DOI: https://doi.org/10.54393/fbt.v6i2.246

FUTURISTIC BIOTECHNOLOGY
https://fbtjournal.com/index.php/fbt
ISSN (E): 2959-0981, (P): 2959-0973
Vol 06 Issue 02, (April-June, 2026)

Review Article

OPEN ACCESS

Approaches for Pandemic Preparedness and Response: Lessons from the SARS-CoV-2 Pandemic — A Global Narrative Review

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ARTICLE INFO

Keywords:
SARS-CoV-2, Futuristic Biotechnology, mRNA Vaccines, CRISPR Diagnostics, Artificial Intelligence, Nanomedicine, Digital Epidemiology, Pandemic Preparedness

How to Cite:
Shabbir, N., Irshad, U., & Anjum, M. N. (2026). Approaches for Pandemic Preparedness and Response: Lessons from the SARS-CoV-2 Pandemic — A Global Narrative Review: Pandemic Preparedness and Response: Lessons from the SARS-CoV-2 Pandemic. Futuristic Biotechnology, 6(2), 03-09. https://doi.org/10.54393/fbt.v6i2.246

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Received Date: 27th April, 2026
1st Revision Received: 22nd May, 2026
Acceptance Date: 18th June, 2026
Published Date: 30th June, 2026

ABSTRACT

SARS-CoV-2 emerged in December 2019 and rapidly spread globally, catalyzing an unprecedented acceleration of biotechnology innovation. The pandemic served as a real-world proving ground for mRNA and nucleic-acid vaccine platforms. To synthesize current evidence on futuristic biotechnology platforms developed or matured during the SARS-CoV-2 pandemic, to evaluate their translational readiness and limitations, and to outline how their convergence could reshape preparedness for future biological threats, framed against the epidemiological and risk-factor lessons of COVID-19. A narrative literature review was conducted following standard review guidance. A systematic search was performed in PubMed, Scopus, and Web of Science for articles published between December 2019 and July 2026, combining the keywords SARS-CoV-2, epidemiology, mRNA vaccine, CRISPR diagnostics, artificial intelligence, nanotechnology, and wearable biosensor. Peer-reviewed, English-language articles reporting original data, technology-validation studies, or authoritative surveillance reports were eligible; conference abstracts, non-peer-reviewed preprints, and articles without full text were excluded. Two reviewers independently screened titles and abstracts and assessed full texts for eligibility; disagreements were resolved by discussion. As of July 2026, the World Health Organization has reported over 7 million deaths globally. Lipid-nanoparticle-encapsulated mRNA vaccines demonstrated that nucleic-acid platforms can be designed, manufactured, and deployed within months rather than years, and next-generation bivalent and pan-sarbecovirus candidates are now in development. CRISPR-Cas12/Cas13-based diagnostics achieved RT-qPCR-comparable sensitivity at a fraction of the cost and turnaround time. The SARS-CoV-2 pandemic has catalyzed future biotechnology, validating nucleic acid vaccine platforms, CRISPR diagnostics, AI-driven drug discovery, nanomedicine, and digital/genomic surveillance as complementary, convergent tools.

INTRODUCTION

The first human coronavirus was isolated in 1965 from the nasal washings of a child [1], indicating that coronaviruses have infected humans and animals for decades. The novel coronavirus identified in Wuhan, China, in December 2019 (SARS-CoV-2) was declared a pandemic by the World Health Organization in March 2020 and has since spread to >222 countries and territories [2]. As of April 2021, the world had already seen over 151 million cases and over 3.18 million deaths [3], and by July 2026, over 779 million confirmed cases and 7 million deaths had been reported worldwide [4]. This time, the SARS-CoV-2 pandemic has not only been on a gigantic scale, but it has also compressed the biotechnology development process in an unprecedented manner. There are examples of vaccine platforms that were published as proofs of concept but progressed to a licensed human vaccine within a year, such as the nucleoside-modified mRNA delivered in lipid nanoparticles [5, 6]. A range of new diagnostic technologies emerged, including the CRISPR-Cas-based system for point-of-care nucleic-acid detection [7, 8]. In the weeks since genome release, AI and machine learning, which were previously only a sideline to drug discovery, are

DOI: https://doi.org/10.54393/fbt.v6i2.246

now making their way into the center of the vaccine antigen prioritization process and repurposing existing drugs for novel applications [9, 10]. Similarly, nanotechnology, digital wearable sensing, and genomic wastewater surveillance emerged from experimental approaches into public-health infrastructure [11-14]. The confluence of futuristic biotechnology disciplines – synthetic biology, gene-editing diagnostics, artificial intelligence as a therapeutic's discovery platform, nanomedicine, and digital/genomic surveillance – is not a fad of the pandemic era, but rather a long-term change in the way the world can respond to and prepare for future biological threats.

