fortune Journals

Research Article

JOURNAL OF NANOTECHNOLOGY RESEARCH

ISSN: 2688-8521

Nanotechnology Applications in Healthcare with Emphasis on Sustainable Covid-19 Management

Frederick A Adrah[1], Mawulorm KI Denu[2*], Maame Araba E Buadu[3]

Abstract

Nanotechnology is an inter-disciplinary branch of science and technology that focuses on the manipulation of matter on the nanoscale, usually between 1-100 nanometers. Nanotechnology blends various aspects of materials science, electrical/electronic engineering, biology, chemistry, physics and computer science to create a synergy of knowledge to improve modern science. The human race was hit hardly during the COVID-19 pandemic, which led to the loss of millions of lives across the globe and has created long-lasting socio-economic problems. Nanomaterials, based on their completely unique properties after fabrication have played a vital role in healthcare, especially combating the coronavirus. This has been achieved through advances in vaccines, drug delivery, diagnostics and personal protective equipment (PPE) for healthcare workers. Scientists must sustain the success of nanotechnology applications in COVID management. This can be achieved by focusing on the applications of nanotechnology that can specifically combat the coronavirus.

Keywords: Nanotechnology; Nanoscale; Fabrication; Nanomaterials

Introduction

Nanotechnology has been critical over the last 30 years with important interventions in global health [1]. This has resulted in brighter prospects in Nano medicine, as well as newly invented terminologies such as "Nano biotechnology" which blends nanotechnology and molecular biology. Nano biotechnology is a field of Nano science research that focuses on fabricating functional nano scale materials by utilizing both chemical and physical techniques. These advancements in research and technology have been geared towards top-notch breakthroughs in the healthcare space. This is because nano materials have distinctive optical, electrical, biological, chemical and magnetic properties [2]. The COVID-19 pandemic resulted in many accelerated applications of nanotechnology in diagnostics and disease management [3]. A holistic and all-inclusive approach to managing the virus will lead to a sustainable outcome based on scientific research. Various methods of nanotechnology can be applied in managing the COVID-19 pandemic in areas such as patient care, co-morbidity management, diagnostics and the design and production of superior Personal Protective Equipment (PPE). Frontline workers are at an increased risk of being infected by the SARS-CoV-2 virus and it is vital to take them into consideration when researching ways of mitigating COVID-19. Although it is pertinent to protect health workers, limited education and awareness, inadequate and less efficient PPEs and point-of-care diagnostic kits have often caused a further spread of the virus in the healthcare setting [4]. Detecting the virus early is more important than treatment. Hence, scientists need to investigate more advanced

Affiliation:

[1]Joint School of Nanoscience and Nanoengineering, University of North Carolina Greensboro, NC, USA

[2]Division of Cardiovascular Medicine, University of Massachusetts Chan Medical School, Worcester, MA, USA

[3]Division of Gastroenterology, Massachusetts General Hospital, Boston, MA, USA

***Corresponding author:**
Mawulorm KI Denu, Division of Cardiovascular Medicine, University of Massachusetts Chan Medical School, Worcester, MA, USA.

Citation: Frederick A Adrah, Mawulorm KI Denu, Maame Araba E Buadu. Nanotechnology Applications in Healthcare with Emphasis on Sustainable Covid-19 Management. Journal of Nanotechnology Research. 5 (2023): 06-13.

Received: April 15, 2023
Accepted: April 20, 2023
Published: May 03, 2023

Adrah FA, et al., J Nanotechnol Res 2023
DOI:10.26502/ jnr.2688-85210037

diagnostics that are more time efficient and less cumbersome using nanotechnology-based approaches [5].

