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Evolving insights into Nanotechnology Competence: Emerging Benchmarks in the Post-Pandemic Transition of Covid-19

S. Sheeba*[1], M. Murugan[1], A. S. Suman Sankar[2]

[1]Department of Organon of Medicine, Sarada Krishna Homoeopathic, Medical College, Tamil Nadu Dr. M.G.R. Medical University, Chennai, Kulasekharam, Kanniyakumari District, Tamil Nadu, India
[2]Department of Repertory, Sarada Krishna Homoeopathic Medical College, Tamil Nadu Dr. M.G.R. Medical University, Chennai), Kulasekharam, Kanniyakumari, District, Tamil Nadu, India

Corresponding author: **S. Sheeba** | E-mail: **sheeba.syduu@gmail.com**

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Abstract

The worldwide spate of coronavirus disease 2019 (COVID-19), triggered through the unadorned acute respiratory syndrome coronavirus 2 (SARS-CoV-2), greatly increased the necessity and aimed at novel approaches in therapy, diagnosis, and prevention. Although former coronavirus epidemics such as SARS-CoV in 2002 and MERS-CoV in 2012 had already highlighted this urgency, a universally effective antiviral treatment has yet to be developed. This limitation has accelerated the exploration of nanotechnology-based approaches as complementary or alternative interventions. Nano medicine offers transformative potential by improving drug delivery, enhancing vaccine efficacy, and enabling rapid diagnostics. This journal acmes the evolving competence of nanotechnology in appealing to COVID-19 and discusses emerging standards that may shape preparedness for future pandemics.

Keywords: *Coronavirus, Nano medicine, Pandemic, Nanotechnology, Respiratory Syndrome.*

Introduction

The COVID-19 occurrence, initially recognised in Wuhan, China in late 2019, swiftly escalated into solitary of the most significant world-wide health predicaments since the 1918 influenza pandemic. Its rapid spread revealed substantial shortcomings in public health preparedness, diagnostic capacity, and available treatment options. [1] Conventional antiviral treatments and vaccines initially struggled to mitigate disease progression and mortality. This necessitated the exploration of alternative technologies capable of addressing the biological complexity of SARS-CoV-2.

Nanotechnology has materialized as a promising interdisciplinary tool capable of overcoming the limitations of traditional medical approaches. Owing to their nanoscale size and tunable physicochemical properties, nanomaterials can significantly improve drug solubility, stability, and targeted delivery. Additionally, nanotechnology-based vaccine platforms such as lipid nanoparticles (LNPs) have demonstrated immense success during the pandemic (e.g., mRNA vaccines), highlighting the practical feasibility of nanoscale interventions (Kumar et al., 2021; Weiss et al., 2020). [1, 2] The following sections discuss the molecular framework of SARS-CoV-2, its multisystem pathogenicity, besides the expanding protagonist of nanotechnology in diagnostics, therapeutics and preventive strategies.

Molecular Architecture of Viruses

Coronaviruses are enveloped, positive-sense RNA viruses with genomes ranging from 26 to 32 kb, the largest among RNA viruses (Fehr & Perlman, 2015). [3] The SARS-CoV-2 genome consists of two primary segments: the 5′ untranslated region, which codes for non-structural proteins (nsps 1–16), and the 3′ region, which encodes the key structural proteins—spike (S), membrane (M), envelope (E), and nucleocapsid (N). Some beta coronaviruses also express hemagglutinin-esterase (HE), which aids receptor binding. The S glycoprotein facilitates viral entry via the ACE2 receptor and is the main immunogenic objective for defusing antibodies, creation as key component in vaccine design. The M protein maintains virion integrity, the E protein assists in viral assemblage and potential, and the N protein binds viral RNA, ensuring genomic stability during replication (Walls et al., 2020). [4] Understanding this genetic and structural organization is critical for designing nanotechnology-based strategies such as nanoparticle vaccines, targeted antivirals and biosensors.

Indulgent Transmission Paths

SARS-CoV-2 spreads through respiratory droplets and aerosols, as well as through direct contact and exposure to contaminated surfaces. Viral particles may also be shed through saliva, feces and urine. Individuals with severe disease typically exhibit higher viral loads, increasing their transmission potential (Li et al., 2020) [5].

Clinical symptoms vary widely, including fever, cough, dyspnea, anosmia, headache, myalgia and gastrointestinal disturbances. Understanding these transmission modes helped shape nanotechnology-enhanced preventive tools such as antiviral coatings, Nano-engineered masks, and contact-inhibiting surface materials [6].

Multisystem Waves of COVID-19: Vital Structures Pretentious

SARS-CoV-2 mainly drags to the ACE2 receptor, which is widely expressed in innumerable tissues in lungs, heart, vascular endothelium, gastrointestinal tract, pancreas, kidneys, and reproductive system. The abundant presence of ACE2 in alveolar type II cells plays a key role in the progress of pneumonia and dire respiratory distress condition (ARDS). Cardiovascular snags include myocarditis, arrhythmias, endothelial dysfunction and thrombosis (Bansal, 2020) [7]. Neurological manifestations arise from neuro inflammation mediated by cytokine storms, microglial activation and possible blood–brain barrier disruption. [8] In pregnant women, elevated ACE2 expression in placental tissues raises concerns regarding fetal exposure and pregnancy complications. The multisystem involvement underscores the need for targeted therapeutic strategies, many of which can be facilitated through nanotechnology due to its capacity for site-specific delivery.

