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Epidemic and Pandemic Preparedness and Management

*Edited by Nicolás Padilla-Raygoza,
Ali Davod Parsa and Russell Kabir*



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IntechOpen Book Series

Public Health

Volume 9

Aims and Scope of the Series

Public health is what we as a society do collectively to contribute to and ensure the health and social conditions for the enjoyment of health as a resource for life. It can also be defined as science and research that promotes health, prevents disease, and improves populations' well-being and quality of life. Its objective is to know the risk factors that determine and condition the populations' health levels at present. At the end of the 20th century and the beginning of the 21st century, it is unjustifiable and regrettable that morbimortality according to age plays a leading role when the causes are mostly well known and therefore preventable, such as obesity, AIDS, cirrhosis, diabetes mellitus, addictions and cancer associated with the consumption of tobacco and alcohol, etc. In short, public health is science based on epidemiology and biostatistics, and currently, new technologies and artificial intelligence must be incorporated to identify patterns and trends in what we do collectively as a society to ensure living conditions and prevent risk factors that affect individual and population health. For all these reasons, it is essential to scientifically investigate and act on the determinants that impede the well-being and quality of life related to the health of people, patients, and populations in general, given that to control the determinants of diseases, it is important to control the environment and genetics. Consequently, the current fight for public health must prioritize the control of the environment, such as atmospheric and biological pollution and environmental and social biodiversity, promoting the sensitivity and training of society and its individuals by empowering them to make free and appropriate decisions about these aspects to lead healthy lifestyles based on motivation and responsibility in the face of the challenges they cope with from an individual point of view, such as dealing with the addictions that exist in today's complex world. Public health also requires an ethical vision and incorporates strategies to reduce social inequality.

Meet the Series Editor



José Antonio Mirón Canelo is a physician, doctor, and professor of Preventive Medicine and Public Health at the Faculty of Medicine and Dentistry of the University of Salamanca with over 30 years of experience. He is the director of the USAL's Expert Degree in Health Management, currently in its 13th edition. Prof. Mirón Canelo directs a research group at the Research Institute of Biomedical Sciences (IBSAL) of the University of Salamanca focused on addressing the challenges and care needs of vulnerable people and patients such as the elderly with multiple pathologies and people with disabilities and dependence. As a teacher, he has been recognized for excellence in teaching three times in a period of five years.

Meet the Volume Editors



Dr. Nicolás Padilla-Raygoza was Professor Titular B at the University of Guanajuato, México, and Coordinator of Research at the University of Celaya, México. He is currently the coordinator of research projects at the Institute of Public Health in the state of Guanajuato. He obtained an MD from Universidad Autónoma de Guadalajara and University Autonomous of México in 1984, a specialization in pediatrics from the Mexican Council of Certification in 1986, a postgraduate degree in Epidemiology from the University of London in 2001, a master's degree and doctorate degree in Science from Atlantic International University in 2006, and a master's degree in Social Gerontology from the International Iberoamerican University in 2017. He has 194 journal articles and 59 book chapters to his credit. He has also edited five books on health. He was recognized as a state researcher in health by the Institute of Public Health of Guanajuato State in 2015 and as a researcher with social impact by Urbanizadora del Bajío, S. A. in 2016. He is a member of the National Researchers System in México.



Dr. Ali Davod Parsa has over 30 years of experience in research and teaching, and has held senior national leadership roles in public health, health management, health economics, and health policy. He is an active researcher in medicine, public health policy, management, and health economics. Dr. Parsa is an Associate Professor of Health Economics, Policy, and Management in the Faculty of Health, Education, Medicine, and Social Care, School of Allied Health, Anglia Ruskin University, UK. He has an established and proven track record of success in senior-level leadership, collaborative research, and teaching excellence at the undergraduate, postgraduate, and doctoral levels. He held a series of high-profile governmental appointments in the Ministry of Health and Medical Education in Iran before joining higher education institutions in the United Kingdom. Dr. Parsa graduated as a qualified general practitioner from the School of Medicine, Zanjan University of Medical Sciences and Health Services, Iran, in 1994. He worked for a decade as a clinician and then held senior management appointments, during which he developed an interest in policy and healthcare management research. Consequently, he was awarded a Ph.D. in Health Economics from the School of Clinical Sciences and a Postgraduate Diploma in Health Services Research (HSR) from the School of Community Health Sciences, the University of Nottingham, UK. Dr. Parsa is an experienced national-level health manager who has been involved in health policymaking at the national strategic level.



Dr. Russell Kabir is a distinguished Associate Professor of Public Health & Biostatistics at Anglia Ruskin University, UK, with over 15 years of exceptional teaching experience. Originally trained as a dentist (BDS, University of Dhaka) and having practiced as a dental surgeon in Bangladesh, he transitioned into public health academia, where he has made remarkable contributions. Dr. Kabir holds a Ph.D. in Public Health from Middlesex University and an MSc in Research Methods. As a prolific researcher with an h-index of 35, he has

published over 200 peer-reviewed articles and holds editorial positions with PLoS One and BMC Public Health. His research encompasses epidemiology, mental health, violence against women, climate change, and the application of AI in healthcare. He has successfully supervised over 20 Ph.D. and MPhil students to completion. A Fellow of the Royal Statistical Society, Dr. Kabir has authored influential textbooks including “Data Analysis with Stata” and “Learning SPSS without Pain.”

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Preface

Recently, as a species, we have faced an increasing number of biological outbreaks that have highlighted the vulnerability of our healthcare systems and modern societies. Epidemics such as Ebola in West Africa, the influenza A (H1N1) pandemic in 2009, and coronavirus outbreaks like SARS and MERS

The COVID-19 pandemic has provided numerous lessons for individuals, communities, and governments worldwide on how to prevent, respond to, manage, and recover from biological emergencies of this nature.

The book's chapters focus on preparedness, mitigation, and recovery from biological outbreaks in various parts of the world, offering opportunities to learn about different approaches to addressing these outbreaks.

Preparedness is crucial for preventing and mitigating the loss of human lives and reducing the economic burden for all countries. Mitigation focuses on minimizing the danger of the emergency while waiting, and the recovery has the objective of enabling communities to resume and return to normal activities.

As editors and co-editors, we hope that readers will gain the experience and knowledge of all authors and co-authors of the chapters, who have worked hard to share their experiences.

I am grateful to Dr. Ali Davod Parsa and Dr. Russell Kabir for their tireless efforts in achieving the goal of completing the book.

Additionally, academic editors want to recognize the important work and support from Dominik Samardzija and Dajana Pemac Polegubic, from the IntechOpen team, in order to achieve the goal of having the book edited.

We hope that reading the book will provide a valuable source of experiences in many parts of the world, enabling us to face biological emergencies more effectively.

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Section 1

Preparedness

Chapter 1

Introductory Chapter: Epidemic and Pandemic Preparedness and Management

Nicolás Padilla-Raygoza

1. Introduction

The World Health Organization (WHO) has defined emergency preparedness as the knowledge, capacity, and organizational systems that governments, preparedness and recovery organizations, communities, and individuals develop to anticipate, respond to, and recover from emergencies [1].

Emergencies have disparate consequences for individuals, communities, and countries. The important thing is that decision-makers do what is necessary to avoid these emergencies and, if they occur, have adequate preparation to mitigate them so that their effects are not as profound and recovery is rapid.

This requires teamwork among all individuals in a community, state, country, and globally.

The coronavirus disease (COVID-19) was an example, where most countries were overwhelmed by the pandemic, with high mortality rates. Mexico was one of the countries that reported the highest case fatality rates [2].

2. Actions of the government of the State of Guanajuato through the Public Health Institute of the State of Guanajuato in response to COVID-19

The state of Guanajuato, located in central Mexico with Longitude # 102°5'49.2"W # 99°40'16.68"W, Latitude 19°54'46.08"N 21°50'21.84"N [3], where the first case of COVID-19 was reported on March 10, 2020 [4],

From here, within 2 weeks of the first reported case, the Guanajuato State government closed schools, public parks, gyms, restaurants, and gatherings of more than 10 people were prohibited. In addition, through the Hospital Network of the Public Health Institute of the State of Guanajuato, the Guanajuato State government strengthened infrastructure, medical equipment, and human resources. An example of this is the rehabilitation of the old General Hospital of León, the acquisition of the Mobile Hospital to care only for patients with COVID-19, the purchase of personal protective equipment, ventilators, monitors, ultrasounds, X-ray equipment and high-quality clinical furniture, as well as the hiring of 1154 health professionals, with an investment of more than 420 million pesos [5].

On March 16, 2020, the state government announced the following: as part of the health protection measures for staff providing services at the Guanajuato State Public Health Institute, it has been determined that the following personnel, without exception, will work remotely from their homes: workers 60 years of age or older, pregnant and breastfeeding women, and those with cancer, HIV, or AIDS [5, 6].

Additionally, the Teaching and Research Directorate of the Guanajuato State Public Health Institute (ISAPEG) implemented training for primary and secondary care health personnel on various aspects of COVID-19 diagnosis and management. Staff training efforts began during the third month of the pandemic in the state, with a significant increase during May and June 2020, reaching its peak during the latter (136.03%). This indicates that during this period, more than one training course was taken per person per month, gradually decreasing until September 2020, with a monthly average of 25.82%. During December 2020, 32.23% of healthcare personnel were trained, which corresponds to the highest peak of positive SARS-CoV-2 cases during the second wave of infections [7].

With the actions of ISAPEG, the positivity rate of COVID-19 cases in the population went from less than 10% in 2020 to less than 20% in 2022 [8]. The hospitalization rate was higher in the state of Guanajuato than in the rest of the country in 2021 and 2022, as were admissions to intensive care units during the same period [8]. Regarding the specific mortality ratio, in Guanajuato it was lower at the beginning of the pandemic (2020 and 2021) but similar to the rest of Mexico for 2022 [8].

Communication between government agencies, the health department of the State of Guanajuato, and the population, allowed the system to be more efficient and effective. The state health system is among the best in Mexico.

In addition to decision-making, investment in health care, public awareness, and a willingness to act in the event of a biological emergency are essential to minimizing the event's impact.

The actions of IPHSG and the state government did not prevent the impact of the pandemic, but they did mitigate its effects and allowed the state's population to return to normal and be in better shape than the rest of the country.

Decision-making is important, but it would have little value if it were not accompanied by information for the population with clear measures on how to behave in the event of an infectious emergency.

Humanity has faced several infectious emergencies so far in the twenty-first century: SARS, MERS, avian influenza, influenza A H1N1, SARS-CoV-2, among others. Despite their effects on the population, humanity has recovered and grown stronger. This may be the preamble to the need to be prepared for the next infectious emergency.

3. Conclusion

The first step in the event of an infectious disease emergency must be preparation at all levels of healthcare organizations, decision-making by government agencies, and effective communication with the community to identify what to do and how to protect themselves during the emergency.

This way, the impact will be less severe and recovery will be faster and more effective.

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I recognize the support of the Institute of Public Health from Guanajuato State for the support to make and publish articles and chapters of books about COVID-19.

Conflict of interest

The author declare no conflict of interest.

Acronyms and abbreviations

COVID-19	coronavirus infectious disease-19
IPHGS	Institute of Public Health from Guanajuato State
WHO	World Health Organization

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Holistic Pandemic Preparedness: Integrating Risk Communication, Community Engagement, Mental Health Support, Economic Resilience and Data Management

U.C. Samudyatha and C. Muninarayana

Abstract

Disease outbreaks and pandemics create a situation of devastation, uncertainty and panic. In such situations, communities often require assistance from both internal and external agencies. To provide assistance, Risk communication and community engagement are vital in the preparedness and response phase of an outbreak. Several intrinsic and extrinsic factors influence the success of risk communication and community engagement in the affected community. These factors, with complex inter-plays and great regional variations, can still be grouped under generic headings to aid in pandemic preparedness planning. Pandemics have an impact that is larger than what meets the eye initially. The mental health of the affected community, as well as that of ground-level responders and healthcare workers, is often neglected, leading to devastating aftereffects. Similarly, economic crises arising from the pandemic have the potential to undo years of social development. Several strategies to protect the mental well-being of people and achieve economic resilience have been documented through years of experience in dealing with several outbreaks of varying magnitudes, such as Ebola and other haemorrhagic fevers in the African continent, avian influenza in Asia and the worldwide spread of COVID-19 recently. All strategies converge on risk communication, community engagement and data management. The chapter discusses various challenges and strategies associated with these important aspects of pandemic preparedness and the means to integrate them.

Keywords: risk perception, crisis communication, community participation, stakeholder involvement, social mobilisation, psychological impact, stress management, economic impact, supply chain management, data-driven decision making, data security, infectious disease outbreak, public health emergencies

1. Introduction

Risk communication is defined by the World Health Organisation (WHO) as the ‘real-time exchange of information, advice and opinions between experts or officials and people who face a hazard or threat to their survival, health, or economic or social wellbeing’ [1]. Risk communication before a disaster or epidemic empowers people facing the disaster to prepare for protecting their lives and property. It enables communities to identify high-risk populations, areas and behaviours, and thereby channel resources optimally. It allows people to make informed decisions and train themselves accordingly. Risk communication during an epidemic is crucial in the effective implementation of preventive and curative services, minimising mortality and morbidity and effective resource utilisation. Effective risk communication controls the spread of rumours and misinformation, which in turn leads to chaos and violence. Risk communication must be coupled with community engagement, where communities are actively involved as partners to mitigate the hazard [1]. Further, pandemics can have a profound and long-lasting impact on the mental health and economic conditions of the people. The pandemic preparedness plan must, therefore, pay due importance to mental health and economic resilience. Finally, effective data management is the cornerstone of the entire pandemic preparedness plan. Data management paints the picture of the ground-level situation, thereby prompting targeted actions and resource allocation. This chapter discusses each of these components of pandemic preparedness.

2. Risk communication and community engagement (RCCE)

2.1 Challenges associated with RCCE in pandemics

Risk communication often determines the success of a pandemic preparedness plan (**Figure 1**). However, risk communication and community engagement (RCCE) activities associated with pandemics or disease outbreaks can be complicated and challenging due to the following reasons.

Urge to take action: During pandemics, emergency actions must be undertaken, which may be unplanned, unfamiliar and overwhelming for the routine healthcare system and the general public. The risk communication during pandemics would also require consultation with non-medical sectors, which may delay actions or even complicate the communication process [2, 3]. Hasty decisions and rapid implementation in the absence of an established risk communication system can compromise community engagement.

Unpredictable nature of the pandemic: The decisions made by the policy makers may be impacted by the unpredictable nature of the pandemic [4, 5]. For instance, viruses, such as COVID-19, undergo rapid mutation during the course of the pandemic, changing their virulence and symptomatology. Emerging and reemerging diseases are particularly unpredictable, forcing policymakers to announce new, and often conflicting, guidelines repeatedly. Rapidly changing guidelines fuel mistrust not only in the general public but also among the local authorities and medical personnel on the ground level. For instance, during the Bovine Spongiform Encephalitis outbreak in 1986 in the United Kingdom, the authorities issued contrasting statements, leading to public mistrust and huge financial losses (**Figure 1**) [6].

Unpredictable reaction of the affected community: The spread of the disease during an outbreak is strongly influenced by the movement, health literacy and behaviour of



Figure 1.
The need for risk communication in the preparedness phase and response phase of a pandemic.

the affected population and those related to them. The spread of airborne diseases is particularly faster, with a high effective reproduction number (R_e). Hence, the RCCE guidance might be directed towards lockdowns, isolation, quarantine and behavioural change, such as wearing masks, culling of poultry or domestic animals and hand hygiene. These guidelines are communicated with the expectation and explanation that they would control the outbreak. However, if the guidelines are not adopted correctly by the community, it appears as if they have failed, thereby developing mistrust amongst the people. This was witnessed during the COVID-19, in several parts of the world.

On the other hand, people may indulge in extreme behaviours, such as avoiding travel, isolating or stigmatising certain groups, avoiding certain food items and avoiding routine hospital visits and healthcare. People also engage in hoarding behaviours, purchasing large quantities of food and medicines, even when there is no actual shortage. These may be extreme behaviours, more than what is called for in the situation. In such cases, social disruption is common, leading to riots, corruption, black market booms and disproportionate economic stress. Economic disruptions can further lead to loss of livelihoods, panic and unplanned migration.

Challenges from the political and media role in RCCE: Political and media activities during the pandemic are double-edged swords. High-level political commitment can help with resource allocation and garner public support. On the other hand, corruption and the denial of scientific evidence by political powers can pose a major setback to RCCE activities and disease control. Political and economic fears of negative

consequences from information sharing, technical and bureaucratic obstacles can hinder timely and transparent communication essential for effective outbreak response [7]. In resource-limited settings and those facing a political transition, this situation is expected all too commonly. Risk communication is hampered and manipulated for economic or personal gain. This eventually leads to public mistrust and unrest.

