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Perspective

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Six Years on: Persistent Structural Gaps in COVID-19 Pandemic Policy and Implications for Future Global Health Crises

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Abstract

Six years after the World Health Organization (WHO) declared coronavirus disease 2019 (COVID-19) as a global pandemic, several key scientific and policy questions remain unresolved—an unsettling state of affairs given the inevitability of future pandemics. This Perspective examines five domains in which progress toward durable pandemic preparedness has stalled—not for lack of scientific innovation, but owing to fragmented data sharing, uneven translation of evidence into policy, and the erosion of public health decision-making by political pressures. These unresolved issues cluster across five domains central to pandemic response: non-pharmaceutical interventions (NPIs), severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) origins, vaccination strategy, information integrity, and socio-political trust. The origins of SARS-CoV-2 remain unresolved, and although NPIs such as masking, school closures, and lockdowns were deployed at unprecedented scale, their real-world effectiveness proved difficult to quantify systematically, yielding evidence that has remained fragmented and insufficiently actionable for future policy planning. Vaccination strategies have been persistently challenged by SARS-CoV-2 evolution, waning immunity, and enduring inequities in global access, revealing gaps not in vaccine science itself but in the speed, coordination, and equity of policy implementation. In parallel, fragmented communication and the spread of misinformation have complicated public health responses, while socio-political pressures have, in some settings, constrained the translation of evidence into policy. In this Perspective, a cross-domain framework of measurable pandemic preparedness metrics is suggested to address these gaps. This framework integrates scientific, operational, and governance indicators to enable continuous assessment of readiness across the full course of a pandemic. Closing the scientific and policy questions gaps that were apparent amid the COVID-19 pandemic will require not only new vaccines or therapeutics, but also sustained global cooperation, transparent risk communication, institutional trust-building, and systematic approaches to countering misinformation. Without such reforms, many of the structural vulnerabilities observed during the COVID-19 pandemic are likely to persist, with implications for the effectiveness of responses to future global health crises.

Keywords: COVID-19 Policy; Vaccination Strategy; Science Communication; Pandemic Preparedness; Misinformation

Abbreviations

COVID-19: Coronavirus disease 2019, NPIs: Non-pharmaceutical interventions, SARS-CoV-2: Severe acute respiratory syndrome coronavirus 2, WHO: World Health Organization

Introduction

The World Health Organization (WHO) declaration of coronavirus disease 2019 (COVID-19) as a global pandemic on March 11, 2020, marked a defining moment in modern public health—one that tested the scientific, institutional, and political foundations of pandemic preparedness worldwide [1-5]. Six years later, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has resulted in more than 770 million confirmed infections and an estimated 7 million excess deaths worldwide [6], disproportionately affecting older adults, individuals with underlying medical conditions, and socially marginalized populations [7, 8].

The early months of COVID-19 pandemic were marked by an unprecedented mobilization of science and public health capacity [9-12]. Within days of the SARS-CoV-2 genome being sequenced, diagnostic assays were developed and deployed globally [13, 14]; within months, multiple vaccine platforms—including mRNA and adenoviral vectors—demonstrated strong protection against severe disease and death [15, 16]. In parallel, genomic surveillance networks capable of tracking viral evolution in near real-time expanded rapidly [17, 18], novel therapeutics were authorized under emergency regulatory pathways [19], and non-pharmaceutical interventions (NPIs) were implemented at a scale rarely seen outside of wartime [20, 21].

Yet despite these extraordinary achievements, several foundational questions remain unresolved—questions that are not theoretical, but central to how nations detect emerging threats, calibrate their responses, and sustain recovery from pandemic shocks. This *Perspective* examines five domains of persistent uncertainty that continue to shape pandemic preparedness and response as shown in (Figure 1).

The Pandemic Paradox: Rapid Science, Fragile Policy

Six years after the WHO declaration of COVID-19 as a global pandemic, the global response landscape remains defined by a striking paradox. The pace of biomedical innovation has been unprecedented: vaccines were designed, tested, and authorized within months; genomic surveillance platforms now enable near–real-time tracking of viral evolution; and novel therapeutics advanced from preclinical development to clinical deployment with remarkable speed [22, 23]. Yet despite these advances, the foundational questions that determine effective pandemic response remain unresolved. Policy and governance frameworks meant to translate scientific breakthroughs into equitable, population-level protection remain fragmented, inconsistently implemented, and in many settings structurally inadequate [5, 24]. If future pandemics are to be managed with strategic precision rather than reactive improvisation, these systemic deficiencies must be confronted as urgent public health priorities rather than deferred as matters of theoretical debate [25].

