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CHAPTER 11

Synthesis, Applications and Challenges of Nanotechnology in the Field of Science

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Abstract: Nanotechnology has revolutionized various fields of science by offering novel materials with superior properties. This chapter discusses the synthesis of nanoparticles (NPs), their wide-ranging applications, and the challenges associated with their use. Various synthesis techniques, including physical, chemical, and biological methods, are examined. The applications of NPs in medicine, environmental science, and material engineering are highlighted, followed by an analysis of the potential risks and ethical concerns associated with nanotechnology. The chapter concludes with future perspectives on overcoming these challenges for sustainable advancements.

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Introduction

Nanotechnology is the manipulation of matter at the atomic and molecular scale, typically within 1–100 nanometres. It enables the creation of materials with novel properties distinct from their bulk counterparts.[1] The term "nanotechnology" was first introduced by Norio Taniguchi in 1974, describing precision machining at the nanometre level (Taniguchi, 1974)[2]. Since then, nanotechnology has evolved into a multidisciplinary field encompassing chemistry, physics, biology, and engineering[3]. The growing fields of nanoscience and nanotechnology have transformed many sectors of industry, with breakthrough applications in the areas of biotechnology, electronic, cosmetics, food sciences, and pharmaceutics[4–5]. [7]

Nanomaterials exhibit unique physical, chemical, and biological properties due to their high surface-area-to-volume ratio, quantum effects, and enhanced reactivity (Roco, 2011)[8,9]. These properties contribute to their increased strength, electrical conductivity, optical behaviour, and catalytic efficiency compared to conventional materials.[10,11] For instance, gold nanoparticles exhibit unique optical properties due to localized surface plasmon resonance, making them highly effective in biomedical imaging and diagnostics[12–13]. Similarly, carbon nanotubes possess remarkable mechanical strength and electrical conductivity, which have made them essential in nanocomposite materials (Ajayan, 1999)[16–17].

The significance of these properties lies in their potential to revolutionize multiple scientific fields. Their small size allows for precise interactions at the cellular and molecular levels, making them particularly valuable in medicine, environmental science, and material engineering (Kumar et al., 2020).[8,9] Nanoparticles such as silver and zinc oxide exhibit strong antimicrobial properties, leading to advancements in wound healing and infection control (Morones et al., 2005)[21–22]. Quantum dots, another class of nanomaterials, have enhanced the efficiency of solar cells and display technologies due to their tunable electronic and optical properties (Alivisatos, 1996)[25–26].

Nanotechnology has found applications in diverse domains such as drug delivery, water purification,[28,4] and electronic devices[29]. The ability of nanoparticles to enhance targeted drug therapy, catalyze pollutant degradation, and improve mechanical properties in materials highlights their transformative impact on modern science. In medicine, liposomal nanoparticles have improved drug bioavailability, reducing side effects and increasing therapeutic efficacy (Torchilin, 2005[30])[31–32]. In environmental science, nanomaterials like titanium dioxide (TiO_2) are used for photocatalytic degradation of organic pollutants, significantly improving water purification processes (Zhang et al., 2019)[35,36].

However, despite their vast potential, nanotechnology also presents challenges related to toxicity, environmental impact, and ethical concerns. The potential cytotoxicity of nanoparticles raises concerns about their biomedical applications (Nel et al., 2006). Moreover, their environmental persistence and unknown long-term effects necessitate rigorous regulatory frameworks[37,38]. This chapter explores the synthesis techniques, applications, and limitations of nanotechnology in science.

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Synthesis Approaches for Nanoparticles

Synthesis of Nanoparticles

Nanotechnology utilizes materials with unique properties at the nanoscale, finding applications across various scientific fields. Nanoparticles ranging from 1-100 nm, exhibit distinct physicochemical properties dependent on their size, charge, composition and coating [39]. Synthesis methods include top-down and bottom-up approaches, as well as physical, chemical, biological, and hybrid methods [40,39].

Approach of NP Synthesis

1. **Top-down Approach:** NPs are produced by breaking down bulk materials using techniques like polishing and etching.
2. **Bottom-up Approach:** NPs are built from atomic or molecular components, often involving the reduction of metallic compounds [41]. An example includes the reduction of metallic compounds into nanoparticles by fungal enzymes or metabolites. The bottom-up approach is generally more cost-effective, less time-consuming, and yields NPs with higher crystallinity [42].