Similarly, the media can be a powerful tool in risk communication. The world has witnessed the emergence of mass media and social media as tools of communication. When used appropriately, social media can act as a fast, widespread, targeted and effective means of communication [8–10]. Media can influence the public perception of risk, encouraging compliance with the recommendations, as evidenced in COVID-19 and SARS [11, 12]. Media can also act as fact-checking agencies and as the voice of the people. This creates an environment where the policymakers, the healthcare system and the government as a whole are constantly urged to be transparent and accountable [11]. On the other hand, if left unchecked, the media can promote misinformation and sensational reporting, leading to panic and irrational behaviour, as witnessed during the Ebola outbreak in Nigeria [13]. Further, if the political commitment is distorted, there will be a lack of transparency and clarity from the government. In this situation, the media will seek its means to identify so-called ‘experts’ and report news shaped by their understanding. This may catalyse public unrest and mistrust.

In today’s digital world, news spreads fast worldwide, and the government’s handling of the outbreak situation will be an open book for the world to scrutinise. In democratic countries that respect press freedom, the authorities will be constantly under the media scanner. Nevertheless, countries may have their own political and economic reasons to conceal outbreaks or their magnitude; hence, authoritarian governments may control the media to report favourable news while concealing most of the information. Concealing information can seriously backfire if divulging it would have helped control the outbreak sooner and maintained public confidence. Further, it is important to recognise that many communities continue to be media illiterate and are not reachable by these means of communication [8]. They may be left out of the prevention and control activities that are communicated through social media and mass media.

Emergency risk communication (ERC) is a difficult task in the absence of scientific evidence in a rapidly evolving outbreak situation. Thus, countries must have a clear RCCE plan, consisting of an RCCE team of professionals to engage the media with continuous, authentic and relevant information during an outbreak or pandemic. However, a clear-cut RCCE plan is too idealistic to be true. Apart from the various challenges discussed previously, the delivery and impact of the RCCE plans are influenced by social, economic, political and cultural factors, which vary greatly even within the same country.

2.2 Recommendations for effective RCCE in pandemics

WHO recommendations are summarised in **Figure 2**, along with the author’s reflections [14].

2.2.1 Trust and RCCE

Establishing and maintaining trust among the communities is extremely important in RCCE. For instance, during Ebola outbreaks in the African countries,



Figure 2.
WHO recommendations on emergency risk communication.

persistent denial of ongoing transmission, public anxiety and confusion, secret burials and movement across porous borders were favoured by widespread public mistrust due to failure in risk communication [15–18]. Factors influencing the trust can be broadly divided into those related to source, message, messenger and recipient.

Sources and messengers of information: During the pandemic, various sources of information may exist, including the government, health authorities, subject experts and members of the general public, who may make their assumptions.

A government source that is backed by demonstrable scientific evidence will garner more trust. Furthermore, this trust is greater if the government has effectively dealt with similar conditions in the past. The speed and accuracy of information dissemination are also important. Pandemics can pave the way for political blame games and mismanagement of precious time and resources, eventually leading to mistrust. All tiers of government must act in coordination and speak with the same voice. Concealing information, particularly regarding the risk estimation and the deaths, may appear to be a short-term solution to control panic. However, this action can brew mistrust, finally compromising the control efforts.

A health authority, usually a well-informed source, must ensure that it phrases the risk communication messages without using more technical terms than warranted. The public may not understand unnecessary medical jargon, and even worse, it can be misinterpreted [19, 20]. For instance, an odds ratio of 1.2 is often misinterpreted as 1.2%. ‘Vaccine efficacy of 80%’ is misinterpreted as ‘the vaccine is effective in 80% of the population’. Hence, clear explanations must accompany these terms.

Medical evidence rapidly pours in during the pandemic, as does uncertainty. The health authorities must be prepared to handle this constant inflow of information, synthesise it into easily understandable terms, and deliver it to the government and the general public. Often, contrasting messages from the health authorities and the government, especially regarding the number of deaths, spark huge debates in the media and spew mistrust. Furthermore, the pandemic also raises several assumptions regarding the pathogen, mode of transmission and risk of morbidity and mortality. Thus, the government and health authorities must double-check the information they receive before announcing it to the public. The uncertainties that are associated with the messages must be the truly uncertain ones, and not products of human error and confusion.

A third source of information is subject experts who are not directly a part of the government or the health authority. During pandemics, it is common for the media to search for such experts and then propagate the theories put forth by them as the truth. Experts must therefore double-check the messages that they pronounce and must be able to provide references for the information. They must be extremely responsible, since the audience is huge and diverse. They must speak to safeguard public health rather than for any ulterior motives. In the case of important information, the experts must try to establish a liaison with the government and health authorities and act on it. For this reason, the government and health authorities must be receptive to such information and feedback from the public and experts.

A fourth source of information is the general public (with and outside the community) itself. In this era of digital media, anyone with access to any social media handle, such as WhatsApp, X, Facebook, Instagram, YouTube, etc., can easily be a source of information, reaching out to millions at lightning speed. An infodemic can be a boon when the source is authentic and responsible. However, it is a bane when it is contaminated with myths and misconceptions [21]. Sources outside the community can also influence infodemics, for good or bad. In many countries, the government and health authorities have social media handles to disseminate authentic information. However, in some countries, restrictions are placed on social media during pandemics in a bid to prevent the spread of news (both true and false). A community that is deprived of timely information during times of suffering is prone to build mistrust. Thus, any responsible government must have a huge network of media surveillance and monitoring systems. This surveillance system can act as a feedback mechanism, as a whistleblower, a fact checker and even alert the government regarding an impending outbreak or panic. All these four sources of information (the government, the health authority, the experts and the general public) will continue to co-exist. Thus, the RCCE plan of any country must be equipped to utilise and monitor them all effectively.

Risk communication message and recipients: The risk communication message, per se, must be clear, complete in essentials and without medical jargon. As discussed previously, repeated changes must be minimised. A consistent channel of communication that provides timely information is also important to build trust. It is prudent to identify community stakeholders who can disseminate the information effectively.

It is worth noting that not all stakeholders are equally trusted by the public. Cultural, racial, religious, political and economic factors that make or break the trust in a person must be acknowledged. For instance, during the Ebola outbreaks in Africa, community engagement was found to be crucial in the safe and effective control of the disease [22]. Different sections of the affected community would require different means to communicate [23]. Hence, in the preparatory phase, it would be wise to identify the various sections and risk groups of the community and the gatekeepers to these sections. Involvement of Non-Government Organisations (NGOs) that work in these sections can also be earmarked. The gatekeepers and the social/mass media must be utilised regularly, even when there is no outbreak, to spread information regarding health and welfare. This helps build trust in the source, the message and the messenger in the community over time, which can be advantageous during a pandemic situation.

2.2.2 Integrating ERC into the health and emergency response team

At the global level, the International Health Regulations and Pandemic Treaty recommend the inclusion of risk communication plans in the pandemic preparedness and response mechanisms. The RCCE plan must be a priority activity at central, regional and local governments. The plan must be drafted in the preparedness phase and must receive government backing.

Training and facilitating roles and responsibilities: The roles of designated spokespersons at the national and regional levels in RCCE must be clearly defined. ERC and RCCE are activities that require rapid initiation and action. However, at the same time, these activities must not impede human rights and the integrity of the country. Similarly, the RCCE personnel who engage the community must be protected from physical and mental abuse. For this reason, laws and regulations safeguarding human rights, national integrity and the safety of the RCCE personnel must be established during the preparedness phase itself. These laws and regulations must be swiftly adopted and monitored at the local level during a pandemic.

The RCCE personnel must be trained in soft skills for communication and in handling conflicts. They must also possess interpersonal relationship skills to identify community stakeholders. They should be trained in understanding the local cultural, social, religious and political context, which can influence the acceptance of control measures. This would empower them to communicate the risk effectively and engage the community safely. During the Ebola outbreak, the traditional burial methods involving direct contact with the deceased posed a significant risk for Ebola transmission. Communicating the need to change these deeply ingrained cultural practices was extremely challenging and often met with resistance [18].

Training in media and community engagement: They should also be trained to handle and use the media to the advantage of public health promotion and outbreak control. Partnerships between media and health officials are essential for effective communication strategies. Training media personnel on ethical reporting can improve the accuracy of information shared with the public [13, 24]. A coordinated approach helps in addressing misinformation and fostering trust in health communications [24]. However, evidence suggests that outcomes of such training programmes have not been thoroughly assessed. Even though simulated exercises can be used for training, it would be beneficial for the personnel to be a part of various national programmes regularly, which constantly require interaction with the community. The members of the community will tend to trust and accept the channels of

communication established during the peace and personnel who routinely interact with them. Such personnel will also be able to identify the at-risk population, minority groups, potential sources of outrage and public unrest and means to prevent them. They must also be trained to adapt the guidelines to the local context and translate them into an understandable and acceptable local language. They should also be trained to monitor the situation, analyse the data (both quantitative and qualitative), and document the same. The inputs of these RCCE personnel engaged in a pandemic control situation will be of paramount importance for future preparedness activities.

Securing funding: RCCE activities can be divided into those that require funding and those that do not. For instance, training and monitoring activities require funding, whereas the use of social media for communication requires no or negligible funding. Nevertheless, most of the RCCE activities require funding. Most of the published literature highlights the lack of funding for risk communication [25]. This is probably because the countries neither earmark a separate budget for these activities nor do they encourage public funding through insurance or pool funding. Further, even when the government decides to fund these activities, it is not clear which agency must provide the funds, and hence funding is delayed. Establishment of a full-time RCCE system that regularly engages in communicating various health issues will be a cost-effective measure in both developing and developed countries. In resource-limited settings, the cost-effectiveness of the same must be evaluated. However, repeated messages and health warnings may lead to ‘information fatigue’ and negligence among the community members, which is undesirable.

WHO recommends the adoption of a strategic communication planning practice for effective RCCE (**Figure 3**).



Figure 3.
Strategic communication planning practice for risk communication and community engagement.

3. Mental health and pandemics

Pandemics are typically sudden occurrences, taking the communities by surprise. At first glance, physical health is the most affected, and healthcare systems become overwhelmed with patients seeking care for these symptoms. Amidst this, the mental health of the affected population may be overlooked or downright neglected. Vulnerable groups, such as healthcare workers, children, and those with pre-existing mental health conditions, can be particularly affected. Several features of the pandemic take a toll on the mental health of people. For instance, in a pandemic such as COVID-19, unique stressors, including social isolation, economic uncertainty and health fears, have intensified the mental health challenges. There are two patterns of mental health challenges during pandemics. First, worsening of symptoms in patients with pre-existing mental health issues may occur, especially in pandemics that last for a long duration, such as COVID-19. The disruptions of routine health services, such as the availability and accessibility of mental health professionals, mental health services and drugs, can contribute to the worsening of the symptoms. Budget and resource re-allocations are common during pandemics. Mental health professionals, like other healthcare professionals, may be involved in the care of pandemic-affected individuals, leaving the patients with mental health issues stranded. Similarly, the non-availability of cheaper, psychotherapeutic drugs through the government-run national programmes may force individuals to look for costlier alternatives or even stop the medications. The sheer stress of the pandemic can perpetuate mental health challenges.

Secondly, there can be new-onset mental health issues among people. For instance, during COVID-19, the fear of infection, uncertainty about the future and economic instability led to increased anxiety and depression among the general population [26–28]. Stress and anxiety have disrupted sleep patterns, further impacting mental health [26]. In several instances, anxiety and depression have taken severe forms, resulting in suicides and forceful, extreme isolation of children by their parents or guardians to protect them from the disease. Measures like social distancing and quarantine heightened feelings of loneliness and isolation, contributing to mental health deterioration [27, 29]. COVID-19 was also a traumatic event for many, leading to post-traumatic stress disorder (PTSD) symptoms, especially among frontline workers and those who have lost loved ones [30]. The medications used to treat the disease, for instance the use of steroids during COVID-19, can themselves precipitate mental health issues among the vulnerable.

It is now clear that mental health challenges, due to and during pandemics, must be anticipated. Hence, pandemic preparedness must also involve plans to mitigate mental health challenges. Incorporating mental health into public health policies and increasing funding for mental health services are crucial steps [30]. The countries must aim to have a strong, full-time functional mental health support system, consisting of adequate numbers of psychiatrists, psychologists and community psychiatry nurses, along with the availability of psychotherapeutic drugs. The general physicians and frontline healthcare workers must be routinely trained in the essentials of psychiatric care, which would help them identify individuals who require psychiatric care. Further, promoting public awareness and community support during the preparedness phase can help mitigate the stigma associated with mental health issues and encourage individuals to seek help [30]. It is essential to tackle stigma, expand access to mental health services, and integrate mental health into broader health and social policies to promote resilience and well-being during and after the pandemic [31]. Implementing early detection strategies and lifestyle interventions can prevent the escalation of mental health issues [30, 31]. Utilising telehealth and digital platforms can improve access to mental health services, especially

in low-resource settings [26, 29, 31]. During the pandemic, a dedicated toll-free helpline should be established to address the mental health challenges. Artificial Intelligence-based interventions must also be piloted to assist in screening and referral. Similarly, the mental health of healthcare workers must be safeguarded by providing safe working environments to protect them from abuse and conflicts with patients and the general public. Institutions will have to chart out the working hours, with rotational shifts, to provide their healthcare staff with adequate food and rest. The confidence and efficiency of the healthcare staff will be boosted through hands-on training and adequate provision of personal protective equipment and other preventive measures. The healthcare workers, like the general public, must also be urged to build coping mechanisms and have access to mental health support [28, 29].

4. Economic impacts and resilience

Pandemics can have profound and multifaceted economic impacts. For instance, COVID-19 disrupted various sectors, leading to significant declines in Gross Domestic Product (GDP) of countries, increased unemployment and shifts in consumer behaviour. Widespread pandemics expose the economic vulnerabilities of countries. In some cases, such as the HIV pandemic, there is a long-term financial impact on governments and individuals. On the other hand, outbreaks of avian influenza among poultry lead to a relatively short-term loss of livelihood with comparatively less impact. Taking the example of COVID-19, the economic impacts can be divided into three. Firstly, pandemics can lead to economic contraction. In COVID-19, there was global economic slowdown, particularly in manufacturing and services, resulting in reduced production and increased unemployment rates [32, 33]. Pandemics generally reduce labour supply [34], which is further affected by lockdowns, restrictions and, in some cases, fear-induced migration. Secondly, COVID-19 plummeted the stock prices and bond yields, creating market volatility due to uncertainty and fear surrounding the pandemic [35, 36]. Oil prices also saw a dramatic decline as a result of reduced demand from affected industries [33]. Tourism, travel and entertainment sectors are also affected during pandemics [34, 35]. Conversely, sectors such as pharmaceuticals and e-commerce have seen growth, indicating a shift in consumer priorities and spending patterns [34, 35]. While the immediate economic impacts of pandemics are severe, pandemics and outbreaks may also catalyse innovation and transformation in various sectors, provided that an opportunity for this transformation exists.

Individuals and governments must adopt economic resilience strategies to mitigate financial stress during pandemics. These strategies encompass personal finance practices, corporate financial management, community empowerment and effective fiscal policies.

Personal finance practices, such as earmarking emergency funds, are crucial at the individual level [37]. Of late, technology and AI assistance for budgeting and financial management are popular, to adapt to the changing economic situations. People who engage in multiple income-generating activities can mitigate the pandemic even when the primary source of income is disrupted. For instance, farmers who have agricultural land and rear poultry may be less affected by the culling of poultry during the outbreaks of avian influenza.

Companies must aim for corporate financial management techniques to maintain operations during economic downturns. Flexible investments and sustainable

practices, anticipating such economic crises, will help in quick adaptation and long-term resilience [38]. However, this may be difficult in the case of smaller companies, which would require government assistance to stay afloat.

Local economies, non-farm small/micro enterprises must be strengthened during the preparedness phase, to be self-reliant and sustainable, with a focus on the circular economy [39]. Families, as a unit, may also play a major role in economic resilience [40]. Governments can implement targeted fiscal measures, especially in sectors like tourism, to stimulate recovery [41].

However, pandemics can be unpredictable, and the pre-planned strategies may not work. This being the case, governments and individuals must use Information and Communication Technology (ICT) to maintain connectivity and remote activities, to mitigate the financial crises [41, 42]. Similarly, it is also important to recognise that not all communities have equal access to resources or support systems, which can exacerbate vulnerabilities during crises.