Background of Nanotechnology in Healthcare

The foundation of nanotechnology was forged on medical and human interventions, albeit with several other contemporary industrial applications today. The foundations of nanotechnology were laid by Richard Feynman in a dinner speech in 1959 where he theorized the exploration of manipulating materials at the atomic and molecular level. He observed that through nanoengineering, new materials could be fabricated similar to the biological system [19]. Nanotechnology made more progress in the 1980s where tracking of atoms led to the creation of materials on the nanoscale. Progress was made in healthcare, therapeutics, medicine, organic chemistry and biomaterials. This made it easier to diagnose more complex diseases and widen research on viral and bacterial pathogenesis [20]. Numerous uses of nanotechnology have been investigated, including advanced water purification, which can lead to sustainable development. This has the ability to benefit humanity and shows that nanotechnology is not only a technical engineering discipline [21]. Nanotechnology has a broad range of applications including treatment and prevention of tissue damage, pain management, water purification and monitoring patient health. Nursing has benefitted from this, especially in curbing infectious diseases where Silver nanoparticles (AgNPs) are deposited on surfaces of medical equipment and wears to inhibit the spread and growth of microorganisms [22]. Presently, nanomedicine has become innovative due to the advantages of using nanoparticles in drug delivery. These nanoparticles are minuscule in size and are made of biodegradable materials in most instances. The efficacy of these drug delivery techniques is reliant on the particle size, large surface area and bioavailability. Incorporating nanoparticles also allow drugs to cross the blood-brain barrier with much more ease and these drugs effortlessly able to enter the endothelium of tumors and the pulmonary system [23].

Nano materials and their Properties

A nanomaterial is essentially any material with at least one dimension in the nanoscale range (1-100 nanometers). Due to their special physicochemical features such as thermal and electrical conductivity, and catalytic properties, they have been applied in various industries [24]. Nanomaterials can be categorized as nanostructured elements where at least one of the basic elements has an outer dimension within 1-100nm; or categorized as nanostructured materials where the entire building blocks are nanoscale. Nanomaterials possess characteristics far distinct from other general materials. An example is depicted in the measurement of the flexural and compressive strength of cement mortar using nano-silica (SiO_2). When measured 28 days later, the nano-induced mortar had superior strength than that of the blank group [25]. Carbon nanomaterials have shown to be vital and received extensive reviews due to the remarkable properties of high mobility, super electrical conductivity and thermal stability. These have been harnessed and applied in bio-sensing to manufacture more efficient and precise diagnostic kits [26]. The special properties of these carbon-based nanoparticles such as greater flexibility and electrical conductivity make them appropriate for use in biological systems. This is observed in carbon nanotubes and graphite sheets where the cylindrical orientation leads to more elasticity. Intrinsic features are also heavily observed in fullerenes, which is a big player in cancer research [27]. Due to all these properties, nanomaterials have been particularly applied extensively to solve health problems. Continuous research has also been important in the selection of nanomaterials based on their properties, as evident in Graphene which has been found to be advantageous over Carbon nanotubes and metal nanoparticles [28]. Researchers have also show than the properties of graphene-based nanomaterials can be enhanced using sulfide nanoparticles to increase anti-bacterial activity [29]. Graphene-based nanomaterials have thus been preferred in the fabrication of bio-sensors to aid medical diagnostics [30]

Broad-Spectrum Applications of Nanotechnology in Healthcare

While the focus of this paper is to examine and review nanotechnology applications in COVID-19 management as a subset of healthcare, it is important to review the general applications of nanotechnology in other aspects of healthcare management.

Nutrition- Many antioxidant nutrients and food components get dissipated on their way to their target tissues and do not arrive in their pure form [6]. Nano-concepts can be applied in nutrient delivery to improve the health and fitness of not only athletes, but all human life, especially in weight management. Nanotechnology can used to alter the quality, taste and coloration of food and examine micro-organisms. Through these concepts, the study of food disorders, physiology and nutrient metabolism can be enhanced [7].

Dentistry- Nano-dentistry is a modern developing field that has the potential of using mechanical nano-robotic dentifrices for oral health care. This can be applied in native anesthesia to remedy ailments of teeth hypersensitivity and make orthodontic re-adjustments. These interventions can save a trip to the dentist as microbes that cause teeth decay can be immobilized [7]. Modern research has also found Silver Nanofluoride (NSF) to be beneficial in the dental care of infants [8].

HIV/AIDS- Nanocarriers can improve the intra-cellular transmission of anti-retroviral drugs to the central nervous

Adrah FA, et al., J Nanotechnol Res 2023
DOI:10.26502/ jnr.2688-85210037

system. The use of nanotechnology has prospects for improving traditional vaccines used for HIV/AIDS prevention and treatment [9]. Nanomaterials have also been found to reduce the toxicity of HIV/AIDS vaccines. Nanoparticles, due to their unique properties also have the ability to hinder virus replication by interfering with the assembly process and hence neutralizing it [10].