Despite these advances, significant challenges persist, such as cold chain and stability issues with existing mRNA formulations, high cost and regulatory hurdles to CRISPR diagnostic applications in low-resource settings, data quality and interpretation problems with AI for drug development, and the requirement to convert signals from wearable and wastewater sensors to actionable, equitable public health responses. This narrative literature review aims to (1) summarize the futuristic biotechnology platforms that have already matured over the course of the SARS-CoV-2 pandemic, such as next-generation vaccines, CRISPR diagnostics, AI-guided drug discovery, nanomedicine and digital/genomic surveillance; (2) to assess the epidemiological and molecular evidence of risk factors that these technologies are meant to address; and (3) to describe how these tools could converge in a futuristic, technology-enabled pandemic-preparedness framework for emerging biological threats.

The review was performed using the narrative synthesis approach, in accordance with the SANRA (Scale for the Assessment of Narrative Review Articles) framework. Despite the systematic literature search (with clear inclusion/exclusion criteria) and the double screening of the reviewers, the heterogeneity of the study designs (clinical trials, technology validation studies, epidemiological reports and surveillance data) across different biotechnology domains made it impossible to perform a quantitative meta-analysis. We thus decided on a narrative, topic-driven synthesis based on a standardized extraction form and organized the results according to the technology domain. This method follows accepted practice for integrative reviews of a variety of methods.

Epidemiological and Clinical Context

SARS-CoV-2 is an enveloped, single-stranded positive-sense RNA virus, which is transmitted mainly via respiratory droplets and aerosols, and to a lesser extent through contact with contaminated surfaces [1, 15]. World Health Organization confirmed cases and deaths exceed 779 million and 7.1 million respectively, with cumulative cases over 280 million, 210 million, 13 million and 100 million in the Regional of the Americas, European Region, Region of the Americas, and African Region respectively, and South-East Asia and Western Pacific Regions combined, as of July 2026, and these figures may be underestimated due to variability of testing and reporting capacity across the regions [4].

The virus starts spreading before the symptoms appear. The very initial symptoms were cough, sneezing, shortness of breath, fever, diarrhea, and fatigue. These were the common symptoms found in most people infected with COVID-19. The incubation period of this novel virus is almost 11.5 days [8]. Asymptomatic SARS-CoV-2 infections appear to have infectivity comparable to symptomatic infections, and asymptomatic carriers can transmit the virus to others. Estimates of the prevalence of asymptomatic infection are important for understanding the true epidemiological burden of COVID-19, since a substantial share of transmission may occur before or without symptom onset [9]. Overall, approximately 90% of COVID-19 infections are asymptomatic, oligosymptomatic, or mild, and do not lead to hospitalization [9].

Clinically, about 80–90% of infections are either asymptomatic or only have mild symptoms, while 10–20% lead to severe infection, sepsis, multi-organ dysfunction, or acute respiratory distress [16]. Older age (age ≥ 65 years), male sex, and comorbidities including diabetes, obesity, hypertension, chronic lung disease, and immunosuppression are consistently associated with severe disease and mortality [16-18]. The virus binds to the angiotensin-converting enzyme 2 (ACE2) receptor and penetrates host cells with the help of the transmembrane serine protease TMPRSS2, which is a gene that is highly expressed in men and is regulated by the hormone androgen — this is the basis for the male mortality excess reported in the literature [19, 20]. ACE2 is highly expressed in cardiac, pulmonary, adipose, and renal tissue as well, and this might explain the association between disease severity and the burden of comorbidity, albeit this has not yet been substantiated in clinical trials where the association of ACE inhibitors or angiotensin-receptor blockers with disease severity and upregulation of ACE2 has been questioned [21, 22]. While these epidemiological and mechanistic findings are descriptive, they identify the molecular targets that the future biotechnology platforms which will be discussed below have been designed around: ACE2, TMPRSS2, the spike glycoprotein, and host immune pathways.