5. Data management during an outbreak

Effective data management requires the optimal use of technology, such as web-based technology, mobile devices, electronic health records and surveillance systems [43]. Data management during an outbreak is crucial for timely response and informed decision making. Several types of data are collected during pandemics, such as morbidity, mortality, epidemiological factors and movement data. While

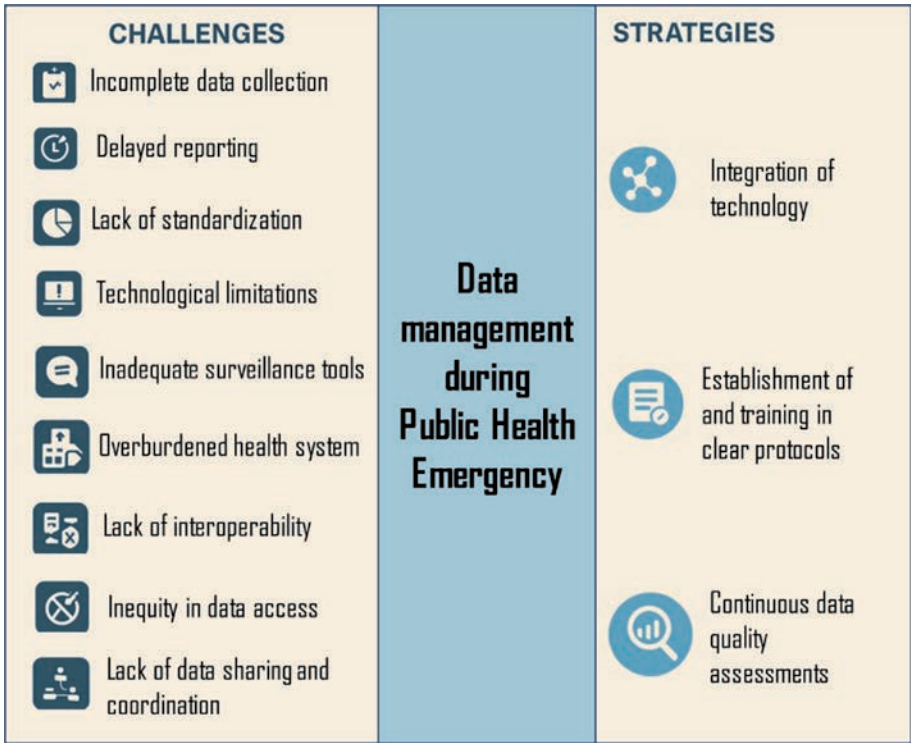


Figure 4.
Challenges in data management during pandemics and strategies to overcome them.

data collection is vital, several challenges can complicate data management efforts, particularly in resource-limited settings (**Figure 4**) [44–49].

Key strategies for effective data management include the integration of technology, the establishment of and training in them, and continuous data quality assessments.

Use of technology can improve the quality and speed of data collection, data sharing and visualisation. Technology-based solutions are generally flexible, making them easy for rapid set-up and adaptable during emergencies. Technological solutions can allow linkages between epidemiological, clinical and laboratory data, thus aiding in the outbreak investigation [44, 50]. These technological interventions can also be built to protect privacy and address legal considerations with data management [44]. Effective data management aims at rapid data collection, analysis, interpretation and dissemination. Thus, during an outbreak, standardised data formats must be prepared [45, 51]. Technology can automate workflows; however, daily validation by human curators and collaboration among data scientists and epidemiologists are essential to analyse data and propose a further course of action [52]. Thus, training of data collection staff and enhanced citizen engagement are crucial in improving the quality of data [45, 46]. Regular meetings between the national, regional and local level data management teams can ensure consistency and clarity in data management [45]. Despite the use of technology-based solutions for data management, a system must be in place for regular data quality audits [45].

6. Integration for holistic pandemic preparedness

A holistic pandemic preparedness plan, by integrating the five components—Risk Communication, Community Engagement, Mental Health, Economic Resilience and Data Management, requires a community-centric, interdisciplinary and equity-centred approach. The following sections describe the strategies that can be adapted by countries for a holistic approach.

Unified governance structure: At the central level, a task force that oversees the different components of pandemic preparedness can be established. At the regional and local levels, task forces must be established to operationalise the integration. The task force must have full political backing, with the expertise and enough funding and resources to connect the public health, economy and communication sectors.

Data-driven approach: Health and economic-related data must be routinely collected using scientific and technology-based solutions. This data must be used to identify health-wise and economically vulnerable populations and monitor public sentiment. Systems that allow interoperability and data sharing across various sectors and departments must be developed.

Community engagement: As discussed previously, all five components require community representation and support. The preparedness plan must evolve to build a system on mutual trust and respect. Community representation and feedback loops will embed community engagement into every component. Integrated communication strategies, which develop unified messaging, must be designed. These strategies must address both health and economic aspects of pandemics.

Resilient workforce: The pandemic response personnel, such as rapid response teams, healthcare workers and community volunteers, must be trained in cross-cutting competencies (such as risk communication with resistant communities, mental health sensitivity, etc.). They must be supported with funding and a strong

digital infrastructure, which can ease access to data systems, telehealth, economic aid distribution and community engagement.

Evaluation and remodelling: The integrated pandemic preparedness model comprising RCCE, mental health support, economic resilience and data management must be evaluated using a monitoring and evaluation framework. The framework must assess the performance in each of these components individually, as well as interoperability. The findings of the monitoring and evaluation framework must be used to modify strategies and adapt sustainable, interconnected solutions.

7. Conclusion

Pandemic preparedness is a multidimensional activity, which requires risk communication, community engagement, mental health promotion, economic resilience and data management. Each of these activities ensures that the affected community recovers sooner and healthier. While these activities are associated with challenges that are ubiquitous, the challenges present in different patterns in different geopolitical and disease scenarios. Thus, a policymaker and healthcare worker who aims to mitigate these challenges must familiarise with the cultural, social, political and economic matrix of the community, identify and network with the key stakeholders, build strategic communication practices and draft a workable pandemic preparedness plan. Since these activities would require time and resources, it is prudent that they be carried out in the preparedness phase and carried over to the response phase. Thus, the integration of risk communication, community engagement, mental health promotion, economic resilience and data management activities with each other, and with the routine healthcare system, is vital for a successful pandemic preparedness plan.

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Pandemic Preparedness Is Essential to Mitigate the Adverse Impact at the National and Global Levels

Subhash Hira

Abstract

Pandemics have remarkably shaped global public health, economic systems, and societies. History highlights the need of having a strong pandemic preparedness, from the STI and plagues of antiquity to the Spanish Flu of 1918, which caused over 50 million deaths, to the COVID-19 pandemic with over 7 million fatalities worldwide. SARS, H1N1 swine flu, Zika, Ebola, COVID-19, and Mpox are just a few of the recent outbreaks that show how infectious diseases are becoming more common as a result of human-animal closeness, globalization, climate change, urbanization, and inadequate public health systems. Global vulnerabilities revealed by the COVID-19 pandemic include a lack of early detection systems, inadequate health infrastructure, unequal access to diagnostics and vaccines, and disjointed international coordination. The crisis also emphasized the psychological, ethical, loss of jobs, and socio-sexual disruptions caused by widespread lockdowns, work from home, misinformation, and inequity in healthcare delivery. Pandemic preparedness is justified not only from a health standpoint but also for economic stability, global security, and equitable healthcare. National-level preparedness begins with regularly updated response plans aligned with WHO guidelines and active coordination among health, defense, and technology sectors. Strengthening hospital capacity, ensuring uninterrupted supply chains, national auditing, and training healthcare workers in ethical and clinical decision-making are critical ones. Stronger governance mechanisms are necessary on a global scale, including a ratified WHO pandemic treaty and amendments to the International Health Regulations (IHR). Ultimately, pandemic preparedness is a moral, socio-economic, and public health imperative. It must be equity-centered, science-driven, and globally coordinated.

Keywords: pandemics, preparedness, national, global, health systems, economic impacts, mitigation, IHR

1. Introduction

Pandemics are not a modern phenomenon. One of the deadliest events in recorded history, the 1918–1919 Spanish Flu killed an estimated 20–25 million people worldwide during World War I. World War I battlefields proved to be an ideal breeding ground for the virus, and it quickly spread [1]. Significant outbreaks of plague and

tuberculosis occurred in Europe during World War II. Around 2000 US Army soldiers died from tuberculosis, a chronic infectious disease, which was made worse by overcrowding, inadequate ventilation, and malnutrition during the war [2]. Since ancient times, there have been descriptions of sexually transmitted infections (STIs). One of the earliest known mentions was by a non-medical writer living around 400 AD [3]. Worldwide, sexually transmitted infections are a major issue that affects both men and women, including mothers and children. An estimated 20–30% of perinatal deaths in Zambian hospitals and maternity homes are attributed to syphilis alone [4]. Since its initial discovery by the US Centers for Disease Control and Prevention (CDC) in June 1981, HIV/AIDS has been a medical disaster. Understanding the sexual transmission of HIV and its biological, behavioral, and structural determinants was made possible by early 1980s pioneers like Dr. King Holmes, who is frequently referred to as the father of modern STI research, and Dr. Peter Piot, who co-discovered the Ebola virus and was a key figure in the global HIV/AIDS response. Their early research not only defined the epidemic but also shaped decades of policy and intervention strategy [5, 6]. Despite advances, there remains no universally accessible cure or vaccine. Both genetic and environmental risk factors are involved in the spread of HIV/AIDS and sexually transmitted infections. Due to the effects of co-receptor mutations, many HIV-positive people rapidly develop AIDS and die, while some remain symptom-free for extended periods of time. There are nine genetically different subtypes of HIV-1 within group M, which is primarily to blame for the global HIV epidemic: A-H, J, and K. Many people are deterred from getting tested and receiving treatment because of the stigma and discrimination surrounding STIs and HIV/AIDS. Poverty and cultural issues also play an important role. India, with its large population, bears the third-highest burden of HIV in the world, after South Africa and Nigeria. Bihar, Western Gujarat, and eastern Andhra Pradesh have the higher rates of HIV-infected men due to high migration, while injection of drugs is a contributing risk factor mainly in the north and east. Community customs like Nag Panchami (annual celebration to pray to snakes) are also risk factors. Because they lack education and empowerment, women and young girls are more susceptible to HIV/AIDS and STIs due to biological, sociocultural, and economic factors. Cost-effective interventions are necessary to control HIV/AIDS and STIs because people in lower socioeconomic strata are more susceptible and at a higher risk of acquiring these diseases due to a lack of education, health literacy, and information about HIV/AIDS and how to prevent it, as well as limited access to HIV and STI screening and treatment services. HIV/AIDS and STI interventions can be either population-based or person-based. People living with HIV should be in their best possible health, and this shall be achieved by overall improvement of sexual health in communities by people being fully aware of preventive measures to avoid the further spread of infection. Active participation of people living with HIV in policymaking is needed. Fighting the stigma and discrimination associated with HIV/AIDS will also help the overall happiness index of HIV patients. Strategic HIV and STI research should address virus replication and gene expression, HIV assembly, virus-cell interaction, viral pathogenesis, epidemiology, and disease transmission, and the complex interactions of the virus with the host [7–9]. The observed number of deaths is higher than the expected number of deaths, and the increasing mortality over the years is significant and observed in both sexes [10]. Globally, HIV/AIDS has killed over 40 million people and infected over 85 million people [11]. Ebola in 1976 (Zaire, now known as the Democratic Republic of Congo), Zika in 2015 from Panama, Monkeypox, which first appeared in children who had not received a smallpox vaccination in the 1980s and has since resurfaced in 2022–2023,

and the recent increase in anthrax cases in Thailand are some other significant outbreaks that demonstrate the resurgence of older infectious diseases [12–15].

Outbreaks of infectious diseases, such as COVID-19, Swine flu, and Severe Acute Respiratory Syndrome (SARS), have significantly increased in the twenty-first century. The risk of a pandemic has increased due to a number of factors. Globalization, in particular, has facilitated the rapid spread of zoonotic diseases to the human kingdom through various routes such as international trade, tourism, student exchanges, migration, and transportation networks [16]. Additional contributor factors include urbanization, and climate change with rising global temperatures enhancing the environmental suitability for the transmission of water-borne, air-borne, food-borne, and vector-borne pathogens [17]. Due to these interconnected factors, pandemics that were once considered rare have become increasingly frequent. One emerging example is the so-called “Parkinson Pandemic,” referring to the growing global burden of Parkinson’s disease linked to environmental and infectious triggers (**Table 1**) [28].

The World Health Organization (WHO) defines a pandemic as the global spread of a novel disease. Pandemics are defined by the National Institutes of Health (NIH) as having eight key features: novelty, low levels of population immunity, explosiveness, rapid spread, wide geographic reach, infectiousness, contagiousness, and severity [29]. A sudden rise in the number of cases of a new or endemic disease above what is typically anticipated in a particular population and region, on the other hand, is referred to as an epidemic [30]. In contrast to regional epidemics, pandemics impose extensive pressure on world leaders, decision-makers, and public health officials, forcing them to make morally difficult choices about containment tactics [31]. Significant societal and economic repercussions also result from policies like lockdowns and social distancing, which raise psychological stress, family conflict, overcrowding, and domestic violence [32].

In recent decades, public health responses have been influenced by a number of noteworthy pandemics. Originating in southern China, the 2002–2003 SARS outbreak claimed 774 lives in 26 countries and produced 8096 reported cases. As a result, WHO-Geneva activated the 2005 International Health Regulations (IHR), which went into force in 2007. Nevertheless, despite the IHR framework, the 2009 H1N1

Pandemic/disease	Year (s)	Pathogen	Estimated global deaths
STI	Ongoing since centuries	25	2.5 million (annually)
Smallpox	Until 1980	Variola major/minor	300 million
Spanish flu (H1N1)	1918–1920	H1N1 Influenza A	50 million
Zaire Ebola virus outbreak	1976	Zaire Ebola virus	280
HIV/AIDS	1981–present	HIV	35.7–51.1 million
SARS	2002–2003	SARS-CoV	774
H1N1 (swine flu)	2009	H1N1 influenza	284,400
Ebola (West Africa)	2013–2016	Ebola virus	11,325
Zika virus	2015–2016	Zika virus (Flavivirus)	51
COVID-19	2019–2025	SARS-CoV-2	7.1 million
Monkeypox	2022–2024	MPXV	220

Table 1.
Global death estimates for major pandemics and outbreaks [11, 18–27].

influenza pandemic exposed persistent weaknesses and highlighted global unpreparedness [33]. The largest, longest, and deadliest Ebola virus outbreak occurred in West Africa between 2013 and 2016, affecting 10 countries and resulting in 28,652 cases and 11,325 fatalities. Delays in pathogen identification, inadequate health systems, a dearth of approved treatments or vaccines, and a sluggish international response with early vaccine trials—all of which were made worse by regional cultural customs—were the major causes of the crisis [34].

The COVID-19 pandemic, which first surfaced in late 2019, has emerged as one of the century’s most disruptive global events, impacting not only public health but also economies, educational systems, and the mental health of people everywhere. While the variants BA.4/BA.5 continued to present new difficulties, the variants B.1.1.7, B.1.351, and B.1.1.28.1 were the ones of concern in India [35, 36]. Asia is facing a concerning situation as the world attempts to re-adjust to a post-pandemic reality. As of May 2025, a new wave of the COVID-19 JN.1 strain of Omicron was detected in Hong Kong, Singapore, China, and Thailand [37–39]. These pandemics, particularly COVID-19, have exposed critical challenges, underscoring the urgent need for global preparedness. Key lessons include the necessity of advancing vaccine research and development, ensuring equitable access to personal protection devices, diagnostics, therapeutics, and vaccines, and securing sustainable funding to build robust public health infrastructures, especially in low-resource settings (Table 2) [41].

Prior to the SARS outbreak, WHO’s approach primarily involved border control to prevent the spread of epidemic diseases. This was based on the lessons learnt in the London city cholera outbreak in 1920, post-WWI. However, SARS was successfully contained within 8 months through mass chicken and bird culling, early human case isolation, and quarantine measures. This experience led to the development of the IHR in 2005 [33, 42–44]. Yet, the COVID-19 pandemic revealed the limitations of existing global frameworks. The SARS-COV-2 virus remained undetected for an extended period, demonstrating unpredictable transmission dynamics and high infectivity, thereby necessitating a revision of the IHR [42, 43]. Major gaps identified in the current system include underfunding, healthcare workforce shortages, and poor global coordination. Recently, as of April 2025, due to rising political issues in the U.S., most federal grants at Harvard University were canceled, which will have a great impact on the economy, research growth, and health of Americans [45]. Furthermore, attaining global health security is severely hampered by the stark disparities between high- and low-income and middle-income nations.