COVID-19 vaccines- The COVID vaccines have likely evolved the fastest in the history of vaccine developments, and over 180 are still in clinical trials [11]. To create a powerful and effective anti-coronavirus vaccine and medication compounds, numerous research laboratories and pharmaceutical corporations are engaged in continuous research and development. Various methodologies used include conventional vaccines, sub-unit vaccinations and nucleic acid-based vaccines. Nanotechnology-based drugs and vaccine delivery systems based on nanoparticles have also been adopted as viable strategies [12].

Medical diagnostics- Nanotechnology is being applied in biomedical engineering to develop nano-enabled imaging diagnostic tools and nano-sensors. The US Food and Drug Administration (FDA) accepted the use of Iron oxide (Fe_2O_3) nanoparticles as contrast agents to enhance magnetic resonance imaging years ago [13]. This complements the efforts of medical practitioners in managing disease prognosis, which are pertinent factors in determining the survival rate of patients. Nano-sensors can also be applied in cancer research where there is on-going work in applying nanoparticles for molecular and biochemical sensing [14]. Numerous nanoparticles have been used to detect infection on site. Gold nanoparticles (AuNP) are one of the most widely used nanoparticles for quick diagnostics [15].

Drug delivery- One of the significant elements in administering drugs to cure diseases is to find the most appropriate drug delivery mechanism. Nanotechnology offers breakthrough in advanced drug delivery [16]. Through nanomedicine, superior mechanisms of drug delivery such as liposomes, niosomes and nanoshells have been used for controlled targeted drug delivery [17]. The advantages are numerous including extended circulation time, less side-effects and enhanced pharmacokinetic clearance of the drugs from the human body; this has been crucial in patients who have a higher risk of contracting viral diseases and may be immunocompromised [18].

Nano medicine

As a branch of nanotechnology that focuses on drug delivery and therapeutics, the contemporary evolution of Nano medicine has seen improvements in cancer therapy where tumors can be targeted to minimize system toxicity. Various Nano medicines have subsequently been engineered chemically, biologically and physically [31]. Delivering drugs through Nano carriers offers more advantages than through the traditional methods. Some obstacles that are surmounted are poor bioavailability, systemic toxicity and short half-life in the body [32]. The future of healthcare breakthrough is dependent on the progress of scientific research in nano medicine, a term which sprung out of nano biotechnology. For patients to benefit more from nano medicine, various science disciplines such as materials science, cellular biology and genetic engineering must be blended to give rise to cutting-edge technology [33]. This has been evident in the advances made in developing fullerenes and nanodiamonds, which are both allotropes of Carbon. Due to the uniqueness of the nanostructure of fullerenes, they can be used as nanocarriers for targeted drug delivery in tissues and specific cells of the human body [34]. The potential of nanomedicine has been so revealing that, nanoscientists have marked it as a solo field in itself. This case is buttressed by innovations such as the chemotherapy drug Doxil© which has received FDA approval in the United States. Other similar nano-therapeutic innovations have been used in tackling heart disease through non-invasive procedures and full-scale cancer treatments [35].

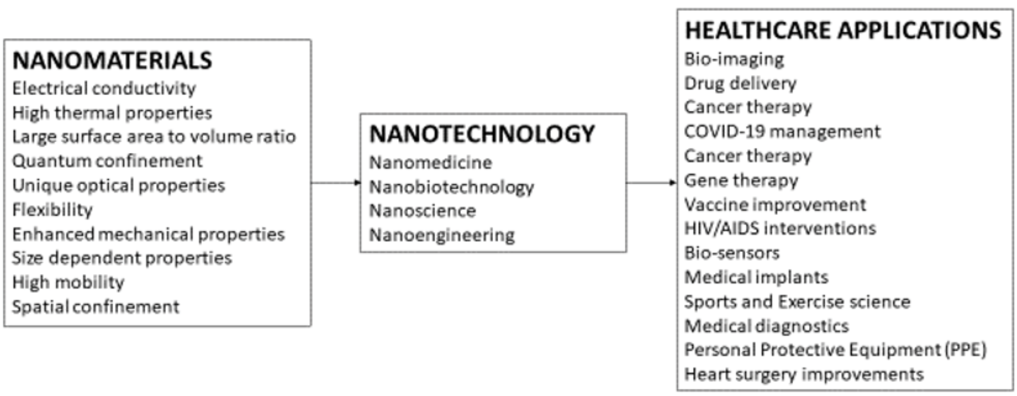

Figure 1: Representation of the broad properties of nanomaterials and the healthcare applications of nanotechnology.