The central nervous system can be affected either through direct viral invasion or indirectly as a consequence of hypoxia. Activation of astrocytes, macrophages, and microglia can initiate a cytokine surge that disrupts the blood brain barrier (BBB), leading to considerable neuronal damage. Liver and pancreatic cells, which show high expression of ACE2 and TMPRSS2, are also prone to infection and may contribute to metabolic disturbances. In the reproductive structure especially in gravid womenfolk the uterus, placenta, and foetal edge express high levels of ACE2, increasing the susceptibility of foetal tissues and raising the menace of morbidity and mortality. Severe COVID-19 is often allied with cytokine release set of symptoms (CRS), marked by eminent pro-inflammatory mediators such as tumour necrosis element (TNF) and interleukins (IL-1, IL-6). These heightened inflammatory responses can intensify multi-organ injury and, when combined with ARDS, significantly raise the likelihood of fatal outcomes. This widespread organ involvement highlights the need to understand tissue-specific liabilities to SARS-CoV-2 in edict to ripen more precise beneficial and precautionary interventions.

Nano medicine Interpolations for Disease Super vision

Nano medicine offers several advantages in addressing viral infections, particularly those affecting the respiratory system. Nano carriers enhance drug solubility and stability, support controlled release, and facilitate targeted delivery to specific organs or cell types. Pulmonary Nano-drug delivery systems represent a promising approach for COVID-19, as they enhance mucosal penetration, enable ligand-based targeting, and allow higher local drug concentrations with minimal systemic toxicity (Zhang et al., 2021). [9]

Nanoparticle-Based Antiviral Strategies

Several nanoparticles, such as silver, gold, graphene oxide and quantum dots, demonstrate intrinsic antiviral properties or serve as efficient drug carriers. [10] Their mechanisms include: - Blocking viral attachment and entry - Inhibiting viral RNA replication - Disrupting transcription and protein translation - Preventing viral budding and release (Sportelli et al., 2020) [8]. Nano-encapsulation of antiviral drugs (e.g., remdesivir, favipiravir) enhances pharmacokinetics while reducing toxicity. Muco adhesive nanoparticles are especially valuable for respiratory infections due to improved retention within the airway mucosa. Nanoparticles-based carriers enable efficient delivery of drugs to infected cells, enhancing therapeutic outcomes while minimizing toxicity relative to traditional formulations. To further strengthen these effects, a range of surface-functionalization strategies has been developed, allowing nanomaterials to exhibit improved adhesion and more precise antiviral targeting.

Nanotechnology-Driven Innovations in COVID-19 Detection:

Nanomaterials have revolutionized diagnostic platforms by enabling rapid, sensitive and point-of-care detection of viral biomarkers. Key advancements include:

- Graphene-based biosensors functionalized with anti-spike protein antibodies
- Gold nanoparticle colorimetric assays for viral RNA detection
- Quantum dot-enhanced fluorescence probes
- CRISPR-based nanoparticle-assisted nucleic acid detection systems (Seo et al., 2020) [11, 12].

These technologies significantly reduce detection time while maintaining high specificity and sensitivity

Leveraging Nanoparticles for Enhanced Vaccine Adjuvant Formulations

Nanoparticles are integral to modern vaccine platforms. Lipid nanoparticles (LNPs) enabled efficient delivery of mRNA vaccines such as Pfizer-BioNTech and Moderna COVID-19 vaccines (Verbeke et al., 2021) [13] Other nanoparticle-based adjuvants include: - Alum (aluminum salts) - MF59 (squalene-based emulsion) - AS03 and AF03 adjuvants - Virus-like particles (VLPs) - PLGA nanoparticles - Cationic liposomes - Nano emulsions Emerging platforms such as cyclic dinucleotide-loaded nanoparticles enhance CD4+ and CD8+ T cell retorts and are undergoing active clinical evaluations. Matrix-M, a saponin-centered nanoparticle adjuvant, is a promising candidate for future COVID-19 vaccine formulations

Traditional methods of delivering molecular adjuvants often face limitations, many of which are addressed by nanoparticle-based delivery systems. Nanoadjuvants such as MF59 have been shown to induce strong humoral responses along with T-helper

1–mediated immunity. Conventional adjuvants like alum continue to be used in vaccines including DTaP, Hib, hepatitis A, and hepatitis B. Several vaccines—such as Epaxal® for hepatitis A and Inflexal® V or Invivac® for influenza—incorporate viral components within their formulation. Adjuvants like MF59 and AS03 are also licensed for influenza vaccines designed for older adults, enhancing vaccine performance in populations with weaker immune responses. Nanoparticle-based adjuvants may provide particular benefit for individuals who are immunocompromised or living with comorbidities, as they can help achieve protective immunity with reduced antigen doses, including in COVID-19 vaccines. [14] Matrix-M, a saponin-derived nanoparticle adjuvant, is being evaluated in phase I clinical trials in combination with a recombinant SARS-CoV-2 spike protein nanoparticle vaccine to determine its safety and ability to stimulate immunity. Overall, the integration of nanotechnology with advanced adjuvant systems represents a promising approach for strengthening vaccine efficacy, especially in elderly and immunologically vulnerable populations.