Given the facts, this chapter will examine the rationale behind pandemic preparedness, highlight important national and international tactics, and provide a roadmap for enhancing resilience in the future. To manage the current and upcoming pandemics, the focus will be on multi-sectoral collaboration, implementation that prioritizes equity, and a science-driven approach.

Country	Reported COVID-19 deaths (2020–2021)	Estimated excess deaths (mean)	Estimated range (low-high)
India	829,413	3,315,582	2,657,964–6,479,563
USA	968,425	925,346	854,096–1,013,269

Table 2.
Estimated COVID-19 deaths in India and USA (2020–2021) [40].

2. Justifying the need for pandemic preparedness: Implications for public health, socioeconomics, and equity

1. Surveillance: Critical shortages in timely mortality and morbidity data during pandemics impair situational awareness in real time and cause delays in evidence-based public health responses. For early detection and global alerting of new threats, it is essential to strengthen national mortality surveillance systems, both passive (routine reporting) and active (sentinel and field surveillance). Global readiness could be greatly enhanced by the real-time integration of digital surveillance platforms such as the U.S. CDC's syndromic surveillance systems and India's Integrated Disease Surveillance Programme (IDSP) [46].
2. Protection of public health and reduction of morbidity: Public health infrastructure and clinical care systems are frontline tools for mitigation. Early detection, testing, triage, and care can greatly reduce morbidity and mortality. For instance, countries with stronger community health systems, such as Kerala in India and Medicaid funding in the US, managed early phases of COVID-19 more efficiently [47–49].
3. Socioeconomic and financial stability: Through decreased worker productivity, higher healthcare costs, and disrupted supply chains and trade, pandemics seriously damage the social cohesion of local communities and national economies. An estimated \$4 trillion was lost in global GDP in 2020 as a result of COVID-19 alone. A robust and equitable pandemic financing architecture is needed—not just limited to the Pandemic Fund but also through long-term national health emergency budgets and insurance-based models [50–53].
4. Global and National Health Security: Health security, as defined by the WHO, involves the capacity to prevent, detect, and respond to health threats. This requires multisectoral coordination among the ministries of health, defense, transportation, and technology. Without preparedness, countries risk national destabilization, as seen during COVID-19 when even high-income countries faced vaccine, antiviral medicines, ventilators, and PPE shortages. Joint preparedness frameworks like the Global Health Security Agenda (GHSA) promote international standards and peer assessments [54–56].
5. Efficient resource utilization: The key to lessening chaos during surges is a coordinated national stockpile strategy for diagnostics, personal protective equipment (PPE), intensive care unit capacity, vaccines, and necessary medications. For instance, the 2021 oxygen crisis in India brought attention to the shortcomings in health logistics, while the United States accelerated the production of ventilators and PPE through the Defense Production Act. Preparedness ensures smoother distribution, reduces panic, and prevents health systems from collapsing [57–59].
6. Equity-centered preparedness: Low-income, marginalized, and racially minority groups are disproportionately impacted by pandemics. This was particularly noticeable during COVID-19, when the mortality rates were much higher among Black and Hispanic populations in the United States and underprivileged rural populations in India. Addressing these inequities requires leadership that

prioritizes universal healthcare access, inclusive communication, and targeted intervention strategies. Preparedness must include equity indicators as essential benchmarks [60–62].

Steps to achieve pandemic preparedness: By implementing the following steps, nations and the international community can build resilient systems capable of effectively managing future pandemics, ultimately safeguarding global health and stability.

2.1 At the national level

1. National preparedness, planning, and governance: The first and foremost step is to develop and regularly update national preparedness and response plans, aligned with the global guidelines. Partnership with international bodies such as the Centers for Disease Control and Prevention (CDC) enable nations to strengthen pandemic preparedness by setting up emergency operations centers and implementing training in infection control, surveillance, clinical care, laboratory diagnostics, and workforce development [63]. High-level decision-making structures at both federal and state levels must enable integrated, multisectoral coordination [64]. Plans must also address regional coordination with WHO collaborating centers and reference laboratories, ensuring compatibility with the IHR and other global treaties. Evaluation timelines and provisions for simulation exercises and mock drills should be incorporated to enhance readiness [65].
2. Strengthening healthcare infrastructure and logistics: Pandemic preparedness demands robust healthcare infrastructure, spanning hospitals, laboratories, medicines, workforce, and real-time reporting systems. During outbreaks, multidisciplinary planning must rapidly expand emergency space, redeploy medical personnel, and build ICU capacity [66]. Coordinated patient transfer centers can optimize hospital resources and reduce overcrowding [67]. Public health laboratories are critical, offering diagnostic, serological, immunological, and prognostic services [68]. Delays in test development significantly hinder public health response. Thus, all challenges related to public health lab capacity must be proactively addressed [69]. Moreover, healthcare systems rely on five key supply categories: pharmaceuticals, PPE, medical devices, medical consumables, and blood. A breakdown in any of these supply chains can cripple the national health response [70].
3. Surveillance and early detection: Early detection of novel pathogens depends on a comprehensive surveillance model. It must include intersectoral actions targeting health promotion, reduction of social determinants of illness, and territorialized health service networks [71]. Strong communication among public and private entities, and coordination of testing and surveillance activities, is critical [72]. India's IDSP and the U.S.'s National Syndromic Surveillance Program (NSSP) are examples of decentralized, tech-supported systems. Essential elements include the following: integrated and decentralized surveillance units; training for medical and paramedical teams; and IT systems for real-time data management and intersectoral coordination for zoonotic surveillance [73]. Emerging technologies such as artificial intelligence (AI) and health devices offer predictive value for identifying early epidemic signals [74, 75].

4. Simulation exercises and workforce training: Regular simulation-based training of healthcare professionals and emergency responders in communities is essential. During COVID-19, decreased face-to-face interactions prompted greater reliance on tele-simulation and virtual reality-based tools [76]. These methods now supplement traditional clinical training, especially in health education programs. Beyond technical skills, training must address ethical issues such as resource allocation, equity, and workforce protection. Early-career professionals, already vulnerable during transitions, require targeted psychosocial and ethical support [77].
5. Communication systems and public engagement: Preparedness includes implementing public communication strategies to promote awareness, build trust, and combat misinformation. Emergency medical services (EMS), including helplines, telemed consultations, and mobile applications, should be optimized for rapid triage and information sharing [78]. Community awareness and behavior are key. Their knowledge, attitudes, and practices influence their adherence to health, wellness, and their emotional resilience during crises [79].
6. Research and development: Pandemic preparedness must include research and innovation—particularly in operations, supply chains, diagnostics, vaccines, and therapeutics. Past pandemics such as SARS, H1N1, MERS, and Ebola exposed gaps in global research collaboration and funding [80, 81]. Robust clinical research infrastructure, digital epidemic modeling, and faster publication pipelines can transform reactive responses into proactive strategies. Moreover, local manufacturing of cost-effective vaccines and therapeutics, as India demonstrated with Covaxin and Covishield, can support global access [82].
7. Legal and policy frameworks: Effective legal frameworks are indispensable for rapid response and public protection. Negotiations for a global pandemic treaty led by the WHO are ongoing, but compliance often depends on soft enforcement mechanisms [83]. At the national level, laws ensuring liability protections and streamlined emergency operations must be kept up to date. Legal immunity frameworks must be known not only to administrators but also to healthcare workers [84]. Finally, low-income countries must prepare for resource scarcity—be it ICU beds, PPE, staff, or oxygen—by legally enabling emergency procurement, fund allocation, and international cooperation (**Table 3**) [97].

2.2 At the global level

1. Strengthening global cooperation and governance: It is crucial to improve regional and global international cooperation. This involves working together with philanthropic organizations, regional public health bodies, and the WHO. Historically, global health governance institutions have struggled to secure full compliance from states regarding international legal obligations—from transparent data sharing to vaccine equity and adherence to WHO guidance [98]. The need for UN reform was rekindled by the COVID-19 pandemic. A comprehensive revision of the IHR and a new pandemic treaty led by the WHO are presently being negotiated. In addition to addressing political sensitivities such as national sovereignty and vaccine nationalism, these updates aim to improve accountability, information transparency, and equitable resource

Preparedness domain	India	United States
National plan framework	MoHFW ¹ + NCDC ² ; IDSP ³	HHS ⁴ , CDC ⁵ , FEMA ⁶ ; national response framework
Surveillance backbone	IDSP, IHIP ⁷ , RRTs ⁸	NSSP ⁹ , EOC ¹⁰ , BioSense
Surge infrastructure	Oxygen plants, DRDO ¹¹ beds, makeshift ICUs	DPA ¹² , federal stockpiles, hospital coalitions
Legal tools	Epidemic Act (1897), DM Act ¹³ (2005)	Stafford Act, Public Health Service Act
Vaccine capability	COVAXIN, Serum Institute exports	Moderna, Pfizer mRNA
Communication technology	Aarogya Setu, IVR ¹⁴ hotlines	CDC Alert System, FEMA alerts

¹MoHFW—Ministry of Health and Family Welfare. ²NCDC—National Centre for Disease Control. ³IDSP—Integrated Disease Surveillance Programme. ⁴HHS—U.S. Department of Health and Human Services. ⁵CDC—Centers for Disease Control and Prevention. ⁶FEMA—Federal Emergency Management Agency. ⁷IHIP—Integrated Health Information Platform. ⁸RRTs—Rapid Response Teams. ⁹NSSP—National Syndromic Surveillance Program. ¹⁰EOC—Emergency Operations Center. ¹¹DRDO—Defence Research and Development Organization. ¹²DPA—Defense Production. ¹³DM Act—Disaster Management Act. ¹⁴IVR—Interactive Voice Response.

Table 3.
Comparison of national preparedness—India vs. United States [74, 85–96].

distribution. For instance, more flexible provisions that address geopolitical concerns (like China’s opposition to intrusive compliance) may contribute to broader ratification of the treaty [99–101].

2. Institutionalizing regional public health agencies: The importance of regional coordination centers is demonstrated by the success of the Africa CDC, which was founded in response to the Ebola outbreak in 2014–2016. Strengthening local public health organizations and personnel, promoting regional production of vaccines and diagnostics, expanding domestic health funding, and forming fair alliances with international organizations are the main objectives of Africa CDC [102]. Inspired by this model, proposals to establish CDC-like regional hubs in Southeast Asia and Latin America have been gaining traction. Particularly in geographically or politically diverse areas, these centers can act as hubs for decentralized response, training, data exchange, and logistics coordination [103].
3. Supporting low- and middle-income countries (LMICs): The resilience of LMICs is critical to global readiness. These countries often face severe constraints in health workforce numbers, diagnostics, PPE, and hospital infrastructure [104]. Overcrowding and under-resourced settings make both mitigation and containment more difficult. Additionally, LMIC hospitals share global supply chains but lack the bargaining power to access critical resources such as ventilators, reagents, or vaccines [105]. Addressing this disparity requires more than aid—it demands capacity building in surveillance, lab testing, workforce development, and supply logistics. A global financing mechanism must be established to ensure surge funding reaches countries at the greatest risk before their systems collapse [106].
4. Equitable global stockpiling and supply chain cooperation: In high-severity pandemics, vaccines and antivirals become scarce rapidly. Thus, global

stockpiling of essential supplies—vaccines, PPE, oxygen concentrator machines, and medicines—must be systematized and equitably managed [107]. Stockpiling offers a cost-effective strategy for protecting high-risk populations but also raises ethical concerns regarding fair access and geographic equity [108]. Public preventive vaccination remains a cornerstone of pandemic response. However, equity in global vaccine distribution is still lacking. The failure of COVAX to meet its targets during COVID-19 underscores the need for enforceable vaccine-sharing agreements and decentralized manufacturing hubs [109, 110].

5. Strengthening and revising the IHR: (Box 1)

International Health Regulations (IHR)

Scope and objectives:

The IHR aims to prevent and control the international spread of diseases while avoiding unnecessary interference with international traffic and trade. They cover all public health risks, whether infectious diseases or other hazards (e.g., chemical or radiological events).

Core components of IHR:

1. Notification and reporting: Nations must inform WHO of any occurrences that might qualify as a Public Health Emergency of International Concern (PHEIC).
2. Core capacity requirements: In order to conduct surveillance, report, and respond to emergencies, nations must build, fortify, and preserve a minimum of core public health capabilities within their boundaries.
3. Temporary recommendations: In an emergency, WHO may recommend short-term actions to control health risks.
4. Legal and administrative measures: Countries agree to implement measures consistent with IHR provisions and to facilitate the international cooperation.

Implementation and compliance:

State parties commit to establishing the national public health response systems. To keep an eye on compliance, regular reporting and assessments are required. WHO will help nations fulfill their responsibilities by offering technical advice and assistance.

International collaboration:

The IHR will promote cooperation between countries and with WHO. It will emphasize transparency, information sharing, and joint response efforts.

Amendments and update:

The IHR is subject to periodic review and amendments to adapt to emerging health threats.

Legal status:

As an international treaty, the IHR is legally binding on all WHO Member States that have ratified or accepted them.

Box 1.

International Health Regulations (IHR) [33, 42–44].

6. Coordinating global research and development: Past pandemics have demonstrated that non-pharmaceutical interventions alone cannot mitigate large-scale mortality, especially in the absence of timely vaccines and therapeutics. The 1918 H1N1 influenza pandemic lacked any biomedical countermeasures, while COVID-19 saw the fastest-ever development of mRNA vaccines—but still suffered immense morbidity and mortality due to slow efficacy trials of re-purposed antiviral medicines, inequities, and late implementation [111, 112]. Global preparedness now demands: pre-positioned research platforms (for rapid vaccine prototyping); global trial networks

(especially in LMICs); robust health and social measures research infrastructure [113]; and collaborative grant frameworks that prioritize long-term, flexible, and multicentric funding [114]. The recently concluded 74th World Health Assembly emphasized a systematic, coordinated global research agenda. However, much of this remains underfunded or fragmented [115].

7. Rapid response teams and outbreak coordination centers: Rapid response teams (RRTs) are critical to early containment of outbreaks. Countries must pre-establish national and regional RRTs with multidisciplinary expertise—including epidemiology, clinical care, logistics, and risk communication [116]. Moreover, central coordination centers—modeled after the U.S. CDC EOC or India’s NCDC—should serve as hubs for triaging, resource tracking, and public messaging during surges. This avoids hospital saturation and reduces triage-related ethical dilemmas [117, 118]. Such centers should be integrated into both routine surveillance and emergency command chains, capable of shifting seamlessly from peacetime monitoring to crisis coordination.

3. Conclusion

Pandemics have impacted public health systems, economies, and societies for a long time. From the 1918 Spanish Flu to HIV/AIDS, SARS, and COVID-19, these crises have caused severe effects worldwide. They have shown how crucial it is to be prepared for pandemics.

With fast urban growth, environmental changes, and globalization, the twenty-first century is often called the “Century of pandemics” by world leaders and United Nations agencies. These changes create a setting where infectious diseases can emerge and re-emerge. The COVID-19 pandemic revealed critical gaps in national and international health systems. It underscored the need for more resources and scientific innovation. This includes disparities in healthcare access, insufficient surge capacity in many countries, data transparency issues, and problems with coordination.

Being prepared is a moral and strategic necessity, not just a choice in policy. Every government’s health strategy must be built on a foundation of improving risk communication, emergency logistics, workforce training, healthcare infrastructure, and disease surveillance at the national level. The capacity to put research into practice by funding the development of relevant vaccines, treatments, and diagnostics is equally crucial. Pandemics have demonstrated the value of cooperation and solidarity on a global scale. Mechanisms such as the proposed global pandemic treaty and the International Health Regulations need to move from aspiration to implementation. The foundation of global response frameworks must be knowledge sharing, equitable resource distribution, and assistance to low- and middle-income nations.

The United States and India offer complementary but opposing case studies: the U. S., with its robust biomedical R&D capabilities and digital health technologies, and India, with its extensive vaccine production and decentralized health initiatives. Both nations must set an example in cooperation with their multilateral partners.

In conclusion, a multisectoral, equity-focused, and science-driven strategy is needed for the future. Being prepared needs to be proactive rather than reactive. When the next pandemic hits, the world cannot afford to make the same mistakes twice. Future generations’ survival, resilience, and well-being will depend on the investments we make today in systems, science, and solidarity.