Types of Nanoparticles

Nanomaterials are classified based on dimension and material composition.

- **Based on Dimension:** Zero-dimensional, one-dimensional, two-dimensional, and three-dimensional nanomaterials.
- **Based on Materials**
  - **Carbon-based:** Fullerenes, carbon nanotubes, graphene, graphene oxide, nanodiamonds, and carbon-based quantum dots.
  - **Inorganic-based:** Metal and metal oxide nanoparticles, including quantum dots and superparamagnetic iron oxide NPs.
  - **Organic-based:** Dendrimers, micelles, and liposomes.
  - **Composite-based:** Multiform structures combining different phases, such as ceramic-matrix, metal-matrix, polymer-matrix, and magnetic nanocomposites.

Synthesis Methods

- **Physical Methods:** Physical methods use mechanical or thermal energy to create nanoparticles [43]. These methods generally involve breaking down bulk materials into nanoscale particles without chemical reactions [44]. Common physical methods include mechanical grinding/milling, evaporation-condensation, laser ablation, and sputtering [45]. Physical methods often require costly equipment, high temperatures, or high pressures [46].

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- **Chemical Methods:** Chemical methods are widespread and efficient for producing metallic nanoparticles [47]. These methods involve chemical reactions to precipitate or grow nanoparticles from precursor materials [43]. Common chemical methods include chemical reduction, the sol-gel method, co-precipitation, and microemulsion/reverse micelle method. While chemical methods are cost-effective and scalable, they often involve toxic chemicals that can be harmful to the environment [47,42].
- **Biological Methods:** Biological methods for NP synthesis are energy-efficient, utilizing microorganisms, plants, and horticultural food waste extracts [39]. Biological synthesis often involves biological compounds found in organisms [48]. The resulting nanoparticles have unique optical, antimicrobial abilities, mechanical properties, and catalytic capabilities [39]. Green synthesis techniques using plant extracts and microorganisms can provide eco-friendly alternatives to conventional chemical synthesis, reducing toxicity and environmental hazards [49].

Applications of Nanotechnology in Science Nanotechnology has had a profound impact on various scientific fields, including:

Medicine and Healthcare Nanotechnology has revolutionized medicine through drug delivery, imaging, and cancer therapy. Nanoparticles enhance drug solubility, bioavailability, and targeted delivery, reducing side effects and increasing therapeutic efficacy (Peer et al., 2007)[50–51]. For instance, lipid-based nanoparticles have been used in mRNA vaccines for COVID-19, demonstrating their significance in modern medicine (Hassett et al., 2021)[53–54]. Additionally, gold and silver nanoparticles have been utilized in biosensors and point-of-care diagnostics, enabling early disease detection (Kalele et al., 2020).[57–58]

Nanomaterials also play a crucial role in regenerative medicine and tissue engineering. Graphene-based nanomaterials have shown promise in bone tissue engineering due to their high mechanical strength and biocompatibility[61,62] (Mahmoudifard et al., 2022). Furthermore, nanocarriers are being developed for gene therapy, providing targeted gene delivery for genetic disorders (Kim et al., 2021).

Environmental Science and Sustainability

Nanotechnology contributes significantly to environmental science by offering solutions for water purification, energy storage, and environmental remediation.

Nanotechnology contributes significantly to environmental science by offering solutions for water purification, air filtration, and pollutant degradation. Titanium dioxide (TiO_2) nanoparticles have been widely used for photocatalytic degradation of organic pollutants in wastewater treatment (Zhang et al., 2019). Moreover, nanostructured membranes enhance desalination processes, improving access to clean water (Wang et al., 2020)[63–36].