Adrah FA, et al., J Nanotechnol Res 2023
DOI:10.26502/ jnr.2688-85210037

Nanotechnology Applications in Covid-19 Management

The first reportage of coronavirus related illnesses in humans was in 2003 with the outbreak of the Severe Acute Respiratory Syndrome (SARS). The second outbreak was the Middle East Respiratory Syndrome (MERS) which was first detected in Saudi Arabia. Coronaviruses have been devastating to humans and the global economy; which was further compounded by the COVID-19 outbreak in 2019, out of Wuhan, China [36]. Although the world is not fully out of the woods from the COVID-19 virus, several interventions across the scientific scope have been essential in mitigating the spread. There is ample space for nano interventions to be applied in vaccine improvement, PPE and treatment. Vaccination remains the best strategy for preventing viral illnesses. At the peak of the pandemic, lipid nanoparticles were used in both Moderna and Pfizer mRNA vaccine to relay the mRNA that encodes the protein spike of SARS-CoV-2. This was a breakthrough in blending nanotechnology and the mRNA technique [37]. The focal benefits of applying nanotechnology in vaccine development is their nano-size. The biological properties of the SARS-CoV-2 and familiar proteins are also in the nano-range. Additionally, nanoparticles can be delivered using intranasal, subcutaneous and oral routes, which overcome the challenges encountered when bypassing tissue barriers or targeting lymph nodes [38]. The application of nanotechnology in COVID management is recognized globally, and aside rapid vaccine developments, several therapeutic agents have been developed over the years [39]. The physiochemical properties of nanomaterials means they can play the role as carriers for the vaccine delivery or adjuvants in formulating the vaccine. Adjuvants are molecules that are delivered in conjunction with the vaccine to stimulate the immune system by activating other receptors to recognize pathogen signals [40]. It has been recognized that, nanovaccines have attributes that overcome the drawbacks of conventional vaccines. This is because nano-systems are designed to prevent the decay of subunit vaccines and increase the efficiency of their delivery. An example is poly (lactic-co-glycolic acid) which has gotten FDA approval and operates as a carrier for the targeted delivery of immunogenic biomolecules [41]. The most widely used method of testing the SARS-CoV-2 has been the reverse transcription polymerase chain reaction (RT-PCR). This is to detect the viral presence through oropharyngeal or nasopharyngeal swabs. Nano-biosensors can offer a cheaper and less cumbersome alternative to conventional testing regimes. As discussed earlier, these sensors harness the unique electrical and optical properties of nanomaterials to combine with synthetic molecules to detect the selectivity of any analyte [42]. Such interventions when applied will enhance the global response to the coronavirus. Additionally, nanomaterials such as quantum dots (QDs), Graphene Oxide (GO) and nanodiamonds have potential for use in the filtration of viral load from air and water. Activated Carbons can further be used in water purification and adsorption processes to kill coronaviruses in a safe manner [43]. Researchers have opined that one of the most encouraging prospects of nanotechnology is in the biomedical field [44]. Nanofibers, nanocomposites and nanoparticle technology can be embedded in the production of masks to increase efficiency while make breathing far easier. Breathability has been a societal problem in mitigating the corona virus pandemic. Nanofibers can also be used in air filtration and purification systems to offer solutions in hospitals, airports and environmental health care spaces [45]. The World Health Organization (WHO) has stated that all health personnel must address all fluids from patients as sources of infection. However, air, mouth and nose droplets, as well as close contact are the main transmission-based sources. It is also almost impossible to totally regulate and determine human responses to health protocols, such as proper wearing of masks, regular hand washing and isolation. Thus, nanotechnology-based approaches which include environmental interventions will be critical in sustainable COVID-19 management [46].

Scientists are continually researching the most efficient inter-disciplinary preventive, diagnostic and treatment methods for the COVID pandemic, including advances in nanotechnology. Nano-based technologies have now been identified as the most effective tool to finally end the pandemic and sustain the gains. Presently, many pharmaceutical companies are focusing on nanotechnology for vaccine development to combat the SARS-CoV-2 [48].