Advancing Prophylactic Measures through Nanotechnology:

Nanofiber filtration layers incorporated into masks significantly improve viral blocking efficiency due to microscopic pore size, high surface area and enhanced electrostatic capture. Nano-engineered personal protective equipment (PPE) includes: - Antimicrobial lab coats - Hydrophobic aprons - Self-sterilizing fabrics coated with silver or copper nanoparticles Nanofibers also reduce breathing resistance and increase comfort, making them suitable for prolonged use. [9]. As mucous membranes act as the primary entry sites for SARS-CoV-2, approaches the block virus-related entry and allow embattled drug transfer crossways these barriers are essential. [10]. Nanotechnology holds considerable promise in enabling the passage of therapeutics over mucosal facades, emphasizing its potential in precautionary strategies beside viral contagions.

Hurdles and Dares for Nominal Nano medicine Enactment:

A significant experiment in Nano medicine lies in the all-encompassing construction of nanoparticles while maintaining cost-effective managements. [11]. Although nominal nanomaterials and nanoparticle-based serums have the potential to lower global healthcare outlays by averting ailments such as COVID-19, the intricacy of trade and scholarly assets limitations can drive up incidentals. Nano particles, despite their therapeutic potential, also pose significant safety concerns. Their small size allows them to interact with tissues in unpredictable ways, leading to possible toxicity and broad systemic distribution, including the ability to cross the blood–brain barrier. Inhaled nanoparticles depending on their physicochemical properties may induce respiratory complications such as epithelial injury, inflammation, or even pulmonary fibrosis.

In addition, nanoparticles can disrupt several fundamental cellular and biological pathways. They may alter oxidative stress responses, inflammatory signalling, mitochondrial activity, macrophage-mediated phagocytosis, and platelet function. Their interaction with cells can also promote the generation of reactive oxygen species (ROS), binding to cell membranes, DNA damage, protein unfolding, and interference with normal cell-cycle regulation. Such effects can manifest acutely or persist as long-term health risks. A major ongoing challenge is the incomplete knowledge surrounding the chronic and environmental impacts of nanoparticle exposure, underscoring the need for continued research and vigilant safety assessments.

Despite its potential, Nano medicine faces several challenges:

Manufacturing Barriers

Large-scale production of nanoparticles requires complex equipment, strict quality control and high costs.

Toxicological Concerns

Nanoparticles may induce: - Oxidative stress - DNA damage - Mitochondrial dysfunction - Inflammation - Pulmonary fibrosis (depending on size and composition)

Regulatory and Ethical Issues

Long-term safety data remain limited, and regulatory frameworks for emerging nanomaterials require strengthening

Conclusion

Nanotechnology has frolicked a transformative protagonist in the global response to COVID-19, reshaping diagnostic methods, vaccine platforms, therapeutics and preventive tools. Nanoparticles, LNPs and virus-like particles have demonstrated their aptitude to enrich antigen solidity, improve immune responses and enable targeted drug delivery. Although challenges persist regarding scale-up, toxicity and regulation, ongoing research continues to refine the safety and applicability of Nano medicine. As global health systems prepare for future pandemics, nanotechnology will remain central to improving antiviral strategies, enabling precision medicine and establishing new standards for infectious disease management. [14, 15]. These platforms facilitate unrelenting and beleaguered conveyance of therapeutics and inoculations, reducing complete horizontal effects while enhancing overall ability. Nanoparticle-based antiviral approaches can unswervingly block viral entry, replication, and transcription, providing a valuable complement to conformist treatments. In the field of diagnostics, nanomaterials have been utilized as biosensors to swiftly and precisely distinguish viral nucleic acids, antigens, and antibodies, improving prompt detection and repression efforts.

Nanotechnology has brought remarkable advancements to vaccine science by serving as a highly effective platform for adjuvant delivery, thereby strengthening immune responses even in populations with diminished immunity, such as the elderly and immunocompromised. Pulmonary nano-drug delivery systems and nano-engineered protective masks further contribute to disease prevention by obstructing viral entry and enabling targeted, localized treatment. Despite these advantages, several obstacles remain, including difficulties in large-scale manufacturing, maintaining batch-to-batch consistency, and understanding the long-term toxicological effects of nanomaterials. [16, 17] In response, regulatory bodies are developing updated guidelines and standards to ensure the safe, reliable, and efficient use of nanomedicine. The combination of nanotechnology with traditional antiviral approaches is paving the way for individualized and precision-based management of infectious diseases. As research progresses, nanotechnology is expected to support the repurposing of established antiviral agents and enhance vaccine design for future outbreaks. Ultimately, the expanding role of nanotechnology in the post-COVID landscape underscores its capacity to reshape global practices in therapeutics, diagnostics, and preventive healthcare.

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