In air purification, carbon-based nanomaterials such as graphene oxide have been integrated into air filters to capture pollutants and volatile organic compounds (VOC) (Liu et al., 2022). Additionally,

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nanocatalysts are employed in green energy applications, such as hydrogen production and CO2 reduction, promoting sustainability (Zhu et al., 2023).[65,66]

Agriculture and Food Science

The application of nanotechnology in agriculture has led to advancements in precision farming, pest control, and nutrient delivery. Nano-fertilizers and nano-pesticides offer improved efficiency compared to traditional formulations, reducing environmental pollution (Lal et al., 2021). For example, silica nanoparticles have been used to enhance plant growth and stress resistance (Tripathi et al., 2022).[67–68]

In food science, nano-encapsulation techniques are employed to enhance the stability and bioavailability of nutrients and antioxidants in food products (McClements & Xiao, 2021). Furthermore, nanosensors are integrated into food packaging to detect contaminants and improve food safety (Li et al., 2021)[71–72].

Material Science and Engineering

Nanomaterials have transformed material science by improving mechanical, electrical, and optical properties. Carbon nanotubes and graphene composites have been widely used in lightweight, high-strength materials for aerospace and automotive industries (Bakis et al., 2021). Additionally, quantum dots are being explored for next-generation displays and optoelectronic devices due to their tunable electronic properties (Kagan et al., 2022).[74,75]

In construction, nano-additives such as nano-silica and nano-clay enhance the durability and strength of concrete, reducing infrastructure maintenance costs (Garg et al., 2021). Moreover, self-healing materials integrated with nanocapsules are being developed to repair microcracks autonomously (White et al., 2020).[76,77]

Electronics and Energy Storage

Nanotechnology has led to breakthroughs in energy storage and electronics, enabling the development of high-performance batteries, supercapacitors, and solar cells. Lithium-ion batteries with silicon nanostructures offer higher energy density and faster charging rates (Lu et al., 2022). Furthermore, perovskite quantum dots are revolutionizing solar energy conversion by improving the efficiency of photovoltaic cells (Wang et al., 2023).[78–79]

In flexible electronics, nanomaterials such as silver nanowires and graphene are used in wearable devices, enabling applications in health monitoring and human-machine interfaces (Someya et al., 2022)[81,82]. Additionally, memristors based on nanotechnology are paving the way for neuromorphic computing and next-generation artificial intelligence hardware (Yang et al., 2023).

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Challenges of Nanotechnology in Science

Despite its remarkable advancements, nanotechnology faces several challenges that hinder its widespread adoption and implementation:

Toxicity and Health Risks Many nanoparticles exhibit cytotoxicity and genotoxicity, raising concerns regarding their biomedical applications. Nanoparticles such as silver and carbon nanotubes have shown potential toxicity in in-vitro and in-vivo studies (Nel et al., 2006). The long-term effects of nanoparticle exposure remain unknown, necessitating extensive toxicological studies.[83–84]

Environmental Impact The disposal and accumulation of nanomaterials in the environment pose potential ecological threats. Some nanoparticles, such as titanium dioxide and zinc oxide, can accumulate in aquatic ecosystems, affecting microbial communities and aquatic life (Maynard et al., 2006). The lack of comprehensive environmental impact studies complicates risk assessment and regulation.[86–87]

Ethical and Regulatory Concerns The rapid development of nanotechnology has outpaced regulatory frameworks, leading to uncertainties in safety standards. Ethical concerns arise regarding the unintended consequences of nanomaterials, including their potential use in surveillance, bioengineering, and military applications (Bowman & Hodge, 2007). Developing standardized regulations and ethical guidelines is crucial for responsible nanotechnology implementation.[88]`

High Production Costs The synthesis and large-scale production of nanomaterials remain expensive, limiting their widespread application. Advanced techniques such as atomic layer deposition and chemical vapor deposition require significant energy and resources, making nanotechnology inaccessible for small-scale industries (Khan et al., 2019). Reducing production costs and enhancing scalability are key challenges for future advancements[89,90].

Future Perspectives To overcome the challenges associated with nanotechnology and ensure sustainable advancements, several strategies must be implemented:

1. **Development of Green Synthesis Methods**: Green synthesis techniques using plant extracts and microorganisms can provide eco-friendly alternatives to conventional chemical synthesis, reducing toxicity and environmental hazards (Iravani, 2011).
2. **Advancements in Computational Modeling and AI**: Machine learning and artificial intelligence can enhance nanoparticle design, predict toxicity, and optimize material properties, reducing trial-and-error in synthesis and application (Chan et al., 2021).
3. **Strengthening Regulatory Frameworks**: Governments and regulatory bodies must implement stringent safety protocols and ethical guidelines for nanomaterials. Standardized toxicity assessment methods will ensure safe integration into industries (Kumar et al., 2020).
4. **Public Awareness and Ethical Considerations**: Increasing public awareness and addressing ethical concerns related to nanotechnology applications can foster trust and acceptance.