Personal Protective Equipment (Ppe)

The use of all kinds of PPE increased, especially at the onset of the pandemic. Stereolithographic methods were utilized in 3D printing for mass production of masks for the public. Although having many advantages, such methods can be improved using nanotechnology [49]. Experts have agreed that in the long-term sustainable management of COVID-19, we will all need safer PPE to enforce the prevention and treatment [50]. Currently, PPE are making use of internet of things (IoT) technology in their design, based on the scope and type of industry. PPE design for healthcare personnel, law enforcement and construction workers are inherently different since the kinds of hazards posed to each industry is different. However, there are ingrained standards that cut across for all PPE. At the heart of Smart PPE is the human activity monitoring functions which make use of nanotechnology, embedded systems and sensing technologies [51]. Researchers have highlighted the importance of anti-viral PPEs in combating the pandemic. Super hydrophobic surgical masks have been developed by adding a layer of Graphene through Laser induced forward transfer (LIFT) mechanisms. When the mask is exposed in the open air to

fortune Journals
Adrah FA, et al., J Nanotechnol Res 2023
DOI:10.26502/ jnr.2688-85210037

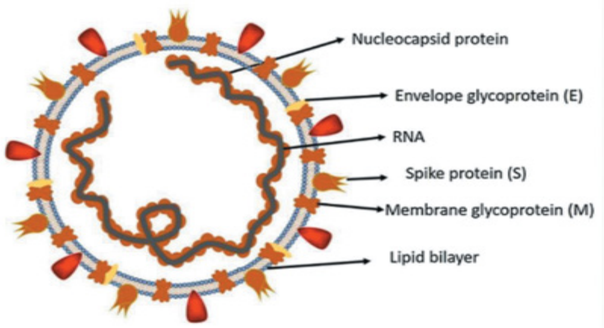

Figure 2: Structure of the Human corona virus (Adapted from Shereen et al [47]: an open source article)

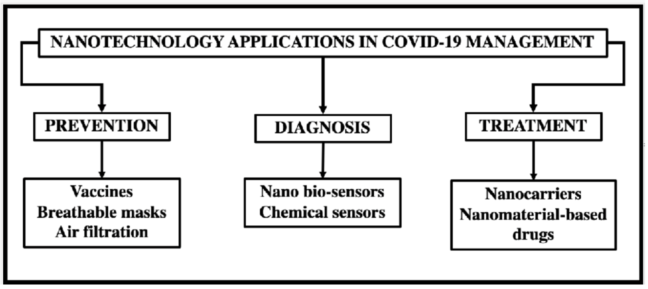

Figure 3: Representation of Nanotechnology applications in COVID-19 management

sunlight for 15 minutes, the surface temperature exceeds 80 degrees Celsius/ 176 Fahrenheit, which is able to sterilize SARS-CoV-2 [36]. Additionally, PPE gears of health personnel including masks and protective eye glasses can be coated with magnetic nanoparticles. These nano-coated equipment offer bright prospects for shielding healthcare workers in the discharge of their duties [52].

Safety, Ethical and Regulatory Considerations

As an emerging and highly sophisticated field of medicine, there remains many safety and ethical concerns about the applications of nanomedicine. There is no doubt that nanomaterials can be unsafe for use in humans [53]. Increased rate of adverse events, anaphylaxis and long-term toxicity can pose crucial safety concerns. The FDA has given warnings about the adverse events associated with ferumoxytol use for MRIs [54]. Carbon-based nanomaterials have been associated with increased risk of mesothelioma [55]. Gold and Silver-based nanoparticles have also been associated with levels of toxicity [56]. The safety concerns may hinder the fast adoption of nanomedicine inventions. Researchers have worked to reduce the toxicity of nanomaterials for medical use. For example, changing the size of gold nanoparticles have been shown to reduce toxicity [57]. There remains safety concerns about the COVID-19 vaccines already developed [58] and their use in mass vaccination programs in many countries [59]. The amplification of nanoparticles in further development of products for COVID treatment will raise more concerns. Ethical considerations also remain a problem with nanomedicine adoption. Nanomedicine has the potential to deepen health disparity across social classes and among nations in global health. The pricing of products developed from nanomaterials will be the main ethical concern. While the COVID-19 pandemic has shown that there is a need for increased health care information sharing, fair trade agreements and sharing of intellectual property rights, investments made in nanomedicine in the past have led to worsening of these problems [60]. The use of nanomedicine products from enhancements, rather than for therapeutic purposes is also a concern. It has implications in competitive sports and sports medicine, cosmetic medicine and cognition and neurology. Regulation of nanomedicine is lacking in many countries. The complex and fast pace means regulators are playing catch-up with industry innovators in nanomedicine. A lack of experts in this field is also a major challenge for regulators, even in advanced countries. A lack of well-developed assessment structures for risk assessment and management compound these ethical issues [60].