NPIs and the Problem of Unmeasured Trade-offs

The first of these challenges lies in the persistent uncertainty surrounding the NPIs. Measures such as lockdowns, school closures, and masking mandates were associated with reductions in transmission and mortality in many settings, but they also imposed substantial social and economic costs that were inconsistently quantified and rarely incorporated into real-time decision-making frameworks [26-29]. The contrast between Sweden's reliance on largely voluntary guidance and China's prolonged use of stringent restrictions underlines the absence of consensus on how "effectiveness" should be defined during public health emergencies [30-33]. Policymakers therefore require standardized, multi-dimensional metrics that integrate epidemiologic benefit of NPIs with indirect harms, including educational disruption, mental health consequences, economic contraction, and delayed medical care [34-38].

Pandemic preparedness strategies are recommended to move beyond the *ad hoc* deployment of NPIs and embed prospective evaluation and scenario-based modeling directly into response planning. For each NPI, authorities should predefine explicit performance targets, including thresholds for reduction in the effective reproduction number (R_t), preservation of hospital and intensive care unit (ICU) capacity, and protection of high-risk populations, alongside quantifiable non-epidemiologic outcomes such as days of in-person schooling lost, excess mental health-related emergency visits, delayed cancer diagnoses, unemployment uncertainty, and forgone routine care.

Additionally, adaptive evaluation frameworks should be embedded within pandemic preparedness plans, leveraging real-time surveillance data and cross-jurisdictional variation, with pre-defined thresholds to guide escalation, modification, or discontinuation of NPIs as benefits decline relative to harms [36]. Scenario-based models—parameterized by age distribution, baseline comorbidity burden, social vulnerability indices, health-system staffing resilience, and empirically measured adherence—should guide the timing, intensity, and geographic targeting of NPIs. Such an approach would permit transparent, auditable calibration of NPIs on the basis of observed benefit–harm trade-offs, replacing politically contingent decision-making with accountable public health governance.

Pathogen Origins and the Limits of Global Oversight

Uncertainty regarding the origins of SARS-CoV-2 highlights a second structural vulnerability in global pandemic preparedness: the absence of enforceable, scientifically grounded mechanisms for international verification and biosafety oversight [23, 39, 40]. The persistence of competing hypotheses—whether zoonotic spillover from an intermediate host or a rare laboratory-associated incident—reflects not a deficit in analytic capability but rather incomplete access to early epidemiologic data, unstandardized meta-data from initial case clusters, and heterogeneous availability of biological and environmental samples [41]. Comparable challenges were observed during the 2002–03 SARS outbreak and the 2013 H7N9 emergence, when delays in sharing viral sequences and exposure histories impeded early risk assessment [42]. Because each plausible emergence pathway entails distinct prevention strategies—wildlife surveillance and market regulation for zoonotic spillover, or enhanced oversight of high-containment laboratories and dual-use research for potential laboratory incidents—an evidence-based preparedness plan must enable rapid, independent evaluation before narratives harden and misinformation fills the vacuum [43, 44].

Strengthening global readiness therefore requires institutionalizing verification rather than relying on voluntary transparency. An updated international framework—potentially an extension to the International Health Regulations or a complementary multilateral treaty—should mandate the registration and public reporting of high-risk pathogen research, including work involving novel viral chimeras, serial passaging, or mammalian-transmissibility studies [45]. Harmonized biosafety audit standards, modeled after the Nuclear Threat Initiative's global biosecurity index or the WHO Laboratory Biosafety Manual, should be required for all facilities conducting research on pathogens with pandemic potential. Equally essential are pre-authorized, time-limited outbreak investigation protocols that guarantee standardized access to clinical records from early cases, cold-chain and supply-chain data, laboratory incident logs, and physical samples for independent genomic and serologic analysis. Such mechanisms would have allowed, for example, more definitive reconstruction of early SARS-CoV-2 transmission chains, as was accomplished retrospectively for the West African Ebola epidemic through internationally coordinated field investigations