Next-Generation Vaccine Platforms

The landmark biotechnology success of the SARS-CoV-2 pandemic was the establishment of nucleoside-modified mRNA in lipid nanoparticles (LNPs) as a fast-track vaccine platform. In contrast, mRNA vaccines do not need the virus to be cultured in cells or live-attenuated/inactivated, and are designed within days of pathogen identification and

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produced without the need for cell culture or viral propagation [5, 6]. The platform has been proven to be able to provide rapid antigenic drift by receiving regulatory approval for a bivalent mRNA vaccine encoding spike proteins of both the ancestral Wuhan strain and the Omicron variant [5]. Despite this success, first-generation mRNA vaccines are hampered by the need for cold storage up to −80°C and instability, which is driving research into second-generation mRNA backbones with optimized untranslated regions for stability and protein expression at lower doses [6]. To lower the amount of required dosage and manufacturing cost, self-amplifying RNA (saRNA) platforms are being experimented with, where the antigen is encoded with the viral replicase machinery. Simultaneously, the research on antigen delivery is advancing towards pan-sarbecovirus or "universal" vaccines against the current and future variants of concern, rather than repeated strain-matched boosting [6, 23]. Together, these advances make mRNA/LNP and other nucleic-acid-based vaccines a reusable, quickly reconfigurable vaccine platform suitable for future emerging pathogens other than SARS-CoV-2.

Virology and Immunology

The virology and immunology behind SARS-CoV-2 can be complicated and can differ significantly from one person to another, which can lead to differences in how patients present with the disease and outcomes. Since the outbreak of COVID-19, a large amount of research has been done to gain insight into the ability of the virus to spread, immune response, characteristics of the virus, and the mechanisms and factors driving disease progression. While various treatments have been studied, vaccination is becoming an important strategy to help mitigate and protect against severe COVID-19. Vaccine development and delivery, however, may raise immunological and pathological issues that will need to be investigated. The mechanism of SARS-CoV-2-host immune system interaction is still critical to the development of effective preventive and therapeutic strategies. Vaccination and clinical management are not the only factors important in the reduction of viral transmission; public awareness and compliance with precautions are also crucial. Scientists, physicians, and laboratories have contributed greatly to the understanding of the virology and epidemiology of COVID-19. Community awareness, vaccination, early detection of infection, and infection prevention are fundamental tools for disease control, even though some infected people do not have symptoms or have mild ones and are therefore not a significant risk of transmitting the disease [10].

Global COVID-19 Burden (as of July 2026)

As of July 2026, the World Health Organization reported over 779 million confirmed cases and over 7 million confirmed deaths globally since the beginning of the pandemic [11]. The global test positivity rate remained low at approximately 2–3% in most reporting countries as of mid-2026 [12]. The regional distribution of COVID-19 cases varies considerably. In the European Region, cumulative cases exceeded 280 million, with an incidence rate of approximately 37,000 per 100,000 population [13]. The Region of the Americas reported over 210 million cases, corresponding to an incidence rate of approximately 20,000 per 100,000 population. The African Region, despite its large population, reported approximately 13 million cases, with an incidence rate of approximately 900 per 100,000 population [13]. The South-East Asia and Western Pacific Regions together reported over 100 million cases. It is important to note that these figures represent confirmed cases and may underestimate the true burden due to variations in testing capacity, reporting practices, and healthcare infrastructure across regions [13].