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Engaging interdisciplinary collaborations will further ensure responsible development (Bowman & Hodge, 2007).

5. **Cost-Effective Manufacturing Techniques**: Scaling up nanomaterial production using cost-efficient techniques such as roll-to-roll nanomanufacturing and 3D printing will make nanotechnology more accessible and commercially viable (Khan et al., 2019).
6. **Interdisciplinary Research and Collaboration**: Collaborative efforts between materials scientists, biologists, and engineers will drive innovation in nanotechnology, leading to breakthroughs in medicine, energy, and environmental sustainability.

These efforts will pave the way for responsible and sustainable integration of nanotechnology into various scientific domains

References

1. J. Hulla, S. Sahu, A. Hayes, Nanotechnology, Vol. 34, SAGE Publishing, 2015, p. 1318.
2. J. J. Ramsden, Nanotechnology: an introduction, Vol. 49, Association of College and Research Libraries, 2012, p. 49.
3. M. Ferreira, J. Filipe, Nanotechnology Applications – The Future Arrived Suddenly, 2018, p. 23.
4. Recent Revolutions in Nanoscience and Nanotechnology with Its Application's, Vol. 3, 2019.
5. J. Filipe, M. Ferreira, Analysis of nanosciences and nanotechnology and their applications, Cornell University, 2021.
6. A.-H. A. Zubair, S. M. Sheshe, M. R. Bashir, S. M. Sade, Lipid Based Drug Delivery System: A Review, Sciencedomain International, 2021, p. 33.
7. S. Onoue, S. Yamada, H. Chan, Nanodrugs: pharmacokinetics and safety, Dove Medical Press, 2014, p. 1025.
8. H.ien M. Darweesh, Nanomaterials: Classification and Properties-Part I, Vol. 1, Royal Society of Chemistry, 2018, p. 1.
9. S. Ameen, In IntechOpen eBooks, IntechOpen, 2020.
10. B. D. Malhotra, Md. A. Ali, In Elsevier eBooks, Elsevier BV, 2017, p. 1.
11. S. P. Patil, V. Burungale, In Elsevier eBooks, Elsevier BV, 2020, p. 17.
12. C. Huang, X. Yin, H. Huang, Y. Zhu, Study of plasmon resonance in a gold nanorod with an LC circuit model, Vol. 17, Optica Publishing Group, 2009, p. 6407.
13. Y. Wu, M. R. K. Ali, K. Chen, N. Fang, M. A. El-Sayed, Gold nanoparticles in biological optical imaging, Vol. 24, Elsevier BV, 2019, p. 120.

ISBN: 978-93-95369-49-7 (electronic) 978-93-95369-48-0 (paperback)|

14. X. Huang, M. A. El-Sayed, Gold nanoparticles: Optical properties and implementations in cancer diagnosis and photothermal therapy, Vol. 1, Elsevier BV, 2010, p. 13.

15. X. Huang, P. K. Jain, I. H. El-Sayed, M. A. El-Sayed, Gold Nanoparticles: Interesting Optical Properties and Recent Applications in Cancer Diagnostics and Therapy, Vol. 2, Future Medicine, 2007, p. 681.

16. J. Sengupta, In Elsevier eBooks, Elsevier BV, 2018, p. 172.

17. N. Wu, Carbon Nanotubes Reinforced Nano-Composite Materials and Their Application in Aeronautics Engineering, Vol. 1, OMICS Publishing Group, 2012.

18. N. G. Sahoo, S. Rana, J. W. Cho, L. Li, S. H. Chan, Polymer nanocomposites based on functionalized carbon nanotubes, Vol. 35, Elsevier BV, 2010, p. 837.