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Chapter 4

The Pandemic Personality: Interacting Levels of Personality Psychology and Behavioral Responses to COVID-19

Eric C. Prichard

Abstract

This chapter explores the idea that the “personality” of Public Health in a country is the emergent property of the collective personalities of individuals making up the society. The chapter argues that pandemics are unique situations that affect the collective personality of Public Health within a society. The chapter borrows from psychological personality theories to explore five levels at which personality can be studied in the context of a pandemic situation. The chapter ends by arguing that assessing the “Pandemic Personality” of a country could help organizations like the WHO predict how countries might respond to a new pathogen and to help craft outbreak mitigation strategies.

Keywords: COVID-19, terror management theory, pandemic preparedness, personality theory, public health psychology

1. Introduction

A paper by Coggon [1] raises a provocative question with its title: Does Public Health Have a Personality (and if so, Does It Matter If You Do not Like It)? The paper itself is about ethics, and not personality psychology per se, but the question is pertinent to this chapter. Coggon cautions against two extreme ways of conceptualizing ethics as it pertains to public health policy. One is to put excessive emphasis on the autonomy of the individual. The other is to put such an emphasis on good health as to make “Public Health” an end in and of itself at the expense of other ends and goods that might be important to people. Speaking of “Public Health” in such a way, there is a danger of personifying it and treating it as an entity with special normative authority. Coggon’s middle ground is to see public health (note I did not capitalize it this time) as a descriptive field that describes health outcomes and health risks within a community and weighs the measures taken to improve health alongside other values that are important to humans and for which they might be willing to engage in some kind of tradeoff.

Though the paper is not exactly a work from psychology, two aspects of it are striking from the year 2025. The first is that the COVID-19 Pandemic saw the debate discussed by Coggon become very relevant outside of the walls of academia. In the United States, for example, debates over the wearing of masks and the mandating of vaccines became heated and, at some points, ugly (e.g., [2, 3]). Especially bewildering from my perspective, these debates became politically polarized. Prior to 2020, my default assumption about the country I grew up in was that, for all of its many flaws, a major national emergency like a pandemic would see people coming together and acting for the common good. If young people from around the country responded to the Attack on Pearl Harbor and risked their lives fighting overseas, surely we could all wear cloth masks that were slightly uncomfortable for a while.

Needless to say, it was not that simple. Mask wearing became a marker of political identity. Conspiracy theories increased [4]. People began driving more aggressively [5]. Students lost learning as schooling went online [6]. Even 5 years later, it does not feel quite like American Society is the same as it was before. Which brings me to the second aspect of Coggon's paper that strikes me 15 years after it was written: Does public health have a personality after all? Is it indeed the proper noun Public Health, and does it matter whether I like it? Granted, Coggon means something different by personality in his paper. He's critical of ethicists committing a category error and treating Public Health as this personified thing that requires policymakers to take actions that are for its benefit. In that sense, I am not literally struck by the exact same question as Coggon. But if one conceives of Public Health as the collective behaviors, policies, and health outcomes of a society, then it raises the question of whether population-level changes in personality will affect Public Health as I defined it. After all, there is evidence that average levels of measurable personality traits can change within a society within a matter of decades. So I will use capital letters when I refer to Public Health, and it will at one and the same time mean two related things:

1. Public Health will refer to the collection of behaviors, policies, and health outcomes in a society.
2. Public Health will also refer to a sort of personified average of the health behaviors and health outcomes of a society similar to the way in which economists talk about homo economicus (e.g., [7]). However, instead of always making rational economic decisions, Public Health constantly negotiates between desired health outcomes, competing desires, and associated risks. In other words, I might use a sentence like, "Public Health in America puts an emphasis on prescription treatment of cholesterol because it is convenient and allows less radical changes to diet and lifestyle." Obviously, there are some Americans who radically change their diets and lifestyles to reduce cholesterol. But, on average, there is a tendency to emphasize medication over radical changes. You are much more likely to meet an American on statins who feels okay getting a cheeseburger than you are to meet one who has gone on a fish only diet and hired a trainer.

The contention of this chapter is that Public Health, as defined above, does have a personality. Or, rather, the personality traits common among the public drive behavior and outcomes. Further, this chapter argues that culture and context affect the prevalence of personality traits in a society. That is not to deny the influence of genes. Like most measurable traits, personality arises from an interaction of factors. The framework that this chapter will adopt is the "New Big Five" model of personality as

discussed by McAdams and Pals [8]. According to this framework, personality can be understood on five levels: Evolution and Human Nature, The Dispositional Signature, Characteristic Adaptations, Life Narratives, and the Differential Role of Culture.

Each of these levels will be briefly summarized in the sections below. The general argument is as follows: Pandemics are majorly disruptive social events. However, the way societies respond to these events is a reflection of how the event interacts with the personalities of the individuals making up the society. Because a Pandemic is a uniquely stressful event, what emerges from a pandemic is what I will call the Pandemic Personality. At the individual level, the pandemic personality is the set of traits and behavioral responses observed in an individual during the unique stressors of a pandemic. At the level of Public Health, the Pandemic Personality consists of the modal behavioral response set and the averages of measurable personality traits that collectively drive a society's response to the pandemic.

The COVID-19 Pandemic will serve as the primary case study in this chapter, although other outbreaks will be mentioned. The goal of the chapter is to encourage researchers and policymakers whose goal is pandemic preparedness to be aware of the ways in which the personalities of individuals and groups act at multiple levels to contribute to how a society responds to a pathogenic threat.

2. Level one: Evolution and human nature

The broadest level of personality, according to McAdams and Pals, is the contribution of human evolution to personality. All humans share an evolutionary history, and it is widely accepted that genetics plays some role in personality. There are a number of theories about how human evolution has contributed to general patterns of behavior and personality, but I want to focus on one in particular because it is especially relevant for a pandemic situation.

Terror management theory (TMT) is a controversial theory from the field of social psychology that argues a large portion of human culture and many common patterns of human behavior stem from humans being unique in our awareness of mortality [9]. Human cognitive evolution has resulted in the development of a sense of self or ego and the realization that death is a threat to this ego or self. The result is the development of cultural beliefs, practices, and institutions that center around creating meaning and assuring some form of post death survival. Whether we are talking about the creation of monumental structures, the development of afterlife beliefs, or strong drives to carry on family names and legacies, TMT proponents argue that this response to mortality is near universal and that it is a product of human evolution.

While some critics argue TMT tries to explain too much about human behavior and may not be directly selected for by evolution (e.g., [10]), there is evidence that increasing mortality salience can alter human behavior. In particular, TMT effects are strongest when people are reminded of their mortality and then placed under cognitive load such that they try to push thoughts of death to the periphery of consciousness [11]. Under such conditions, people have been shown to prefer more authoritarian candidates [12], double down on personally meaningful belief systems [13], and to become more hostile to outgroups with whom they have had previous tension [14].

Since death is a universal human experience and the systems and beliefs we develop to deal with death are universal, it might be expected that a large-scale mortality salience inducing situation would increase behaviors that are associated

with mortality salience. COVID-19 provided something of a perfect storm. At the same time as daily news about death counts filled the airways, people were trying to navigate life and work in an environment in which society was partially shut down and the parts that remained open rapidly changed. As such, some trends consistent with mortality salience emerged. For example, there were documented rises in xenophobia and anti-Asian sentiments during the pandemic [15]. Q-Anon, an unusually conspiratorial and authoritarian American movement, grew out of the pandemic. This movement included fantasies about Donald Trump eventually arresting and executing liberals and John F. Kennedy Jr. revealing himself to be alive and aligned with Trump's war against the deep state [16].

In addition, the pandemic also saw something of a behavioral boomerang effect. As one might expect, some people engaged in threat reduction behavior such as masking and getting vaccinated. But some people actively refused to participate in these behaviors [17]. Conspiracies about the vaccine and mistrust for medical professionals and experts became common, especially among the right wings of Western political parties. One way to potentially understand these behavioral responses is to understand them as manifestations of the general human tendency to manage terror. Responses to the pandemic became so closely associated with political preference in countries like the United States that it can be argued that masking or not masking became a visible form of affiliation with a group [18]. Even though the behaviors were seemingly the opposite, a TMT approach might argue that they both reflect the same processes.

The first broad statement to make about the Pandemic Personality is that it is a systematic response to a threat. It is the pattern of personality that we see mortality salience is activated.

3. Levels four and five: Narrative and cultural context

According to McAdams and Pals [8], the dispositional signature consists of the general traits measured at the level of the individual. Personality theories like the Big Five and the Dark Tetrad fall within this level.

As traits are discussed, it is important to keep in mind that the findings discussed still occur within a context of mortality salience. In other words, this paper assumes that even asking participants about their COVID-related beliefs and behaviors can alter their responses by reminding them of mortality. Further, it is assumed that mortality salience in some way interacts with individuals' dispositional signatures to affect their behavior.

During and in the years after the pandemic, I was involved in two lines of research on human personality and the response to the pandemic. One was at the level of the dispositional signature [19, 20]. The second was at the level of culture [21]. My research on dispositional signatures focused on traits associated with authoritarianism (as a dispositional trait), conspiricism (as a trait), and the Dark Triad. These traits are narcissism, Machiavellianism, and psychopathy. More recent research also incorporates measures of sadism and refers to the Dark Tetrad.

In my initial study, the "authoritarian personality" was measured by agreement with statements from the authoritarian dominance subscale of the Right-Wing Authoritarianism Scale [22]. The "conspiratorial personality" was measured using the Generic Conspiracist Belief Scale. Two hundred American adults were surveyed and those who were more authoritarian were less concerned about the

virus and reported less frequent mask wearing. Both those who scored higher on the measure of authoritarianism and those who were more conspiratorial were more likely to agree with the statement “China is directly responsible for the infection rates and death toll in the United States.” It is important to note that this item does not merely ask one to agree that the virus originated in China. Direct responsibility implies a greater degree of either agency or negligence on the part of the Chinese government in handling the outbreak and minimizes the role of U.S. policy in mitigating infection and death rates.

In a second study, a colleague and I sought to replicate the finding that authoritarian tendencies were associated with reduced self-reported mask wearing. The finding was replicated in a sample of 996 American participants. In addition, we used the Short Dark Triad (SD3) Questionnaire [23] to measure traits associated with psychopathy, narcissism, and Machiavellianism. Higher scores related to all three traits were associated with less self-reported mask wearing. Authoritarianism and psychopathy were also associated with less self-reported trust in advice given by scientists about the pandemic. Later, I discovered a paper by Blagov [24], which showed that individuals who scored high on measures of dark personality traits were less likely to endorse compassionate messages related to reducing COVID-19 and more like to report intending to engage in behaviors that could put others at risk.

One of the reviewers questioned the result of the replication under the premise that a previous study [25] found both Left Wing Authoritarianism and Right-Wing Authoritarianism were correlated with more support for anti-COVID measures in early 2020. However, the data from the studies published by my colleagues and I were collected months later. What happened in the meantime was a shift among American conservatives. In our paper, we pointed to previous research showing that Donald Trump’s supporters show authoritarian tendencies and that he frequently downplayed the seriousness of the virus and attacked experts such as Anthony Fauci [26]. We argued that whether an authoritarian personality supported strict lockdown measures or opposed them depends on whether their party and leadership is for or against lockdown measures. Hence, it was not authoritarianism per se that led people to resist lockdown measures. Instead, authoritarians take strong cues from their leaders, and their behavior reflects how their leaders respond to situations.

This brings the chapter to the third level of personality as defined by McAdams and Pals: characteristic adaptations. Their model is meant to address personality psychology’s version of the nature and nurture debate. To what extent are behavior and personality traits driven by genes and to what extent are they driven by situations? However, the characteristic adaptations refer to people’s behavioral response to situations. The inclusion of this level allows for the fact that different life roles and different situations may elicit different behavioral responses from the same individual. A person may be highly authoritarian, but an authoritarian may be apt to strictly enforce rules in situations where they are in power and believe the rules are important. They may be particularly defiant in situations where they perceive the rules to be an attempt by some kind of enemy or other to control them. Hence, the paradox of groups like QAnon. Superficially, they might appear anti-authoritarian because they were opposed to a perceived “deep state,” but analysis of content on QAnon forums displayed an obsession with punishing and carrying out acts of violence against perceived enemies [16]. Authoritarianism is a tendency to follow or enforce rules. It’s a tendency to believe coercive means may be required to force society to conform to the “correct” sets of values and rules. Had Donald Trump and the American Republican

Party supported strict lockdowns and severe punishments for those who violated them, there is reason to believe my colleagues and I would have obtained the opposite findings.

The second broad statement to make about the Pandemic Personality is that it emerges from an interaction with the dispositional signatures of the individuals who live through it. During a pandemic, some people get sick. Others lose loved ones. Others are called into work because they are considered essential workers. Some people live in states and countries that will have strict lockdown measures. Others will live in places with looser measures. Some people will live in places with high infection rates. People bring different political orientations to the situation. How a person responds will depend on their traits and the situation. A highly neurotic individual in a location with a high infection rate might react differently to pandemic mitigation efforts than a person with conspiracist tendencies who lives in an area with relatively fewer infections. The complexities of these interactions make universally effective public health messaging difficult, but being aware of the complexities is better than naively assuming people will generally take rational risk mitigation measures.

4. Levels two and three: The dispositional signature and characteristic adaptations

McAdams and Pals [8] include the concept of the narrative identity as a key part of personality. Individuals often view their lives in terms of a story. Early, this chapter discussed the idea of Terror Management Theory (TMT). According to TMT, mortality salience is associated with seeking affiliation and with a greater emphasis on meaning making activities. It is also associated with more xenophobia [9].

Taken together, it should not be surprising that the aforementioned QAnon became so popular during the pandemic. The conspiracy made sense of a disordered world, blamed the pandemic on scapegoats, and also gave participants a sense of meaning. The infamous “Q drops” would contain supposed clues and messages that made those who followed them feel as if they were heroic individuals part of an epic struggle against evil [27].

These developments were alarming, but these scapegoat narratives are not unheard of during pandemics. Borrini [28] published a case study of scapegoating during a bubonic plague outbreak in Italy from 1629 to 1631. Interestingly, public health officials were the ones blamed for the pandemic. In Milan, the health commissioner, Guglielmo Piazza, was accused of spreading a dark substance on the walls of the city and spreading plague. As paranoia swept through the city, Piazza was arrested and tortured, and eventually promised to be allowed to live if he implicated his “conspirators.” Under duress, he “confessed” and named several others, including a barber named Giangiacomo Mora. All, including Piazza, were executed. This is a sad story, but there is a disturbing parallel between this incident and the COVID-19 pandemic. Health officials were at the center of conspiracy theories. Those trying to help were blamed for causing the outbreak. But why? Pandemics often show the limitations of expertise. What we know about pathogens and how to fight them evolves quickly, and occasionally, initial findings or recommendations turn out not to be correct. As opposed to accepting that the situation is chaotic and science is an imperfect process, some people prefer a straightforward narrative of blame. There are clearly delineated good guys and bad guys, and we can defeat the bad guys. This kind of narrative does several things from a TMT perspective. It reduces the terror of the

possibility of randomly getting a disease. By knowing who is poisoning the walls of Milan or orchestrating the “pandemic [29],” people can regain a sense of agency and a sense that they can avoid the illness or that the illness might not even be a threat. The story gives order to their disordered universe and gives them a group of “good guys” to affiliate with and “bad guys” to oppose.

Narratives can have a positive effect too. If public health officials and essential workers are seen in a heroic light, and taking precautions against infection is seen as a prosocial or heroic act, then people can feel they are part of a heroic narrative by masking, washing their hands, or getting vaccinated.

Finally, it is important to note that personality develops and manifests within the broader context of a culture. The second area of pandemic-related research of which I have been a part has been the investigation of the relationship between tight and loose cultures and COVID-19 outcomes. My graduate school advisor from my Ph.D. years (2011–2016) and still a frequent collaborator, Stephen (Steve) Christman, is an expert on human handedness. A few years ago, he became interested in the relationship between Gelfand et al.’s [30] concept of tight versus loose cultures and the prevalence of left-handedness. Tight cultures, as defined by Gelfand et al. [30], are cultures that are associated with more top-down control of behavior and less tolerance for supposed deviant behavior. Left-handedness has been considered deviant in the past to such an extent that the word “sinister” comes from the Latin word for “left” [31]. Steve expected that tighter societies would have fewer left-handers. When you study handedness, it is not uncommon for people to ask why the research is “important.” In this case our previous work on personality and mask wearing made us interested in the question of whether these other variables, which at the population level can be seen as the reflection of a culture, predicted behavior and outcomes during the pandemic.