Future Outlook of Nano technology in Covid-19 Management

Nanomedicine offers a bright future in the management and prevention of mortality and spread of COVID-19. Efforts with vaccine development have been fruitful in part due to nanomedicine advances. The efforts for therapeutics for medications have not been as successful globally as that for vaccine development. The future holds promise of employing nanomedicine processes and techniques in developing efficacious medicines for viral infections including COVID-19. The main promise though remains the promise of research into nanomedicine techniques that will lead to a reduction in the cost of production of many products employed in the fight against COVID-19 including testing, imaging, follow-up and monitoring of sequelae of many complications of COVID-19 including Long COVID.

Challenges

Financing of nanomedicine techniques is one of the biggest challenges in the area. Developing these products are costly, require highly skilled labor and can be painfully slow. Decades of research and work are often required to make major breakthroughs. Regulation and slow adoption of nanomedicine products is another major challenge. The long and undulating process of clinical trials needed to get validation and approval of the products are also major roadblocks. Few governments understand nanomedicine and provide support to researchers working in the area. This is further burdened by the lack of a regulatory framework that promotes the research into nanomedicine.

Conclusion

Nanotechnology is a rapidly progressing field of engineering and medicine that holds that key to advancing medical care in many areas. Nanomedicine was particularly instrumental in the development of vaccines, testing and therapeutics during the COVID-19 pandemic. Despite the many challenges that it faces, nanotechnology remains key to uncovering many innovative interventions in furthering the fight against the COVID-19 virus.