19. R. P. Raffaelle, B. J. Landi, J. D. Harris, S. G. Bailey, A. Hepp, Carbon nanotubes for power applications, Vol. 116, Elsevier BV, 2004, p. 233.

20. S. Radhakrishnan, J. Mathiyarasu, In Elsevier eBooks, Elsevier BV, 2018, p. 187.

21. T. J. Webster, I. Seil, Antimicrobial applications of nanotechnology: methods and literature, Dove Medical Press, 2012, p. 2767.

22. B. Guo, P. Han, L.-C. Guo, Y. Cao, A. Li, J. Kong, H. Zhai, D. Wu, The Antibacterial Activity of Ta-doped ZnO Nanoparticles, Vol. 10, Springer Science+Business Media, 2015.

23. R. Nivethitha, M. Jeevitha, S. Rajeshkumar, S. Jayaraman, Antimicrobial Activity of Zinc Oxide Nanoparticles Synthesized Using Leaves Extract of Abies webbiana, Sciencedomain International, 2021, p. 3702.

24. S. T. Galatage, A. S. Hebalkar, S. V. Dhobale, O. R. Mali, P. S. Kumbhar, S. V. Nikade, S. G. Killedar, In IntechOpen eBooks, IntechOpen, 2021.

25. X. F. Wang, J. Ding, J. Y. Li, H. Jiang, Z. H. Wang, W. Shi, Applications of Quantum Dots in Cancer Research, Vol. 345, Trans Tech Publications, 2011, p. 29.

26. J. Drbohlavová, V. Adam, R. Kizek, J. Hubálek, Quantum Dots — Characterization, Preparation and Usage in Biological Systems, Vol. 10, Multidisciplinary Digital Publishing Institute, 2009, p. 656.

27. L. Liu, Q. Miao, G. Liang, Quantum Dots as Multifunctional Materials for Tumor Imaging and Therapy, Vol. 6, Multidisciplinary Digital Publishing Institute, 2013, p. 483.

28. S. Hasnain, S. S. Ali, Z. Uddin, R. Zafar, Application of Nanotechnology in Health and Environmental Research: A Review, Vol. 5, 2013, p. 160.

29. R.Kanaoujiya, S. K. Saroj, V. D. Rajput, A. Alimuddin, S. Srivastava, T. Minkina, C. A. Igwegbe, M. Singh, A. Kumar, Emerging application of nanotechnology for mankind, Vol. 6, Springer Science+Business Media, 2023, p. 439.

ISBN: 978-93-95369-49-7 (electronic) 978-93-95369-48-0 (paperback)

30. F. de M. Garcia, Nanomedicine and therapy of lung diseases, Vol. 12, Instituto Israelita de Ensino e Pesquisa Albert Einstein, 2014, p. 531.
31. E. Kim, H. Jeong, Liposomes: Biomedical Applications, Vol. 57, 2021, p. 27.
32. N. Lamichhane, T. S. Udayakumar, W. D'Souza, C. B. Simone, S. R. Raghavan, J. Polf, J. Mahmood, Liposomes: Clinical Applications and Potential for Image-Guided Drug Delivery, Vol. 23, Multidisciplinary Digital Publishing Institute, 2018, p. 288.
33. W. Gao, C. J. Hu, R. H. Fang, L. Zhang, Liposome-like nanostructures for drug delivery, Vol. 1, Royal Society of Chemistry, 2013, p. 6569.
34. N. Filipczak, J. Pan, S. S. K. Yalamarty, V. P. Torchilin, Recent advancements in liposome technology, Vol. 156, Elsevier BV, 2020, p. 4.
35. H. Choi, S. R. Al-Abed, D. D. Dionysiou, In Elsevier eBooks, Elsevier BV, 2009, p. 39.
36. I. Gehrke, A. Geiser, A. Somborn-Schulz, Innovations in nanotechnology for water treatment, Dove Medical Press, 2015, p. 1.
37. N. Zhang, G. Xiong, Z. Liu, Toxicity of metal-based nanoparticles: Challenges in the nano era, Vol. 10, Frontiers Media, 2022.
38. G. Martínez, M. Merinero, M. Pérez-Aranda, E. M. Pérez-Soriano, T. Ortíz, E. Villamor, B. Begines, A. Alcudia, Environmental Impact of Nanoparticles' Application as an Emerging Technology: A Review, Vol. 14, Multidisciplinary Digital Publishing Institute, 2020, p. 166.
39. L. Agustina, S. Suprihatin, M. Romli, P. Suryadarma, Current development, potentials, and challenges of biological synthesis of nanoparticle (as a photocatalyst): A review, Vol. 980, IOP Publishing, 2020, p. 12005.
40. V. N. Kalpana, V. D. Rajeswari, In Elsevier eBooks, Elsevier BV, 2017, p. 293.
41. C. Yu, K. Y. Tam, E. Tsang, In Handbook of Metal Physics, Elsevier BV, 2008, p. 113.
42. N. A. Ismail, K. Shameli, N. W. C. Jusoh, R. R. Ali, S. N. A. M. Sukri, E. D. M. Isa, Preparation of Copper Nanoparticles by Green Biosynthesis Method: A Short Review, Vol. 1051, IOP Publishing, 2021, p. 12084.
43. C. Dhand, N. Dwivedi, X. J. Loh, A. N. J. Ying, N. K. Verma, R. W. Beuerman, R. Lakshminarayanan, S. Ramakrishna, Methods and strategies for the synthesis of diverse nanoparticles and their applications: a comprehensive overview, Vol. 5, Royal Society of Chemistry, 2015, p. 105003.
44. T. Cele, Preparation of Nanoparticles, 2020.
45. T. Yokoyama, C. Huang, Nanoparticle Technology for the Production of Functional Materials, Vol. 23, 2005, p. 7.