Using archival data from several sources, including tightness scores for U.S. states from Harrington and Gelfand [32], we found the expected correlation between lower rates of left-handedness and more tightness. We also found that states with higher levels of tightness had lower vaccination rates, higher COVID-19 rates, and higher death rates. States with fewer left-handers had lower rates of mask wearing. What is going on? The tighter states tended to be highly concentrated in the center and south of the United States. There are also states that are Republican strongholds and ones in which Donald Trump has a tendency to do well. Earlier in the chapter, I argued that whether or not someone with authoritarian tendencies will be for or against pandemic mitigation policies will depend on whether or not those whom they view as legitimate leaders will be for or against pandemic mitigation policies. One might expect tight cultures to be in favor of strict lockdown measures, but it is reasonable to expect tight cultures to behave like authoritarian individuals. If the legitimate authority is pro-lockdown, the people will follow. If they are skeptical of lockdowns, as many Republican governors were, then the people will be wary of lockdowns. The broader culture is interacting with the other levels of personality mentioned in this chapter.

5. So, what is the pandemic personality and what should public health officials do about it?

It is time to profile the Pandemic Personality. It is the collective behavioral response of a group to a pandemic and is the emergent property of many individual responses. It is Public Health’s personality under pandemic conditions. What does Public Health look like during a pandemic?

Public Health is affected by mortality salience. Mortality salience can lead to an increase in risk reduction behaviors or a boomerang effect, xenophobia, and conspiracism. In part, whether or not Public Health behaviors spread or mitigate the virus will depend on an interplay between the traits of individuals, their specific situations, the narratives they use to understand what is happening, and the broader culture.

Different combinations can lead to different outcomes. A tight, homogenous, and even authoritarian culture might take strict pandemic mitigation measures if those perceived as legitimate authorities by the majority of the culture support them and cultivate heroic narratives about virus mitigation. The same sort of culture might see hostility toward public health officials and an uptick in pathogen spreading behaviors if those they see as legitimate authorities express skepticism about the pathogen's existence, virulence, or the effectiveness of lockdown measures. Public Health is at all times being shaped by all of these interacting levels.

So, what can be done to facilitate pandemic mitigation? Suppose “Novel Virus X” begins to spread, and one is an official for an organization such as the World Health Organization. International cooperation is necessary to mitigate a pandemic threat, but how reliable is that cooperation? How does one approach the various state actors who each oversee their own public health agencies? The recommendation of this chapter is to assess the state of Public Health in regions that are experiencing outbreaks as if one is doing a personality profile. There are a lot of variables one could measure or investigate, but I mentioned specific ones throughout the chapter. I am also adding a few here. These are my own “big five” traits that I believe should be assessed when strategizing about how to approach officials in an outbreak mitigation scenario:

1. Authoritarian vs. permissive: As stated earlier, authoritarian does not refer to rule following. It refers to the degree to which coercion is seen as an appropriate response to enforcing conformity. An authoritarian society may strictly enforce public health measures or may signal to its followers that measures can be ignored. A permissive society may have a lot of individuals who voluntarily take mitigation measures or who ignore unpopular measures on individualistic grounds.
2. Tight vs. loose: This is similar to authoritarian or permissive. The distinction for the purpose of this chapter is the authoritarian vs. permissive dimension should look at the state. The tight vs. loose dimension should look at a culture. In theory, a democratic culture with little official regulation coming from the state may still be very collectivist and conformist, with social control resting with the family or social institution like the Church. An authoritarian regime might be unpopular with the majority and a vibrant counterculture might develop in the context of government oppression.
3. Prevention focus vs. treatment focus: In the context of a society's public health policies, are people incentivized to seek preventative care, or are they incentivized to wait until something is wrong? The way the system conditions individuals to respond to health may affect whether a country or state will invest in preventive measures once an outbreak becomes a concern or wait for the disease to start spreading.

4. Tolerant vs. intolerant: Once again, there is some overlap between this dimension and the first two. But, in the context of this chapter, I am referring specifically to tolerance for ethnic, religious, and sexual minorities. Where tolerance is low, scapegoating narratives are more likely to emerge. These narratives detract from actual public health measures and lead to the victimization of scapegoats.
5. Information flows freely vs. information restricted by state: Once again, this might appear to overlap with other categories. However, there is some nuance. A mostly democratic and open society might still have strict regulations about how scientific information is presented in the media. A repressive society may censor important science. A society in which information flows freely might be more susceptible to conspiracy theories.

A rating system based on these dimensions could give a country a Pandemic Personality profile. It could be used for several purposes. It could predict how state actors will respond to an outbreak. It can predict the difficulty of public health messaging within the context of a given country and might offer some insight into how public health messages should be crafted. Finally, it might help craft strategies for approaching specific state actors in attempts to get them to cooperate with global pandemic mitigation efforts.

There are several caveats and limitations that should be considered when carrying out a procedure such as the one recommended above. First, as should be evident from my discussion of the United States' pandemic response, culture varies widely even within a state or country. Second, an approach such as the one discussed above can be excessively reductionistic. Reducing something complex like a nation's pandemic response to scores on a series of dimensions invariably leads to a loss of nuance and information *if* it is not supplemented by other kinds of data, including qualitative data. However, the approach can be used as a predictive and strategic tool in a fast changing and chaotic pandemic situation.

We cannot expect that everyone everywhere will behave rationally the next time a pandemic happens. But if we know the personality of Public Health in different countries, we might be able to predict what their Pandemic Personality will look like. And for groups like the WHO, that could be invaluable in the early days of an outbreak.

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Section 2

Mitigation and Recovery

COR-MORE and Pandemic Resilience: A Multisystemic Approach to Resource Loss and Recovery

*Hadas Egozi-Farkash, Mooli Lahad and
Limor Aharonson-Daniel*

Abstract

The COVID-19 pandemic underscored the critical need to understand how societies adapt, endure, and recover from prolonged disruptions. This chapter addresses a central question for future pandemic preparedness: Which psychological resources determine whether populations emerge resilient or traumatized during global health emergencies? Drawing on Hobfoll's Conservation of Resources (COR) theory, empirical evidence from a large-scale Israeli study (April 2020), and additional theoretical perspectives, we demonstrate that resource loss—particularly the depletion of hope—was the strongest predictor of COVID-19-related traumatic symptoms. Women, low-income groups, secular individuals, and caregivers exhibited heightened vulnerability, while religious affiliation and strong social networks functioned as protective resources supporting resilience. Based on these insights, we propose a novel framework—COR-MORE (Conservation of Resources – Model of Resilience and Ecosystemic Integration). This multisystemic model reconceptualizes resilience as the coordinated management of resources across personal, familial, community, and environmental domains. The findings highlight that psychological preparedness is as essential as medical readiness, requiring the safeguarding of material, psychological, and social resources. Strengthening human–environmental interconnections can foster psychological immunity and promote more equitable resilience in the face of future global health crises.

Keywords: COVID-19 pandemic, resilience, conservation of resources, loneliness, stress, post traumatic symptoms, psychological distress, resource loss, resource gain, vulnerable populations, multisystemic model

1. Introduction

This chapter presents a narrative literature review of resilience during the COVID-19 pandemic through the lens of COR theory. In addition to the review

of existing studies, this chapter draws upon findings from a large-scale empirical study conducted by the authors in collaboration with Hobfoll [1] during the early stages of the COVID-19 pandemic. The study investigated the interplay between background variables, psychological distress, resilience factors, and resource dynamics, using an online survey administered in April 2020 to a diverse adult sample. Results revealed clear associations between resource loss, stress, loneliness, and post-traumatic symptoms, while resilience-related factors emerged as key protective elements. These findings reinforce the relevance of the COR framework for understanding the psychological impact of the pandemic. Accordingly, the present chapter integrates both theoretical insights and empirical evidence, with particular emphasis on the study we conducted as a central foundation for the analysis presented.

2. Mental health challenges during the COVID-19 pandemic

The global outbreak of the COVID-19 pandemic had major sociopsychological consequences [2, 3]. While much scholarly attention has been directed toward the virological and epidemiological dimensions of the crisis—including morbidity, vaccinations, and physical health—its psychological and social impacts are critical to understand. Pandemics usually constitute prolonged, multiphase crises that extend far beyond the immediate health emergency. Recovery from a pandemic is inherently dynamic and often evolves over years, as illustrated by the global trajectory of COVID-19. These complex and long-lasting crises demand not only sustained public health measures and economic adaptation but also continuous and integrated mental health support to address the evolving psychological consequences for individuals and communities.

The COVID-19 pandemic presented a unique form of crisis, characterized by uncertainty, chronic stressors, and disruptions to everyday life. It affected education, social welfare, mobility, and especially psychological well-being and social connectedness [4]. The pandemic triggered widespread psychological distress, with researchers framing it as a traumatic global event [5–8]. Mental health challenges associated with the COVID-19 pandemic included heightened levels of depression, anxiety, stress, traumatic symptoms, loneliness, substance use, and social withdrawal responses. The long-term consequences of these phenomena are still unclear [7, 9, 10]. In addition, research has shown increased vulnerability to psychological disorders such as overeating [11], alcohol consumption [12], binge-watching [13], drug use [14], and gambling [15]. The global decline in psychological well-being during the COVID-19 pandemic can be attributed, in part, to key psychological stressors: intolerance of uncertainty [16], disruption of functional continuity, and a heightened fear of death. The fear of death was intensified through continuous media coverage reporting daily numbers of deaths and infections [17]. While essential for infection control, social isolation, quarantine, and distancing were associated with loneliness, reduced physical activity, weakened social ties, and financial hardship—leading to emotional distress, frustration, guilt, sadness, and depression [18]. Studies also reported increased suicide risk [19]. These factors combined to generate significant emotional strain across the global population. As such, the COVID-19 pandemic provides a valuable lens through which to explore both distress and losses, recovery and adaptive coping, with implications for public health, preparedness, management, and both national and community-level interventions.

3. From personal to community resilience in pandemic times

Resilience, whether personal or communal, serves as a critical buffer against the losses faced during pandemics. It reflects the capacity—or the ongoing process—through which individuals, communities, or systems cope with disruption, recover functionality, and potentially grow in the aftermath of disaster [20, 21].

Personal resilience, as defined by Bonanno [22, 23], refers to stable psychological functioning following trauma. He posits that most individuals demonstrate resilient trajectories after adversity, emphasizing the role of flexible self-regulation in adaptation. One of the earlier theoretical efforts to conceptualize personal resilience was Lahad's BASIC Ph model, which identified six coping dimensions underlying resilience: belief, affect, social, imaginative, cognitive, and physiological factors [24]. Numerous studies have confirmed that higher levels of personal resilience are linked to improved mental health, including lower rates of anxiety, psychological distress, and depression [5, 25].

Community resilience, by contrast, is a multidisciplinary construct that spans psychology, ecology, infrastructure, and public policy. It plays a vital role in both disaster preparedness and the daily functioning of communities [26]. Defined as a dynamic process, it links a community's adaptive capacities to its ability to achieve positive adaptation in the face of adversity. This includes the capacity to prepare for, respond to, and recover from crises [27]. Personal and community resilience are deeply interconnected, highlighting their mutual dependence. During pandemics, both forms of resilience are influenced by access to and preservation of key resources, as articulated by the Conservation of Resources (COR) theory.

Pre-pandemic literature identified several core components of community resilience, including leadership, collective efficacy, preparedness, place attachment, and social trust [28]. Among these, preparedness is especially crucial, as communities often must initiate immediate life-saving responses with limited external support in the early stages of disaster [29]. Yet resilience is not static; it evolves under pressure. Communities may face internal stressors—such as resource inequities, fragmentation, or social conflict—that weaken their adaptive capacity. These so-called “dark sides” of resilience call attention to the need to address vulnerabilities as well as strengths within communal systems [30, 31].

Pandemics like COVID-19 are global in scope, transcending national boundaries and profoundly disrupting the social fabric of communities [32]. The pandemic revealed significant disparities in how communities managed its prolonged social and economic consequences—including school closures, rising unemployment, social isolation, and the shift to remote work. These disruptions placed enormous strain on community structures, exposing both latent weaknesses and strengths.

While some communities struggled to adapt, others demonstrated remarkable flexibility and local-level resilience. In the face of adversity, community members—distributing personal protective equipment, supporting isolated older adults, and providing emotional and social support. These community-driven efforts highlighted the essential role of solidarity, mutual aid, and local agency in managing public health crises [33, 34]. Such initiatives illustrate that resilience is not solely institutional—it is also reflected in the relational fabric of communities and expressed through collective action.

4. Conservation of resource theory (COR)

Among the various conceptual frameworks proposed for understanding stress responses and coping in times of crisis, Hobfoll's well-established psychological

Conservation of Resources (COR) theory [35, 36], has gained particular prominence and relevance across diverse contexts. COR theory posits that individuals strive to obtain, retain, and protect their valued resources, defined broadly to include material assets (e.g., income, housing), social resources (e.g., support networks, community ties), and psychological strengths (e.g., self-efficacy, self-esteem, optimism). Crisis events threaten or deplete these resources, affecting individuals' status, economic stability, relationships, self-concept, and beliefs. Stress, according to COR, arises primarily from the actual or threatened loss of these valued resources. Resource loss strongly predicts PTSD and other trauma-related outcomes, particularly in ongoing unsafe environments like conflict zones marked by violence, fear, and hopelessness [37].

In addition to its focus on resource loss, COR theory highlights the critical role of resource gain, especially under conditions of adversity. When individuals experience significant losses, the acquisition of new, meaningful resources becomes more valuable, both emotionally and functionally. These gains can offer psychological relief, restore a sense of purpose, and support the pursuit of personal or collective goals in the midst of crisis [38]. Importantly, resource loss is seen as disproportionately more impactful than resource gain, typically occurring more rapidly and powerfully, a dynamic known as loss spiral. Thus, individuals who begin with fewer resources are more susceptible to loss spirals that exacerbate vulnerability over time, while resource gain, though beneficial, typically has a more modest effect.

From this perspective, resilience emerges in environments where individuals have access to a broad range of personal, social, material, and energetic resources—conditions that not only buffer against loss but also support growth and recovery. Moreover, the sharing of resources—whether among individuals, families, or communities—can play a restorative role, especially for those experiencing distress or depletion [38].

5. Resource loss in the pandemic era

The COR framework is particularly relevant to pandemic contexts, where the COVID-19 pandemic intensified multiple forms of resource loss, ranging from economic instability, health-related threats, job loss, and diminished social contact to loss of predictability or control. Within the framework of COR theory, resource loss is not only disruptive but poses a significant threat to an individual's capacity to maintain psychological stability. Findings from early studies during the pandemic demonstrated a strong association between loss of resources and increased distress, particularly trauma-related symptoms such as anxiety, loneliness, and fear of infection.

However, while COR theory has been widely validated in contexts of trauma and disaster, its specific application to the COVID-19 pandemic remains relatively limited, but highly valuable. Several empirical studies have offered important insights into how resource dynamics shaped psychological outcomes during the pandemic.

This integrative review synthesizes current knowledge on COR theory in the context of the COVID-19 health crises, with a focus on psychological distress and resilience. In doing so, it highlights the explanatory power of the COR framework and outlines directions for future interventions.

6. Resource loss during the pandemic: Losing what we value

Various studies have explored how resource loss influenced mental health during the COVID-19 pandemic. A study examining university students found that resource

loss was strongly linked to anxiety, depression, and concern [39]. Moreover, those who experienced job loss as a result of the COVID-19 pandemic reported higher levels of depressive symptoms and anger [40]. Similarly, losses of financial resources, deterioration of health, and reduced self-esteem were associated with depression and peritraumatic distress [41]. Additionally, studies applied COR theory to the COVID-19 context, reported about loss in fun, in future control, in financial resources, and in social relationships during the pandemic [42]. Other studies underscored the profound impact of resource loss, linking it to elevated levels of posttraumatic stress [43], among patients during hospitalization that were infected with COVID-19 [44], among teachers adapting to remote learning with increased job burnout [45], and significant gender disparities, with women experiencing greater resource loss than men [46].

Our research demonstrated that resource loss was a significant predictor of psychological distress during the COVID-19 pandemic [1]. Notably, the loss of valued psychological resources—such as hope, life purpose, or a sense of meaning—emerged as the most substantial risk factor contributing to COVID-19-related traumatic symptoms. These emotional resources, while less tangible, are fundamental to psychological resilience, and their loss can trigger existential crises. The observed association between such losses and trauma symptoms highlights the depth of the pandemic's psychological costs. Our study also suggested that among the many psychological losses, loss of hope was most strongly associated with COVID-19-related traumatic symptoms, emphasizing the importance of hope as a crucial psychological resource during crises. Only little was known about the role of hope in the context of the pandemic. Some studies found that hope was a protective resilience factor that promotes physical and mental health, holistic wellness, and positive health behaviors across cultures and contexts during the COVID-19 pandemic [47], even protecting individuals from suicidal thoughts [48]. Additionally, intrapersonal hope, which means the conscious process of turning into oneself in order to assess and apply inner resources, was found as a significant protective coping with stress during the pandemic [49].