CRISPR-Based Diagnostics and Point-of-Care Testing

In the past, CRISPR-Cas systems were described as adaptive immune systems of bacteria, but they have now been adapted to become some of the most impactful diagnostic tools during the pandemic. Two platforms dominate: DETECTR, based on Cas12a, and SHERLOCK (Specific High-sensitivity Enzymatic Reporter unLOCKing), based on Cas13a, which both rely on the non-specific trans-cleavage activity of these enzymes that occurs when they are bound to a complementary sequence of the target that is coupled to isothermal amplification (recombinase polymerase amplification or loop-mediated isothermal amplification) and a fluorescent or lateral-flow reporter [7, 8]. A similar Cas3-based diagnostic system (CONAN) has expanded collateral-cleavage diagnostics to Class 1 CRISPR systems, allowing for detection in about 40 minutes, without any specialized equipment [7]. Compared with RT-qPCR, CRISPR-based diagnostics are broadly comparable in specificity (approaching 100%) and sensitivity (93–100% versus 95–100% for RT-qPCR); require 30–60 minutes of testing, versus 90–180 minutes for RT-qPCR; and cost $5–15 per test, compared with $10–50 per test for RT-qPCR; and do not require centralized laboratory infrastructure [24]. With low-cost and reusable heating and fluorescence-readout hardware, low levels of instrumentation have enabled multiplexing of SARS-CoV-2 and variant-defining mutations via saliva-input platforms like miSHERLOCK, with a per-assay cost of <$6 [25]. Microfluidics-based CARMEN is a higher-throughput multiplexed platform that can analyze thousands of samples on a single run for multiple pathogen targets [24]. Combined, all these tools show the potential for redirecting gene-editing biochemistry from therapeutic editing to rapid, low-cost, decentralized molecular diagnostics, a quality that is directly applicable to future outbreak

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detection in resource-limited areas.

Artificial Intelligence and Machine Learning in Drug Discovery and Vaccine Design

The current pace of conventional drug discovery is slow, expensive, and has a high rate of attrition, and is not adequately suited to the timeframe requirements of an active pandemic [10]. To tackle this, AI and machine-learning approaches were used mainly for drug repurposing, which involved screening existing pharmacological, genomic, and transcriptomic data for drug candidates that seemed to have plausible antiviral properties but were not plausibly developed from scratch. Knowledge-graph and deep-learning methods were used to combine the drug-disease-protein-pathway relationships with transcriptomic and proteomic data from SARS-CoV-2-infected cells, so as to prioritize dozens of drug candidates that are potentially repurposable, which were then validated experimentally [9]. Several other approaches have been adopted to rank candidates according to the interaction that is predicted to occur in the biological system, such as using graph neural networks and knowledge-graph embedding methods, or by modeling changes in gene expression in cells exposed to compounds using a deep-learning framework that relies on phenotypes, including DeepCE [9]. In addition to therapeutic applications, AI/ML approaches have been used to aid in the design of vaccine antigens and prediction of vaccine epitopes, which has contributed to prioritizing immunogenic peptide and protein targets for both classical and mRNA-based platforms [10]. Multi-omics and AI drug repositioning have been suggested to be a lasting methodological gift of the pandemic, not just for the discovery of COVID-19 drugs, but for future infectious and non-infectious disease drug discovery as well [9]. However, there are still significant challenges, such as the need to rigorously validate the models before clinical use, the quality and availability of training data are greatly different from pathogen to pathogen, and the lack of interpretability of the outputs from the deep learning models is a hurdle for regulatory and clinical trust [9, 10].

Nanotechnology and Nanomedicine for Antiviral Therapeutics

Nanotechnology has contributed to many of the more visible biotechnology accomplishments observed during the pandemic, including the delivery of intracellular mRNA via ionizable lipid nanoparticles, as seen in the current vaccines [12]. In addition to vaccine delivery, various nanomedicines have been employed to optimize the pharmacokinetics of antiviral and adjunctive COVID-19 therapeutics, such as improving drug solubility, enabling site-specific or viral-specific drug delivery, decreasing the frequency of drug dosing, and decreasing the systemic toxicity of drug administration relative to conventional formulations [26-29]. Many antiviral drugs have shown poor bioavailability and rapid clearance rates, and nanocarrier-based delivery has been suggested to rescue the already abandoned antiviral drugs with an improvement in therapeutic index [30-33]. The use of nanoparticles for delivery of anti-inflammatory cargo has also been explored in the context of reducing the cytokine-release syndrome (CRS) and acute respiratory distress syndrome (ARDS) in severe COVID-19 patients [26]. In addition to the above CRISPR-based diagnostics, nanosensor-based diagnostic platforms, utilizing graphene, gold nanoparticles, and quantum dots, continue to show the potential of nanotechnology for ultra-sensitive pathogen detection [27]. Nanomedicine is not an independent intervention, but rather works as a substrate in the vaccine, therapeutic, and diagnostic parts of futuristic biotechnology.