ISBN: 978-93-95369-49-7 (electronic) 978-93-95369-48-0 (paperback)|

46. Ö. Erdoğan, M. Abbak, G. M. Demirbolat, F. Birtekoçak, M. Aksel, S. Paşa, Ö. Çevik, Green synthesis of silver nanoparticles via Cynara scolymus leaf extracts: The characterization, anticancer potential with photodynamic therapy in MCF7 cells, Vol. 14, Public Library of Science, 2019.

47. P.Szczyglewska, A. Feliczak-Guzik, I. Nowak, Nanotechnology–General Aspects: A Chemical Reduction Approach to the Synthesis of Nanoparticles, Vol. 28, Multidisciplinary Digital Publishing Institute, 2023, p. 4932.

48. R. Álvarez-Chimal, J. Arenas-Alatorre, In IntechOpen eBooks, IntechOpen, 2023. P.213

49. Norah Salem Alsaiari. Plant and Microbial Approaches as Green Methods for the Synthesis of Nanomaterials: Synthesis, Applications, and Future Perspectives. Molecules. 2023 Jan 3; 28(1):463

50. P. S. Shah, Use of Nanotechnologies for Drug Delivery, Vol. 31, Springer Nature, 2006, p. 894.

51. Cao Yu, Global research trends and emerging hotspots in nano-drug delivery systems for lung cancer: a comprehensive bibliometric analysis, Volume 16, article number 33, discover oncology, 2025, p. 1-20

52. S. Malik, K. Muhammad, Y. Waheed, Emerging Applications of Nanotechnology in Healthcare and Medicine, Vol. 28, Multidisciplinary Digital Publishing Institute, 2023, p. 6624.

53. M. S. Khan, S. A. Baskoy, C. Yang, J. Hong, J. Chae, H.-J. Ha, S. Lee, M. Tanaka, Y. Choi, J. Choi, Lipid-based colloidal nanoparticles for applications in targeted vaccine delivery, Vol. 5, Royal Society of Chemistry, 2023, p. 1853.

54. B. Wilson, K. Geetha, Lipid nanoparticles in the development of mRNA vaccines for COVID-19, Vol. 74, Elsevier BV, 2022, p. 103.

55. K. Swetha, N. G. Kotla, L. Tunki, A. Jayaraj, S. K. Bhargava, H. Hu, S. R. Bonam, R. Kurapati, Recent Advances in the Lipid Nanoparticle-Mediated Delivery of mRNA Vaccines, Vol. 11, Multidisciplinary Digital Publishing Institute, 2023, p. 658.