7. Resource gain during the pandemic: A path to recovery

Additional studies have highlighted a set of protective factors consistent with COR theory. Several studies have emphasized the critical role of personal resources—including coping styles and perceptions of stress—in shaping individuals' resilience during the COVID-19 pandemic [50]. One such study demonstrated that higher levels of psychological capital, consisting of self-efficacy, hope, resilience, and optimism, were associated with improved psychological well-being among employees during the pandemic [51]. Together, these findings suggest that the presence and activation of internal psychological resources played a vital role in buffering the psychological burden of the crisis.

Moreover, our study described that resource gain, while less impactful, was positively correlated with resilience factors [46]. The potential of gaining resources such as time with loved ones, time for pleasure, and life-meaning during the pandemic, corresponds with the Post-Traumatic Growth approach [52, 53], meaning that within every difficulty and loss lies an opportunity for recovery and growth and it points to the mental flexibility associated with resilience. Former studies have shown that a severe traumatic event of a mass nature, such as natural disasters, appears to influence both the development of post-traumatic symptoms and post-traumatic growth,

reflecting that symptoms and growth might occur because of the cognitive processes of questioning and changing certain beliefs that a highly stressful and suffering event produces [54, 55].

In addition, the COVID-19 pandemic has highlighted the urgent need to reassess humanity's relationship with its environment's resources, not only at the personal and societal level but also in terms of ecological sustainability. According to COR theory, the loss of environmental resources also poses a long-term threat to global health security. The pandemic serves as a wake-up call for policymakers, emphasizing that restoring and protecting ecological resources is not a luxury, but a necessity. Coordinated action across individual, local, national, and international systems is essential to ensure the preservation of natural systems that support human life. Investing in resilience-building through ecological responsibility can help mitigate future pandemics and secure a more sustainable future for the next generations [56]. In the wake of COVID-19, ecological recovery efforts should prioritize an integrated "One Health" approach [57]. The "One Health" approach recognizes the deep connection between human health, animal health, and the environment. The term emerged in response to early 2000s disease outbreaks, highlighting the need to link human, animal, and environmental health. It promotes integrated actions across these sectors to prevent disease, protect ecosystems, and support long-term global health and sustainability.

8. Risk factors and vulnerable populations for loss of resources

While the pandemic affected broad populations globally, specific demographic groups experienced disproportionate psychological strain. We have found that women, individuals with lower socioeconomic status, secular orientation, and caregivers of dependents with special needs were identified as particularly vulnerable [46]. These findings support prior research emphasizing the wide effects of preexisting vulnerabilities on psychosocial outcomes. Reduced access to employment, social support, and mental health resources in these groups contributes to a heightened susceptibility to resource loss spirals, which is key to understanding their increased risk under the COR theory.

Mental health outcomes during public health emergencies are deeply shaped by underlying social determinants. The disproportionate burden experienced by socioeconomically disadvantaged, health-compromised, and caregiving populations reflects long-standing structural inequalities. Viewed through the lens of Social Vulnerability [58–60], these disparities reveal how systemic inequities influence individuals' ability to prepare for, endure, and recover from destabilizing events.

9. The protective role of religiosity and spirituality

Religiosity emerged as a notable protective factor in reducing trauma-related symptoms. Religious beliefs can foster meaning, acceptance, and hope during crises, often providing individuals with a sense of purpose and a reassuring belief in a guiding, transcendent force. This sense of spiritual may balance the disruptive effects of loss and enhance the capacity to cope with prolonged uncertainty and isolation. Former studies highlighted the role of valuable resources, such as faith and community belonging, in shaping mental health outcomes during the COVID 19 pandemic [61, 62].

10. Family dynamics and unequal resource distribution

The pandemic placed families under immense strain, exacerbating existing inequities, especially families with limited financial means or members requiring special care. Conversely, families with greater economic and social capital, particularly those who were religious, and upper-middle class, were more likely to report resource gain, suggesting that resilience at the family level is linked with baseline resource availability.

Families with underlying emotional, social and physiological challenges were more prone to experiencing psychosocial disruptions during the COVID-19 crisis. These researches underscore the need for policy-level interventions that address resource inequality of protective factors and target support to vulnerable family systems [63, 64].

11. Gender differences in response to crisis

Gender differences in psychological response were particularly striking. Women reported higher levels of distress, yet they also demonstrated greater gains in emotional and relational resources. This duality may be understood through the lens of emotion-focused coping styles, where deeper emotional engagement exposes women to both higher risk and higher potential for growth.

Additionally, women's traditional caregiving roles, which intensified under lockdown, may have increased their exposure to stress while simultaneously providing meaning-making and adaptive function in their homes, reinforcing COR theory's ideas of complex resource trade-offs during crises [65].

12. Trust in authorities and the credibility of media information

Trust in authorities and the credibility of information emerged as critical determinants of public behavior during the COVID-19 pandemic. Numerous studies have shown that individuals who perceived government and health agencies as trustworthy were significantly more likely to comply with public health guidelines, including mask-wearing, social distancing, and vaccination [66–68]. Trust served not only as a foundation for behavioral adherence but also as a mediator of emotional responses: in contexts where trust in institutions was high, empathy—not fear—was more likely to drive support for restrictive policies [69]. Conversely, inconsistent communication, perceived politicization of health guidance, and conflicting messages from multiple sources eroded social and institutional trust and undermined public cooperation [70–72]. Cross-national analyses further suggest that higher media freedom, while crucial for transparency, may reduce trust in government directly and indirectly—by increasing critical assessments of governmental responses as either too lenient or too strict. However, education appears to moderate this effect, with more educated individuals showing greater trust and a more balanced view [71, 73].

Patterns of media use also shaped perceptions of credibility. According to Li et al. [74], younger adults (18–45) found social media more useful than older adults, while those aged 65 and above preferred television as their primary source of information. These findings underscore the need for differentiated, demographically sensitive communication strategies. In sum, trust and perceived credibility were not peripheral to pandemic response; they were central pillars shaping how societies navigated the crisis.

13. COR-MORE: Seeing the whole picture – A multisystemic model of resilience through resource dynamics

For many years, research on human resilience tended to focus on isolated features—examining one or two protective characteristics at a time. Scholars often focused on either the individual, the family unit, or the broader community, attempting to understand how each dimension contributed to coping [75]. Yet the COVID-19 pandemic challenged this fragmented view. It revealed just how deeply interconnected these levels are and how resilience is not a fixed trait, but a dynamic process that evolves across time, relationships, and shifting environments.

In recent years, a growing body of research has redefined resilience as a multisystemic phenomenon, emphasizing the dynamic interplay between individuals and their social, structural, and ecological environments. Rather than viewing resilience as an internal trait, scholars increasingly recognize it as a relational and context-dependent process [76–79]. In this chapter, we propose a novel conceptual framework—COR-MORE (Conservation of Resources – Model of Resilience and Ecosystemic integration)—which seeks to capture the full picture of how individuals cope with global crises such as pandemics.

Rooted in Hobfoll's Conservation of Resources (COR) theory [34], COR-MORE extends the original model by integrating an ecosystemic perspective. It conceptualizes resilience as an active, adaptive process of managing resource gains and losses across interconnected systems—personal, familial, communal, environmental and structural. This expanded view emphasizes that individuals do not confront adversity in isolation; rather, they are embedded within complex systems that shape their access to, and capacity to mobilize, resources.

COR-MORE also introduces a powerful narrative within the evolving discourse of resilience: people strive not only to protect themselves but also to safeguard the matrix of resources—material, emotional, relational, and environmental—upon which their wellbeing depends. In the context of a pandemic, these interdependencies become starkly visible, as the loss or gain of resources spreads across individuals, families, and communities, influencing collective capacity to adapt and recover.

This model contributes a multidimensional framework for understanding the psychosocial impacts of pandemics like COVID-19. It highlights how systemic inequities, fragmented support networks, and cultural mismatches in response mechanisms can exacerbate vulnerability. Importantly, COR-MORE offers a practical, context-sensitive foundation for designing interventions that are not only individual-focused but also community-embedded, culturally attuned, and policy-informed. By fostering resource integration and coordination across systems—health, education, welfare, and beyond—COR-MORE promotes a more adaptive, inclusive, and sustainable response to large-scale disruptions, such as pandemics. **Figure 1** presents the CORE-MORE framework.

14. Building resilience across systems: Insights from COR-MORE framework for crisis preparedness

Viewing resilience through a multisystemic lens, as proposed by the Conservation of Resources (COR) theory, offers a powerful framework for designing more responsive and humane pandemic management strategies. Crises such as COVID-19 reveal not only the fragility of healthcare systems but also the interconnectedness of individuals, families, communities, and institutions systems in maintaining psychological

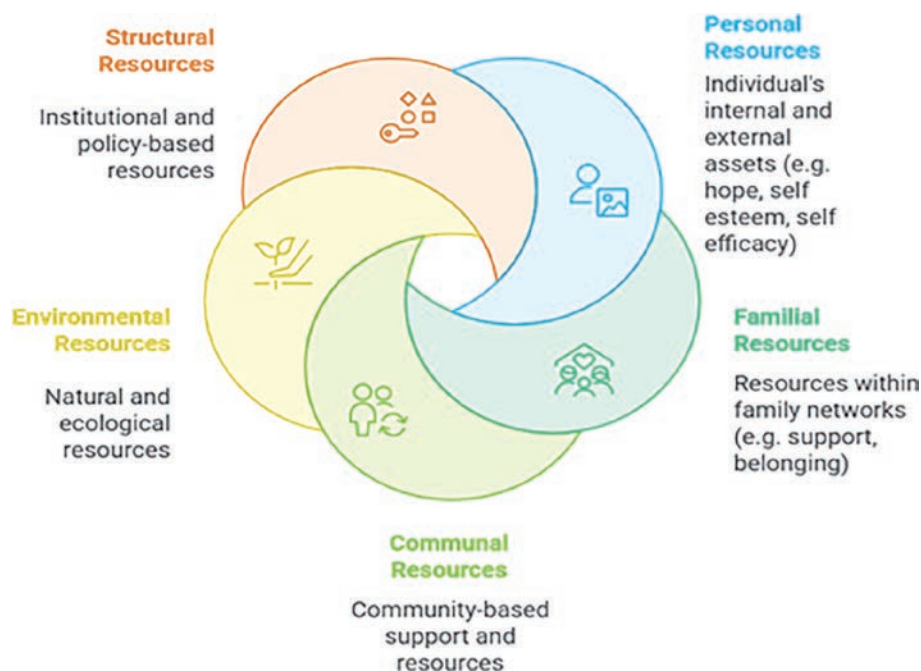


Figure 1.
 COR-MORE: Conservation of resources – Model of resilience and ecosystemic integration (made with Napkin.ia).

and social well-being. This perspective emphasizes that resilience is not merely an inner trait but a dynamic process shaped by access to, and interaction with, diverse forms of resources.

15. COR-MORE framework: Conclusions and implications for future pandemic preparedness

15.1 A multisystemic perspective on resilience

Viewing resilience through a multisystemic lens, as proposed by the Conservation of Resources (COR) theory and extended in the COR-MORE framework, offers a powerful perspective for designing more responsive and humane strategies for pandemic preparedness and recovery. Crises such as COVID-19 expose not only the fragility of healthcare systems but also the interconnectedness of individuals, families, communities, and institutions in maintaining psychological and social well-being. COR-MORE highlights resilience not as a static trait but as a dynamic, relational process shaped by access to, and interaction with, multiple resource domains.

15.2 Recommendations for policy and preparedness

Policy and preparedness efforts must move beyond siloed interventions and instead engage multiple levels of society simultaneously. Interventions should aim to protect material resources—such as income, housing, and access to services—while also fostering psychological ones, such as meaning, emotional stability, information and hope. Preventing early-stages of resource loss is critical, as COR

theory warns of “loss spirals” that can intensify distress over time. Furthermore, enhancing community resilience—through relational networks, shared narratives, and local leadership—can foster resource gain and create social reservoirs that buffer against prolonged adversity. Ultimately, a multi-level, resource-informed approach is not only more aligned with the lived experience of populations during pandemics but also better equipped to promote recovery, equity, and long-term well-being.

15.3 Applied implications for resilience promotion

Policymakers, educators, healthcare professionals, and media actors all play roles in embedding protective strategies within institutions. Emphasis should be placed on cultivating new psychological resources, enhancing self-efficacy, and fostering social connectedness. Particular attention is needed for vulnerable populations who experienced significant resource loss or chronic loneliness during the pandemic—especially those with low socioeconomic status or caregiving responsibilities. Tailored interventions and fair and inclusive policies are required to address these disparities.

As part of a comprehensive, multisystemic approach to pandemic preparedness, particular attention must be given to strengthening trust in authorities and enhancing the perceived credibility of public health information. Trust is not only a social byproduct—it is a functional component of resilience, enabling individuals and communities to navigate uncertainty, adhere to guidelines, and maintain psychological stability during crises. When information is perceived as credible and authoritative sources are trusted, the likelihood of behavioral compliance increases significantly—potentially saving lives in future pandemics or natural disasters.

Accordingly, public health and governmental systems must invest not only in logistical readiness but also in consistent, transparent, and culturally attuned communication strategies. This includes carefully considered, sensitive, and informed choices of media channels tailored to age, gender, and the specific needs of vulnerable populations—including individuals with hearing loss [80]—in order to reach as broad and inclusive an audience as possible. Building and sustaining trust should be seen as a strategic resource, integral to risk management and emergency preparedness.

15.4 Research directions and evaluation

Future research should explore mediating and moderating factors such as health information access, coping strategies, and social resources that influence distress and resilience. Studies should also investigate how resource loss and gain—related to employment, health, and family structure—affect psychological trajectories during health crises. Evaluating how systems interact and adapt over time is crucial for improving integrative, ecosystemic responses.

15.5 Strategic vision for future crises

The COVID-19 pandemic underscored the need for a paradigm shift—a transformation toward a holistic, ecosystemic approach to resilience and recovery such as the “One Health” [57] approach. Investments in climate resilience, sustainable infrastructure, and cross-sector collaboration are critical resources for human and

environmental well-being. COR-MORE supports connecting human, community, and environmental resources to enable societies to navigate complex disruptions. International collaboration emerges as a vital protective resource for promoting global public health and future crisis readiness.

15.6 Leadership, responsibility, and recovery

In the wake of the COVID-19 pandemic, a multisystemic perspective calls for a new kind of leadership—psychological, health-oriented, and policy-driven—that recognizes individuals within their broader social and ecological contexts. The COR-MORE model underscores the need for structures that not only respond to crises but also act with vision and shared responsibility.

Recovery, in this sense, is more than a return to stability. It is an opportunity to foster resilience through thoughtful coordination across human and environmental domains—ensuring that health systems are grounded in care, fairness, and a sustainable sense of public wellbeing.

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Conflict of interest

The authors declare no conflict of interest.

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Chapter 6

Clinical Microbiology in Early Diagnosis and Rapid Response to Infectious Outbreaks

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Abstract

Clinical microbiology laboratories play a main role in controlling outbreaks, epidemics, and pandemics. This chapter explores their contributions to the early detection of infectious pathogens, timely diagnosis, and response during outbreaks, epidemics, and pandemics. It shows how microbiologists contribute to rapid diagnostics, guide infection prevention strategies, and support antibiotic stewardships. Based upon the experiences of outbreaks, including the pandemic of COVID-19, and data on antibiotic resistance, the chapter outlines how laboratory data can trigger early outbreaks and inform public health decision-making. It also shows the urgent need for capacity building, networking, and integration into national preparedness plans in low- and middle-resource settings.

Keywords: microbiology, outbreak response, epidemic preparedness, pandemic management, rapid diagnostics, infection prevention, AMR surveillance, laboratory capacity, emerging pathogens

1. Introduction

Clinical microbiology laboratories play a main role in outbreaks, epidemics, and pandemics prevention and control. They enable early pathogen detection, monitoring of pathogen transmission, and guiding outbreak responses. Evidence from the 2003 SARS pandemic, the 2009 H1N1 pandemic, and the 2019 COVID-19 pandemic has shown that the community is key to controlling the pandemic, rapid diagnostics are crucial for transmission control, and timely intervention is essential [1–3].