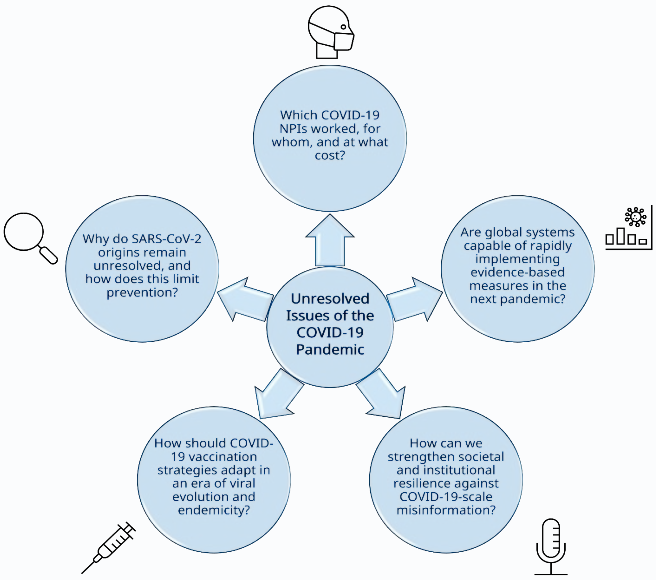

Figure 1: Persistent unresolved issues from coronavirus disease 2019 (COVID-19) that threaten future pandemic preparedness. NPIs: Non-pharmaceutical interventions.

and sample sharing [46, 47]. By operationalizing scientific verification through binding commitments rather than aspirational norms, the global community can reduce the uncertainty that fuels misinformation, accelerate attribution during future outbreaks, and ensure that prevention strategies are tailored to the true pathways through which novel pathogens emerge. In the absence of such reforms, future pandemics will once again begin in an informational vacuum.

Vaccination Policy: From Crisis Universalism to Precision, Sustainability, and Global Security

Vaccination policy represents a third domain in which scientific progress has outpaced governance, creating strategic drift at a critical moment. First-generation mRNA vaccines averted millions of deaths and dramatically reduced hospitalization rates during the acute phase of the pandemic, yet the combination of rapid viral evolution, waning immunity, and limited mucosal protection has complicated long-term control strategies [48, 49]. Moving forward, vaccination policy must shift from crisis-era universalism to precision-based, risk-stratified approaches that reflect contemporary epidemiologic realities. Age-structured booster recommendations—anchored in the sharply graded risk of severe outcomes between older adults and younger, healthier populations—should replace uniform schedules [50]. To operationalize such precision, governments will require durable immunization infrastructure including real-time vaccine effectiveness monitoring, flexible procurement mechanisms capable of rapidly incorporating updated antigenic formulations, and communication systems that can pivot swiftly in response to shifting evidence. At the scientific level, investment must accelerate toward next-generation vaccine platforms—particularly mucosal and pan-sarbecovirus candidates—which hold the potential to reduce transmission and blunt the selective pressures driving variant emergence [51]. Yet no national strategy can succeed if vast regions remain under-vaccinated; the global inequity that allowed the COVID-19 Delta and Omicron waves to spread underlines that vaccine access is not a humanitarian aspiration but a core element of pandemic security [52]. A restructured global supply infrastructure—featuring regional mRNA manufacturing hubs, transparent technology transfer, and binding procurement commitments—will be essential to ensuring that immunization is both timely and geographically equitable [53]. Without such reforms, vaccination policy will remain reactive, scientifically sub-optimal, and vulnerable to the same geo-political bottlenecks that hindered the early pandemic response [54].

From Misinformation to Public Trust: A Missing Preparedness Pillar

The COVID-19 pandemic demonstrated that viral transmission was paralleled—and often accelerated—by an "infodemic" capable of eroding public trust faster than evidence could be generated [55]. The propagation of misinformation was not merely a sociological inconvenience; it altered risk perception, reduced vaccine uptake, delayed care-seeking, and materially changed epidemic trajectories [56-58]. Traditional policy tools, including reactive fact-checking and episodic platform moderation, proved insufficient because they intervened only after falsehoods had disseminated [59, 60].