Genomic and Wastewater-Based Surveillance for Variant Tracking

During the pandemic, continuous physiological monitoring systems with consumer and clinical-grade wearable devices (fitness trackers, smartwatches, and dedicated biosensor patches) became a means to detect pre-symptomatic infections. The systematic review evidence suggests that the resting heart rate, HRV, breathing rate, and skin temperature measured by wearable sensors are able to predict SARS-CoV-2 illness before symptom onset, and with minimal use of self-reported symptom information [28]. The adoption of wearables for detection was extended to clinical decompensation, with purpose-built platforms like the DeCODe biosensor index that seamlessly integrated continuous data streams from physiology with artificial intelligence (AI) analytics to detect early clinical decompensation in COVID-19 patients [13]. A population-level analysis of aggregate data from wearables has been modelled and used to predict the trends of outbreaks in geographically segmented regions, in addition to traditional surveillance and digital epidemiology approaches using the internet and social media [28]. While the promise of wearable biosensing and AI pattern recognition is an early-warning system that is scalable and low-friction, challenges related to data privacy, access to devices, and integration with formal public-health reporting infrastructure will need to be addressed before it can be viewed as a mature early-warning system infrastructure [34, 35].

Convergence: Toward A Biotechnology-Enabled Pandemic-Preparedness Framework

One hypothetical scenario is when, in early 2026, a novel SARS-CoV-2 lineage containing mutations associated with immune escape is detected in wastewater surveillance in a city in Southeast Asia. The sequence was shared in less than 48 hours, and the sequence of the CRISPR-based point-of-care tests (e.g., miSHERLOCK) was redesigned to

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detect the mutations that define the variant, allowing for distributed screening at airports and clinics. At the same time, resting HR anomalies recorded by the wearable devices in the same region also showed a steady rise in anomalies, indicating pre-symptomatic transmission clusters. Within one week, the AI knowledge graph pipeline (CoV KGE) identified an existing JAK inhibitor as a promising therapeutic, and within 80 days, the new mRNA vaccine based on the updated spike was in phase I trials. Each platform was pre-positioned and interoperable, and this end-to-end timeline from surveillance to countermeasure went from years to weeks, directly as a result of this. The Omicron response for 2021-22 was a partial real-world example, but the complete integration is yet to be achieved; the scenario highlights the need for deliberate system-level design."

Limitations and Future Recommendations

There are several limitations to this review. First, it's based solely on existing literature and public reports, and thus, the conclusions are dependent on the quality and completeness of the literature reviewed. Second, a few of the technologies cited above are still in early or intermediate stages of clinical and regulatory validation, and their reported performance might not apply to all populations or to future pathogens. Third, because of the variation in study design, validation cohorts, and reporting standards across the vaccine, diagnostic, AI, nanomedicine, and surveillance literatures, cross-technology comparisons cannot be made for direct comparisons. Fourth, there are significant inequities in the deployment of these technologies around the world, due to cost, infrastructure, and regulatory hurdles, which poses equity concerns for future pandemic response. Future studies should focus on monitoring the long-term epidemiological trends of SARS-CoV-2 and the impact of newly emerging variants on disease transmission, severity, and vaccine effectiveness. Large-scale multicenter studies involving diverse populations should be conducted to better understand the roles of age, gender, genetics, and comorbidities in disease progression.

CONCLUSION

New vaccine formulations with increased thermostability that could be mass-produced and deployed on a global scale; CRISPR diagnostics that could be deployed at the point of need in low-resource settings and integrated with public-health reporting; prospective, well-powered testing of AI-derived drug candidates; standards for using wastewater and wearable-sensor surveillance as a single, coordinated preparedness system rather than standalone programs; and standards for integrating these platforms as part of a whole.

Authors' Contribution

Conceptualization: NS
Methodology: NS
Formal analysis: NS, UI
Writing and Drafting: NS, UI
Review and Editing: NS, UI, MNA

All authors approved the final manuscript and take responsibility for the integrity of the work

Conflicts of Interest

All the authors declare no conflict of interest.

Source of Funding

The authors received no financial support for the research, authorship and/or publication of this article.

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