials

1.7 Nanomedicine and COVID-19

Nanotechnology played a significant role during the COVID-19 pandemic by aiding in the development of diagnostic tools, treatment techniques, and vaccines. Nanoparticles can bind to the coronavirus, helping in its detection and treatment. They have been used in face masks with antiviral coatings, diagnostic tests, and the development of antiviral drugs and vaccines. The small size and functional properties of nanoparticles make them effective in preventing the virus from entering cells and increasing drug efficacy in treating COVID-19 [Abd Ellah et al.,2020; Gupta et al.,2021; Sharma,2022; Thi et al.,2021; Vahedifard Chakravarthy,2021].