56. E. Musielak, A. Feliczak-Guzik, I. Nowak, Synthesis and Potential Applications of Lipid Nanoparticles in Medicine, Vol. 15, Multidisciplinary Digital Publishing Institute, 2022, p. 682.

57. C. Li, M. Chan, Y. Chang, M. Hsiao, Gold Nanoparticles as a Biosensor for Cancer Biomarker Determination, Vol. 28, Multidisciplinary Digital Publishing Institute, 2023, p. 364.

58. S.Sargazi, U. Laraib, S. E. Zeybekler, A. Rahdar, M. Hassanisaadi, M. N. Zafar, A. M. Díez-Pascual, M. Bilal, Application of Green Gold Nanoparticles in Cancer Therapy and Diagnosis, Vol. 12, Multidisciplinary Digital Publishing Institute, 2022, p. 1102.

59. M. M. Mihai, M. B. Dima, B. Dima, A. M. Holban, Nanomaterials for Wound Healing and Infection Control, Vol. 12, Multidisciplinary Digital Publishing Institute, 2019, p. 2176.

ISBN: 978-93-95369-49-7 (electronic) 978-93-95369-48-0 (paperback)

60. N. R. S. Sibuyi, K. L. Moabelo, A. O. Fadaka, S. Meyer, M. O. Onani, A. M. Madiehe, M. Meyer, Multifunctional Gold Nanoparticles for Improved Diagnostic and Therapeutic Applications: A Review, Vol. 16, Springer Science+Business Media, 2021.

61. N. Dubey, R. Bentini, I. Islam, T. Cao, A. H. C. Neto, V. Rosa, Graphene: A Versatile Carbon-Based Material for Bone Tissue Engineering, Vol. 2015, Hindawi Publishing Corporation, 2015, p. 1.

62. A.Hermenean, S. Dinescu, M. Ioniță, M. Costache, In InTech eBooks, 2016.

63. M.Khraisheh, S. Elhenawy, F. Almomani, M. A. Al-Ghouti, M. K. Hassan, B. H. Hameed, Recent Progress on Nanomaterial-Based Membranes for Water Treatment, Vol. 11, Multidisciplinary Digital Publishing Institute, 2021, p. 995.

64. S. Sarkar, A. Sarkar, C. Bhattacharjee, In Elsevier eBooks, Elsevier BV, 2017, p. 355.

65. S.Sundarrajan, K. L. Tan, S. H. Lim, S. Ramakrishna, Electrospun Nanofibers for Air Filtration Applications, Vol. 75, Elsevier BV, 2014, p. 159.

66. N. Sharma, H. Ojha, A. Bharadwaj, D. P. Pathak, R. K. Sharma, Preparation and catalytic applications of nanomaterials: a review, Vol. 5, Royal Society of Chemistry, 2015, p. 53381.

67. H. Siddiqui, K. B. M. Ahmed, F. Sami, S. Hayat, In Sustainable agriculture reviews, Springer International Publishing, 2020, p. 129.

68. R.Periakaruppan, X. Chen, H. Li, S. Rehaman, P. Vanathi, K. A. Abd–Elsalam, X. Li, In Elsevier eBooks, Elsevier BV, 2020, p. 437.

69. F. Zulfiqar, M. M. R. Navarro, M. Ashraf, N. A. Akram, S. Munné-Bosch, Nanofertilizer use for sustainable agriculture: Advantages and limitations, Vol. 289, Elsevier BV, 2019, p. 110270.

70. S. S. Patil, S. S. Balpande, M. Sajid, M. R. Pandao, Green Synthesis and Characterization of Nano Phosphorus Fertilizer for Wheat, Vol. 9, Excellent Publishers, 2020, p. 19.

71. M. Shafiq, S. Anjum, C. Hano, I. Anjum, B. H. Abbasi, An Overview of the Applications of Nanomaterials and Nanodevices in the Food Industry, Vol. 9, Multidisciplinary Digital Publishing Institute, 2020, p. 148.

72. I. J. Joye, M. G. Corradini, L. M. Duizer, B. M. Bohrer, G. LaPointe, J. Farber, P. A. Spagnuolo, M. A. Rogers, A comprehensive perspective of food nanomaterials, Elsevier BV, 2019, p. 1.