References

1. F Salamanca-Buentello, AS Daar. Nanotechnology, equity and global health. Nature Nanotechnology 16 (2021): 358–361.
2. S Anjum, et al. Emerging applications of nanotechnology in healthcare systems: Grand challenges and perspectives. Pharmaceuticals 14 (2021): 707.
3. R Medhi, P Srinoi, N Ngo, et al. Nanoparticle-based strategies to combat COVID-19. ACS Applied Nano Materials 3 (2020): 8557–8580.
4. MK Ahmed, M Afifi, V Uskoković. Protecting healthcare workers during COVID-19 pandemic with nanotechnology: a protocol for a new device from Egypt. Journal of infection and public health 13 (2020): 1243-1246.
5. KR Chaudhary, S Kujur, K Singh. Recent Advances of Nanotechnology in COVID 19: A critical review and future perspective. OpenNano (2022): 100118.
6. S Nickols-Richardson, K Piehowski. Nanotechnology in nutritional sciences. Minerva Biotecnologica 20 (2008): 117.
7. S Modi, et al. Recent trends in fascinating applications of nanotechnology in allied health sciences. Crystals 12 (2022): 39.
8. MS Dhaliwal, KS Nat, GS Waraich. Silver Nanoparticles and Its Application in Pediatric Dentistry: A Review.
9. P Yatham, M Nair, A Kaushik. Nanotechnology in Treating HIV in the Brain. Nanoscience & Nanotechnology-Asia 10 (2020): 93-94.
10. Y Liu, C Chen. Role of nanotechnology in HIV/AIDS vaccine development. Advanced Drug Delivery Reviews 103 (2016): 76-89.
11. B Hashemi, et al. Emerging importance of nanotechnology-based approaches to control the COVID-19 pandemic; focus on nanomedicine iterance in diagnosis and treatment of COVID-19 patients. Journal of Drug Delivery Science and Technology 67 (2022): 102967.
12. PK Prabhakar, et al. Aspects of Nanotechnology for COVID-19 Vaccine Development and Its Delivery Applications. Pharmaceutics 15 (2023): 451.
13. MR Bashir, L Bhatti, D Marin, et al. Emerging applications for ferumoxytol as a contrast agent in MRI," Journal of Magnetic Resonance Imaging 41 (2015): 884-898.
14. V Leso, L Fontana, I Iavicoli. Biomedical nanotechnology: Occupational views. Nano Today 24 (2019): 10-14.
15. HA Owida, JI Al-Nabulsi, NM Turab, et al. Nanotechnology role development for COVID-19 pandemic management. Journal of Nanotechnology 2022 (2022): 1-12.
16. S Mohanan, X Guan, M Liang, et al. Stimuli-Responsive Silica Silanol Conjugates: Strategic Nanoarchitectonics in Targeted Drug Delivery. Small (2023): 2301113.
17. MH Ansari, SS Yadav, Nanotechnology: Reviewing the New Concept of Drug Delivery. Int J Med Phar Sci 13 (2023): 1.
18. AE Peter, B Sandeep, BG Rao, et al. Nanotechnology to the rescue: treatment perspective for the immune dysregulation observed in COVID-19," Frontiers in Nanotechnology 3 (2021): 644023.
19. NA Ochekpe, PO Olorunfemi, NC Ngwuluka. Nanotechnology and drug delivery part 1: background and applications. Tropical journal of pharmaceutical research 8 (2009): 3.
20. B Mubeen, et al. Nanotechnology as a novel approach in combating microbes providing an alternative to antibiotics. Antibiotics 10 (2021): 1473,.
21. M Sajeer. Unveiling philosophy and social aspects nanotechnology-A short review (2022).
22. BT Dikmen, E Bağriaçik, MY van Giersbergen. Knowledge and awareness of nursing students on the use of nanotechnology in healthcare. Acta Paulista de Enfermagem 35 (2022).
23. ZM Mazayen, AM Ghoneim, RS Elbatanony, et al. Pharmaceutical nanotechnology: from the bench to the market," Future Journal of Pharmaceutical Sciences 8 (2022): 12.
24. G Cao. Nanostructures & nanomaterials: synthesis, properties & applications. Imperial college press (2004).
25. Q Wu, W Miao, Y Zhang, et al. Mechanical properties of nanomaterials: A review," Nanotechnology Reviews 9 (2020): 259-273.
26. N Nesakumar, S Srinivasan, S Alwarappan. Graphene quantum dots: Synthesis, properties, and applications to the development of optical and electrochemical sensors for chemical sensing. Microchimica Acta 189 (2022): 258.