Effective preparedness requires treating information integrity as a core public health function rather than an adjunct to communication offices. Governments, health agencies, and multi-lateral institutions must therefore implement pre-emptive, evidence-based strategies that build population-level cognitive immunity [61, 62]. These include pre-bunking interventions—forward-looking educational tools that expose individuals to weakened forms of misleading narratives before they encounter them [63, 64]. Public health systems should embed community-trusted communicators, such as local clinicians, pharmacists, and faith leaders, into formal risk-communication hierarchies, as real-time surveys during COVID-19 repeatedly showed that these actors hold more durable credibility than governmental or international bodies [65, 66].

Additionally, the digital platforms should be subject to mandatory transparency standards, including disclosure of algorithmic amplification parameters and real-time publication of highly viral health-related content trends, enabling independent

Table 1: Cross-domain preparedness metrics for the post–COVID-19 era.

Domain	Key Structural Gap	Core Preparedness Metric	Operational Indicators (Examples)	Policy Targets / Benchmarks
Non-Pharmaceutical Interventions (NPIs)	Absence of standardized frameworks to assess net benefit; variable and reactive implementation	NPI Benefit-Harm Balance Index (NPI-BHB) integrating epidemiologic, social, economic, and educational outcomes	Time to measurable reduction in transmission following NPI implementation; Quantified educational disruption (e.g., learning loss indices); Mental health and economic impact measures; pre-defined epidemiologic thresholds for escalation and de-escalation	Pre-specified evaluation metrics incorporated into national pandemic plans; Regularly updated public reporting of NPI impact; Transparent trigger and exit criteria
Pathogen Origins and Biosafety Verification	Limited enforceable mechanisms for timely data sharing, laboratory transparency, and independent biosafety assessment	Global Biosafety Verification Score (GBVS) assessing compliance with standardized reporting, audit, and investigation protocols	Registration of high-risk pathogen research; Frequency and standardization of biosafety audits; Response time to independent investigation requests; Completeness and timeliness of data and sample sharing	Mandatory international registry for high-risk research; Routine external audits of Biosafety level (BSL)-3/4 laboratories; Defined timelines for outbreak investigation activation
Vaccination Policy and Immunization Systems	Limited risk stratification, inequitable global access, and constrained platform adaptability	Adaptive Immunization Readiness Index (AIRI) integrating targeting precision, platform flexibility, and equity considerations	Risk-stratified vaccine uptake rates; Time to update vaccines for emerging variants; Coverage disparities across regions; Cold-chain capacity and distribution efficiency	Risk-stratified national immunization strategies; Target timelines for updated vaccine deployment; Minimum global coverage thresholds prior to expanded booster use
Information Integrity and Public Communication	Fragmented responses to misinformation and variable communication timeliness	Information Resilience Metric (IRM) capturing communication speed, public trust, pre-bunking capacity, and platform transparency	Time from evidence emergence to public communication; Reach of pre-bunking interventions; Platform transparency and data access compliance; Behavioral indicators of misinformation susceptibility	Defined rapid-response communication timelines; Institutionalized pre-bunking strategies; Transparency requirements for major information platforms
Socio-political and Institutional Trust	Politicization of public health decisions and limited structured community engagement	Public Health Trust and Governance Index (PHTGI) assessing institutional independence, legitimacy, and participatory governance	Stability and independence of public health leadership; Community participation in preparedness planning; Adherence to legal frameworks during emergencies; Longitudinal public trust indicators	Legal protections for institutional independence; Formalized community advisory structures; Routine public reporting of trust and governance indicators

epidemiologic monitoring of misinformation spread analogous to pathogen surveillance [67, 68]. National preparedness plans must also fund behavioral and social science units capable of rapid message testing, sentiment analysis, and deployment of evidence-optimized communication strategies during crises [69]. Ultimately, the speed, clarity, and credibility of public communication should be recognized as quantifiable determinants of outbreak control, on par with surveillance capacity or vaccine availability; without institutionalizing these measures, future pandemics will again be shaped not only by the biology of a pathogen but by the nature of the narratives that surround it [70].

The Socio-political Foundations of Effective Pandemic Response

The final and perhaps most sobering lesson of COVID-19 is that biological readiness is insufficient without socio-political resilience [71]. Even the most sophisticated vaccine platforms, genomic surveillance systems, and forecasting epidemic models cannot overcome declining public trust, politicized health institutions, and fragmented social cohesion [5]. The protests against COVID-19 mandates were not simply reactions to specific policies; they reflected deeper failures in risk communication, transparency, and participatory governance [72-74].