73. L. Mei, Q. Wang, Advances in Using Nanotechnology Structuring Approaches for Improving Food Packaging, Vol. 11, Annual Reviews, 2020, p. 339.

74. T.Sankaramoorthy, A. B. K. Bharathi, K. G. Thirugnanasambantham, R. Karthikeyan, Study of graphene epoxy composites and its recent development in nano science, Vol. 45, Elsevier BV, 2020, p. 2228.

ISBN: 978-93-95369-49-7 (electronic) 978-93-95369-48-0 (paperback)|

75. A. Kausar, Technical imprint of polymer nanocomposite comprising graphene quantum dot, Vol. 58, Taylor & Francis, 2019, p. 597.

76. E. M. Abdelsalam, M. Samer, A. Seifelnasr, M. A. Moselhy, H. Ibrahim, M. Faried, Y. A. Attia, Effects of Al2O3, SiO2 nanoparticles, and g-c3n4 nanosheets on biocement production from agricultural wastes, Vol. 13, Nature Portfolio, 2023.

77. H. Saleem, S. J. Zaidi, N. A. Alnuaimi, Recent Advancements in the Nanomaterial Application in Concrete and Its Ecological Impact, Vol. 14, Multidisciplinary Digital Publishing Institute, 2021, p. 6387.

78. B. Li, Y. Meng, W. Tang, The role of nanotechnology in the design of materials for Lithium-ion battery, Vol. 308, EDP Sciences, 2021, p. 1009.

79. B. Kurc, M. Pigłowska, Ł. Rymaniak, P. Fuć, Modern Nanocomposites and Hybrids as Electrode Materials Used in Energy Carriers, Vol. 11, Multidisciplinary Digital Publishing Institute, 2021, p. 538.

80. J. Liu, Perovskite Cells Based on Carbon Quantum Dots: Structure, Optimization, Vol. 27, 2022, p. 540.

81. J. Kwon, Y. D. Suh, J. Lee, P. Lee, S. Han, S. Hong, J. Yeo, H. Lee, S. H. Ko, Recent progress in silver nanowire based flexible/wearable optoelectronics, Vol. 6, Royal Society of Chemistry, 2018, p. 7445.

82. H. Sohn, C. Park, J. Oh, S. W. Kang, M. Kim, Silver Nanowire Networks: Mechano-Electric Properties and Applications, Vol. 12, Multidisciplinary Digital Publishing Institute, 2019, p. 2526.

83. A. Adhikari, J. Sengupta, Toxicity of Carbon Nanomaterials, 2021.

84. R. Singla, C. Sharma, A. K. Shukla, A. Acharya, Toxicity Concerns of Therapeutic Nanomaterials, Vol. 19, American Scientific Publishers, 2018, p. 1889.

85. J. E. Perez, N. Alsharif, A. I. Martínez-Banderas, B. Othman, J. S. Merzaban, T. Ravasi, J. Kosel, In InTech eBooks, 2018.

86. Waseem S. Khan, Eylem Asmatulu, Ramazan Asmatulu, Nanotechnology emerging trends, markets and concerns,Nanotechnology safety, second edition, 2025, p. 1-21

87. Y. Zhu, X. Liu, Y. Hu, R. Wang, M. Chen, J. Wu, Y. Wang, S. Kang, Y. Sun, M. Zhu, Behavior, remediation effect and toxicity of nanomaterials in water environments, Vol. 174, Elsevier BV, 2019, p. 54.

88. D. E. Babatunde, I. H. Denwigwe, O. M. Babatunde, S. L. Gbadamosi, I. P. Babalola, O. Agboola, Environmental and Societal Impact of Nanotechnology, Vol. 8, Institute of Electrical and Electronics Engineers, 2019, p. 4640.

ISBN: 978-93-95369-49-7 (electronic) 978-93-95369-48-0 (paperback) |

89. W. S. Ebhota, T. Jen, In IntechOpen eBooks, IntechOpen, 2019.

90. J. M. Köhler, Challenges for Nanotechnology, Vol. 1, Multidisciplinary Digital Publishing Institute, 2021, p. 618.

ISBN: 978-93-95369-49-7 (electronic) 978-93-95369-48-0 (paperback)|