Adrah FA, et al., J Nanotechnol Res 2023
DOI:10.26502/ jnr.2688-85210037

27. NB Fernandes. et al. Fullerenes for the treatment of cancer: an emerging tool," Environmental Science and Pollution Research 29 (2022): 58607-58627.
28. C Santhosh, V Velmurugan, G Jacob, et al. Role of nanomaterials in water treatment applications: a review," Chemical Engineering Journal 306 (2016): 1116-1137.
29. P Kumar, P Huo, R Zhang, et al. Antibacterial properties of graphene-based nanomaterials. Nanomaterials 9 (2019): 737.
30. EF Marondedze, LO Olasunkanmi, A Singh, et al. Emerging Nanomaterials in Healthcare," Emerging Nanomaterials and Their Impact on Society in the 21st Century 135 (2023): 284-303.
31. J Liao, et al. Physical-, chemical-, and biological-responsive nanomedicine for cancer therapy. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology 12 (2020): e1581.
32. S Jindal, P Gopinath. Nanotechnology based approaches for combatting COVID-19 viral infection. Nano Express 1 (2020): 022003.
33. S Logothetidis. Nanomedicine: the medicine of tomorrow. Nanomedicine and Nanobiotechnology (2012): 1-26.
34. BH Al-Tamimi, SB Farid. Fullerenes and Nanodiamonds for Medical Drug Delivery. Materials at the Nanoscale (2021): 85.
35. S Massaro, G Lorenzoni. Nanomedicine: a socio-technical system. Technological Forecasting and Social Change 173 (2021): 121066.
36. G Muthiah, et al. Nanotechnology Toolkit for Combating COVID-19 and Beyond. ChemNanoMat 8 (2022): e202100505.
37. C Xu, C Lei, S Hosseinpour, et al. Nanotechnology for the management of COVID-19 during the pandemic and in the post-pandemic era," National Science Review 9 (2022): 124.
38. G Chauhan, MJ Madou, S Kalra, et al. Nanotechnology for COVID-19: therapeutics and vaccine research. ACS nano 14 (2020): 7760-7782.
39. A Dube, S Egieyeh, M Balogun. A Perspective on Nanotechnology and COVID-19 Vaccine Research and Production in South Africa. Viruses 13 (2021): 2095.
40. YH Chung, V Beiss, SN Fiering, et al. COVID-19 vaccine frontrunners and their nanotechnology design," ACS nano 14 (2020): 12522-12537.
41. A Hasanzadeh, et al. Nanotechnology against COVID-19: Immunization, diagnostic and therapeutic studies. Journal of Controlled Release 336 (2021): 354-374.
42. C Weiss. et al. Toward nanotechnology-enabled approaches against the COVID-19 pandemic. ACS nano 14 (2020): 6383-6406.
43. E Ruiz-Hitzky, et al. Nanotechnology responses to COVID-19. Advanced healthcare materials 9 (2020): 2000979.
44. SS Ray, J Bandyopadhyay. Nanotechnology-enabled biomedical engineering: Current trends, future scopes, and perspectives. Nanotechnology Reviews 10 (2021): 728-743.
45. V Valdiglesias, B Laffon. The impact of nanotechnology in the current universal COVID-19 crisis. Let's not forget nanosafety!. Nanotoxicology 14 (2020): 1013-1016.
46. A Maher, MS Abdo, HS Abdo. Nanotechnology-Enhanced Face Masks: Future Scopes and Perspectives. Advances in Materials Science and Engineering 2022 (2022).
47. MA Shereen, S Khan, A Kazmi, et al. COVID-19 infection: Emergence, transmission, and characteristics of human coronaviruses," Journal of advanced research 24 (2020): 91-98.
48. AT Yayehrad, EA Siraj, GB Wondie, et al. Could nanotechnology help to end the fight against COVID-19? Review of current findings, challenges and future perspectives," International Journal of Nanomedicine 16 (2021): 5713.
49. A Tharayil, R Rajakumari, CJ Chirayil, et al. A short review on nanotechnology interventions against COVID-19. Emergent Materials 4 (2021): 131-141.
50. MC Sportelli. et al. Can nanotechnology and materials science help the fight against SARS-CoV-2?," Nanomaterials 10 (2020): 802.
51. RA Basodan, B Park, HJ Chung. Smart personal protective equipment (PPE): current PPE needs, opportunities for nanotechnology and e-textiles. Flexible and Printed Electronics 6 (2021): 043004.
52. G Konvalina, H Haick. Sensors for breath testing: from nanomaterials to comprehensive disease detection. Accounts of chemical research 47 (2014): 66-76.
53. R Asmatulu, B Zhang, E Asmatulu. "Safety and Ethics of Nanotechnology," in Nanotechnology Safety. Elsevier (2013): 31-41.
54. SS Vasanawala, et al. Safety and technique of ferumoxytol administration for MRI. Magnetic resonance in medicine 75 (2016): 2107-2111.
55. K Donaldson, FA Murphy, R Duffin, et al. Asbestos, carbon nanotubes and the pleural mesothelium: a review

Adrah FA, et al., J Nanotechnol Res 2023
DOI:10.26502/ jnr.2688-85210037

of the hypothesis regarding the role of long fibre retention in the parietal pleura, inflammation and mesothelioma," Particle and fibre toxicology 7 (2010): 5.

56. T Kim, M Kim, H Park, et al. Size-dependent cellular toxicity of silver nanoparticles," Journal of biomedical materials research Part A 100 (2012): 1033-1043.
57. Y Pan, et al. Size-dependent cytotoxicity of gold nanoparticles. Small 3 (2007): 1941-1949.
58. R Piltch-Loeb, et al. COVID-19 vaccine concerns about safety, effectiveness, and policies in the United States, Canada, Sweden, and Italy among unvaccinated individuals," Vaccines 9 (2021): 1138.
59. MK Denu, et al., "Freedom of Choice to Vaccinate and COVID-19 Vaccine Hesitancy in Italy. Vaccines 10 (2022):1973.
60. A Udhrain, KM Skubitz, dDW Northfelt. Pegylated liposomal doxorubicin in the treatment of AIDS-related Kaposi's sarcoma. International journal of nanomedicine 2 (2007): 345-352.