Effective pandemic preparedness therefore requires deliberate investment in social science that enables public health action [75, 76]. Governments must build institutional firewalls that protect health agencies from partisan interference, establish permanent community advisory structures to ensure bidirectional engagement during crises, and embed behavioral and social science expertise within emergency response operations [76]. Legal frameworks should be modernized to balance rapid decision-making authority with independent oversight, while guaranteeing procedural clarity in areas such as mandate issuance, data privacy, and emergency powers [77]. These reforms must be accompanied by international mechanisms that standardize data-sharing, biosafety governance, and the management of cross-border misinformation—elements now as central to global health security as laboratory capacity or vaccine delivery. Ultimately, pandemic preparedness will be measured not by how quickly a pathogen is sequenced or a vaccine manufactured, but by how effectively science is integrated into policy and policy is translated into public trust. Rebuilding that trust is not an ancillary task; it is the precondition for any successful future pandemic response.

Cross-Domain Metrics for Pandemic Readiness

Translating the lessons of COVID-19 into actionable preparedness requires standardized, cross-domain metrics that enable benchmarking and the identification of persistent structural vulnerabilities. Table 1 presents a preliminary parallel measurement framework spanning five domains: NPIs, pathogen-origin transparency, vaccination strategy, information integrity, and socio-political resilience. By integrating indicators across scientific, operational, and governance dimensions, the preliminary suggested framework is intended to support continuous assessment of preparedness, rather than episodic evaluation during crises. It can provide a structured basis for health systems and international bodies to detect gaps, guide policy calibration, and align reforms across jurisdictions. Importantly, these metrics are suggested to be applicable before, during, and after a pandemic, thereby reframing preparedness as a measurable and evolving function of system performance.

A central feature of the proposed framework is the importance of timeliness as a determinant of effectiveness. Across domains—including NPIs, pathogen-origin assessment, vaccine deployment, and public communication—delays of even days to weeks were associated with disproportionate downstream effects [78]. Preparedness, therefore, requires the incorporation of time-to-action benchmarks as core performance indicators, marking a shift from descriptive reporting to real-time operational assessment.

The framework also expands the scope of preparedness to include domains traditionally considered peripheral. Information integrity and socio-political trust emerge as co-determinants of outcome, influencing adherence, policy legitimacy, and epidemiologic trajectories. This broader approach recognizes that the effectiveness of interventions depends on biological efficacy as well as the social systems in which they are implemented. A further insight is the structural tension between national accountability and global interdependence. Domains such as biosafety oversight and vaccine equity highlight that preparedness cannot be achieved in isolation. Yet, existing global health mechanisms remain limited in standardizing transparency, coordinating response, and ensuring equitable access. Accordingly, preparedness must be both nationally operationalized and internationally coordinated, or systemic vulnerabilities are likely to persist.

The framework also emphasizes a shift from reactive policy-making to pre-specified decision architectures. The absence of pre-defined thresholds during COVID-19 contributed to variability and delay [79, 80]. Embedding transparent, evidence-based criteria in advance may reduce discretionary uncertainty while preserving flexibility during crises. Finally, preparedness is better understood as an auditable continuum rather than a binary state. Composite indices enable granular, longitudinal assessment across domains, allowing identification of incremental gains, emerging gaps, and trade-offs that would otherwise remain obscured.

Conclusion

The next pandemic is not a matter of if but when, and the contours of that threat are already visible — accelerated pathogen evolution, expanding ecological interfaces, and increasingly interconnected societies. Meeting this inevitability with the fragmented health systems and reactive governance that characterized much of the COVID-19 era would represent a preventable failure of global health. The scientific community will almost certainly be ready: platforms for rapid vaccine design, genomic surveillance, and therapeutic discovery are now embedded in routine practice. The decisive question is whether our policies — and the political structures that shape them — will evolve at a pace commensurate with the biology. Preparedness cannot hinge on improvisation. It demands institutionalized transparency, interoperable data systems, anticipatory regulation, durable public trust, and a governance architecture capable of translating scientific advances into equitable protection. The world has the tools to prevent the next pandemic from becoming a generational catastrophe. Whether those tools are deployed effectively will depend not on scientific capacity, but on the collective will to build policies worthy of the science.

Declarations

The author used OpenAI's ChatGPT-5 to assist in refining the language and improving the clarity of the manuscript. All scientific content, interpretations, and conclusions are the author's own.

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