The key role of clinical microbiology laboratories in controlling outbreaks is to rapidly identify pathogens, especially when symptoms are nonspecific. Accurate diagnosis guides infection control and supports surveillance among hospital systems. For example, the gold standard testing method, real-time polymerase chain reaction, was used for SARS-CoV-2 detection during the COVID-19 pandemic, enabling early identification, large-scale monitoring, and timely containment [4]. Clinical microbiology laboratories are essential for detecting resistance and guiding treatment in multidrug-resistant *Mycobacterium tuberculosis* (*M. tuberculosis*) [5].

Clinical microbiologists are testing experts in outbreak responses. They have contributed to diagnostic strategies, outbreak control policies, and biosafety practices.

2. Surveillance and early warning systems in clinical microbiology

2.1 Laboratory-based surveillance and its significance

Laboratory surveillance plays a main role in the outbreak, epidemic, and pandemic prevention and control. Laboratory surveillance aims to detect and respond to outbreaks promptly and effectively. Surveillance is the ongoing, systematic collection, analysis, interpretation, and timely sharing of data for the prevention and control of outbreaks. Laboratory surveillance supports this process by identifying and confirming causative infectious pathogens, enabling accurate and timely responses, monitoring antimicrobial resistance, evaluating public health interventions, identifying transmission patterns/routes, and early/rapid detection of outbreaks [6, 7].

Effective surveillance requires cooperation with national and international platforms (e.g., WHO GLASS and WHONET). Clinical microbiology laboratories have provided critical data, especially during pandemics, for timely diagnostic, outbreak control, and biosafety practices [6]. Clinical microbiology laboratories reported real-time case tracking during the COVID-19 pandemic. These results directly inform interventions, vaccine strategies, and policy development. Likewise, *M. tuberculosis* control based on laboratory data to monitor resistance trends, antibiotic resistance analysis, resistance tracking, guide treatment, and the development of infection control policies [8].

2.2 The role of clinical microbiology in early outbreak detection

Early detection is crucial for containing outbreaks. Clinical microbiology laboratories are often the first to identify unusual or emerging pathogens. Rapid confirmation enables timely public health interventions and reduces the spread of infection.

2.2.1 Timely identification of index cases

The index case is initially identified as a case of new or recurrent pathogens in a person in whom others may have been exposed. Index cases are frequently identified via routine testing in clinical microbiology laboratories. A rise in positive results or identification of rare or unusual pathogens may signal an outbreak. For example, early detection by clinical microbiology laboratories was critical in the initial identification of SARS (2003) and MERS (2012) [9, 10].

Routine analysis of microbiological data allows microbiologists to identify rising positivity rates, changes in antimicrobial resistance, and rare or unusual pathogens. These signals often appear before epidemiological recognition and trigger further investigation or outbreak response [11].

2.2.2 Laboratory alerts and case confirmation

Clinical microbiology laboratories issue alerts based on the detection of pathogens that are of public health concern, including rare or unusual pathogens. Laboratory-confirmed pathogen cases are shared with relevant authorities, e.g., infection control

and public health authorities, to guide appropriate interventions and preventive actions. For example, during early COVID-19, laboratories confirmed initial SARS-CoV-2 cases outside China by real-time RT-PCR, enabling rapid contact tracing and containment [12].

2.2.3 Support for epidemiological linkage

Clinical microbiology laboratory data is the most common method for case finding in outbreak surveillance; therefore, the most crucial role of the clinical microbiology laboratories is to promptly and accurately detect health concern pathogens, novel infectious agents, novel antimicrobial-resistant pathogens, and new governmental and public health mandates [13].

Microbiological data are essential for identifying outbreaks and transmission routes/patterns. In hospital systems, techniques like pulsed-field gel electrophoresis or whole-genome sequencing are used to confirm nosocomial spread. In the community, laboratory-confirmed cases support mapping of infection spread, which enables a straightforward and timely assessment of infectious outbreaks and the impact of interventions. This enables decision-making related to control measures by suggesting their selective application [14].

2.2.4 Bio-surveillance and variant tracking

In the early outbreak period, mNGS results of infected patients' samples enable the identification of the causative infectious pathogens. mNGS and WGS methods can help identify infectious pathogens, which may play a major role in the initial stage of an infectious outbreak. These methods enable a better understanding of the viral origin, outbreak dynamics, transmission, and evolution. mNGS and WGS are unbiased methods for identifying all taxonomic ranks in a sample. These methods allow for the identification of unculturable organisms or infectious pathogens that remain poorly characterized [15].

Metagenomics has been used to confirm a novel coronavirus-related human respiratory disease in China [16]. Metagenomics has been performed to identify SARS-CoV-2 variants, including Alpha, Delta, and Omicron, as well as respiratory co-pathogens that may contribute to the symptoms of COVID-19. The SARS-CoV-2 variants inform vaccine updates and pandemic response strategies [15, 17].

2.2.5 Role in sentinel and community-based detection

In general, any laboratory able to examine specimens that may contain pathogens of public health concern serves as sentinel units in the surveillance network. Although these laboratories are grouped as sentinel sites, their duties differ within the system. Sentinel Clinical Laboratory is certified to perform high complexity testing for the specialty of Microbiology [18].

Clinical laboratories that test human specimens often act as the first point of contact between patients and public health services. They conduct numerous key diagnostic tests, offer rapid reporting, and supply data on nationally reportable diseases and other emerging threats. Clinical microbiology laboratories should be integrated into the public health laboratory system. This coordination is vital for surveillance and response to epidemics and pandemics, including the detection of

threatening infectious pathogens such as SARS-CoV-2, resistance monitoring, and the development of appropriate vaccines [18].

Clinical laboratories cooperate with public health bodies to detect pathogens that may endanger the population. Sentinel clinical laboratories serve as the foundation for quickly recognizing threat pathogens and for initiating an appropriate response [18].

3. Rapid diagnostic technologies in epidemics

Rapid diagnostic tests play a major role in supporting infectious disease management, as accurate and timely diagnosis enables informed clinical decision-making, notably when effective therapies or vaccines are lacking. Rapid diagnostic tests are broadly divided into two groups: molecular (nucleic acid) tests and antibody-based tests. The critical role of rapid diagnostic tests in the containment efforts has been demonstrated during the COVID-19 pandemic [19].

3.1 Molecular methods: PCR, RT-PCR, and isothermal amplification

Various molecular methods have been employed to rapidly identify infectious pathogens in the combat against the pandemic; each of these methods has its advantages and shortcomings. The molecular techniques include PCR, RT-PCR, and isothermal amplification.

3.1.1 Conventional PCR

Polymerase chain reaction (PCR) and reverse transcription polymerase chain reaction (RT-PCR) are molecular methods used to amplify DNA or RNA from pathogens, allowing detection even when pathogens are present in low quantities. Reverse transcription PCR (RT-PCR) detects RNA by converting RNA into cDNA before amplification [20].

In outbreaks, PCR has been used to identify pathogens, such as *M. tuberculosis*, *Neisseria meningitidis*, and *Bacillus anthracis*, with high sensitivity and specificity. However, conventional PCR demands advanced thermal cyclers and skilled staff, which may limit its use in low-resource settings. Multiplex PCR can detect various pathogens in a single test. Several commercial PCR kits that target viruses, such as *influenza*, *RSV*, *adenovirus*, and *coronaviruses*, are available and are improving diagnostic efficiency [21, 22].

3.1.2 Real-time PCR

Real-time PCR quantifies viral load and has been utilized in outbreak diagnostics for infectious disease outbreaks, including *influenza* and SARS-CoV-2. The nucleic acid of infectious pathogens is diagnosed with the aid of real-time PCR/RT-PCR, which is the first-line screening for SARS-CoV-2. The real-time RT-PCR is considered to serve as the reference standard for SARS-CoV-2 testing due to its excellent sensitivity, quick turnaround, and consistent performance. This technique is the most suitable method, as it allows viral detection, quantification, and differentiation of SARS-CoV-2 in the samples from symptomatic and asymptomatic patients [19].

The level of nucleic acid of pathogens has affected both the sensitivity and specificity of the real-time PCR assay. Thus, the time of specimen collection and the stage of the disease may lead to inaccurate results (false negatives or positives). Therefore, real-time PCR results are depended on variables such as sampling time, disease phase, and sample origin. Different factors can influence the sensitivity, stability, and accuracy of the real-time PCR assays. Changes in the genetic targets may produce false-negative results. False-negative results prevent the accurate diagnosis of infectious patients and at-risk patients [19].

Real-time RT-PCR was recognized as the reference assay for detecting *SARS-CoV-2* during the COVID-19 pandemic. This assay enables early and quick monitoring of transmission routes and containment efforts. Its rapid results supported timely public health and outbreak responses [23].

3.1.3 Isothermal amplification (e.g., LAMP)

Isothermal amplification is widely applied to amplify DNA or RNA without the need for expensive instruments typically required in PCR or real-time PCR. This technique exhibits high sensitivity and specificity. A LAMP positive reaction can be visually observed as turbidity. This technique is both time-efficient and economical, regarding reagents and tools. LAMP is considered a point-of-care test, easily used by non-expert personnel. PoC tests are crucial and urgently needed for identifying *SARS-CoV-2*. LAMP was further developed to detect numerous viruses, including the *H7N9 influenza* virus, the *Zika* virus, *MERS-CoV*, and *SARS-CoV* [19].

Unlike real-time PCR, commercial kits for *SARS-CoV-2* detection by RT-LAMP remain scarce. The ID Now COVID-19 (Abbott, USA) is the most used. The kit can detect *SARS-CoV-2* in just 5 minutes, but with lower sensitivity compared to the real-time PCR test. Thus, further studies have been performed to improve the LAMP performance so that it can be helpful in clinical laboratories to support the preliminary detection of *SARS-CoV-2* in suspected patients [24].

Like real-time PCR, RT-LAMP can be influenced by several factors that affect its performance. Designing sequence-specific primers and optimizing reaction conditions are the main challenges of LAMP. Challenges in primer design and the use of multiple primers can result in nonspecific amplification and misdiagnosis. Mutations in the target genes can reduce the reliability of RT-LAMP results. Another limitation of LAMP is that false-positive amplification can be common [19].

Isothermal amplification techniques (e.g., LAMP) are rapid and simplified alternatives to PCR and RT-PCR. These are portable platforms and well-suited for point-of-care use because they do not require thermal cycling. LAMP has enabled rapid screening for *SARS-CoV-2* during the COVID-19 pandemic, particularly in low-resource settings where RT-PCR infrastructure is limited [25].

3.2 Antigen detection methods

Antigen detection methods identify specific proteins of pathogens. It is easy to use and is prevalent in outbreaks. Rapid antigen tests offer the advantages of a fast turnaround time and low-cost detection of pathogens, but are less sensitive than PCR tests. Antigen detection is an accurate, rapid, early, and simple method for detecting infectious pathogens [21].

Increasing the frequency of testing can contribute to lowering infection rates and better control of outbreaks. Pathogens may be identified through their nucleic acids

(DNA/RNA) or surface antigens. Antigen tests are used to detect infected patients. Antigen detection methods can identify *SARS-CoV-2* from small viral loads and provide results in about 15 minutes. They serve as a major tool to rapidly detect and separate positive patients. Thus, it enables reducing further transmission [26].

In the COVID-19 pandemic, antigen detection methods are widely used for population screening. To suppress an epidemic, early detection and timely isolation of infected patients are paramount. Recognizing infections even after the acute phase is crucial for preventing secondary infections. Thus, the frequency of testing is vital in pandemic control [26].

Tests that allow for more frequent testing or immediate testing to detect infectious pathogens during outbreaks should be prioritized. Self-testing every 3 days with a rapid antigen test and isolating positive cases promptly could help reduce further transmission of COVID-19 [27]. Rapid antigen tests were initially recommended primarily to control local outbreaks and identify symptomatic patients quickly [28]. These tests are available, convenient, and effective in detecting current infections, which aids in preventing further spread.

There are several key advantages of rapid antigen detection tests, including fast turnaround, minimal equipment requirements, user-friendly, suitability for individuals without laboratory training, and cost-effectiveness. These features make them suitable for use in early outbreak response and rapid screening across clinical and community settings [29].

The antigen tests' sensitivity is lower compared to that of molecular methods. The sensitivity depends on viral load, ranging from 50 to 80%. However, specificity has remained high, often above 95% [30]. Antigen detection has been widely used for diagnosing infectious diseases, including *influenza*, *Malaria*, *RSV*, and group A *Streptococcus*. These assays enable early clinical decisions and infection control, particularly in settings where molecular diagnostics are limited [31].

3.3 Metagenomic next-generation sequencing (mNGS)

The mNGS enables high-throughput, unbiased sequencing approach for direct detection and characterization the whole genomes of infectious pathogens. Unlike PCR, it does not require prior knowledge of pathogens, allowing identification of novel, rare, or unusual pathogens [32].

In the field of medical microbiology, mNGS facilitates quick analysis of nucleic acids present in patient samples and compares them to known genome sequences of pathogenic microorganisms to report the types and relative abundance of pathogens within a given sample. This approach is ideal for the genomic analysis of all pathogens in a sample, including both cultured and uncultured microorganisms [33].

3.3.1 Advantages of mNGS in clinical applications

There are several advantages of mNGS: (1) mNGS is a broad, unbiased strategy that does not depend on existing knowledge of infectious agents. This method can simultaneously identify different infectious agents, such as bacteria, viruses, fungi, and parasites, from one clinical sample; (2) mNGS can identify all pathogens with high sensitivity from one sample without the requirement for pathogen-specific primers. This property is particularly beneficial for detecting rare, unculturable organisms or novel pathogens such as *SARS-CoV-2*; (3) mNGS is particularly valuable in detecting infections among immunocompromised

individuals, who are often infected with multiple organisms or uncommon pathogens; (4) mNGS can detect all antibiotic resistance genes, supplying vital information that helps direct appropriate treatment. The time to results is shorter, while culture testing often requires 2–3 days and more than a week for slow-growing organisms like *M. tuberculosis*. The average turnaround time for mNGS is 48 hours, and (5) mNGS is effective in identifying infected patients who have already been treated with antibiotics, which can inhibit pathogen growth in media cultures and lead to negative results despite ongoing infection [34].

3.3.2 Limitations of mNGS in clinical applications

There are several limitations of mNGS: (1) mNGS is unable to determine viable pathogens and differentiate colonizing and pathogenic pathogens. The DNA sequence in a clinical sample only indicates the presence of pathogens; (2) it roughly determines the species of pathogens, but in a small proportion, it is highly likely to yield a negative result. Therefore, a negative result may reflect a sample high levels of non-pathogenic nucleic acids, rather than absence of pathogens; (3) the sensitivity of mNGS might be reduced in case of low levels of intracellular bacteria (e.g., MTB, *Legionella*); (4) contamination risk, which can lead to false positives; (5) it is difficult to obtain the full-length sequence of drug resistance genes from the short reads sequence (<300 bp), and it is not possible to correlate the drug resistance genes with the corresponding microbial species; (6) high cost and infrastructure requirements, leading to limited accessibility; (7) complex data analysis, requiring specialized bioinformatics expertise; and (8) longer turnaround time than rapid tests [34].

3.3.3 Applications in outbreak settings

mNGS is increasingly applied during outbreaks, epidemics, and pandemics, such as the detection of novel pathogens (e.g., SARS-CoV-2 in Wuhan, 2019); the identification of undifferentiated infections in critically ill or immunocompromised patients; the characterization of polymicrobial infections and co-infections; and the surveillance of antimicrobial resistance and virulence genes. mNGS has also supported responses to outbreaks of *Ebola*, *Zika*, and unexplained pneumonia [16].

3.3.4 Role in the future

As sequencing costs decrease, mNGS is expected to become more accessible across hospitals. It may be applied in multiple clinical contexts: (1) gathering data on virulence traits and antimicrobial resistance; (2) surveillance of outbreaks and facilitating epidemiological investigations; and (3) identifying microbial colonization that precedes clinical disease.

In the field of medical microbiology, mNGS could be applied to (1) collecting data on virulence factors and resistance genes; (2) monitoring infectious disease outbreaks and conducting epidemiological studies; and (3) detecting early pathogen colonization before clinical symptoms appear. In pandemic preparedness, it serves as a valuable tool for promptly detecting and verifying newly emerging pathogens. The mNGS complements traditional diagnostics, offering broad-spectrum detection, especially when pathogens are unknown [35, 36].

4. Rapid laboratory response in hospital settings

A rapid laboratory response plan in hospital settings for outbreaks helps facilitate early identification of outbreaks. The hospital's Clinical Microbiology Laboratory develops the plan in collaboration with relevant authorities and experts. The plan should be designed based on lessons learned from the previous international outbreak responses (e.g., Zika, Ebola in West Africa, and the COVID-19 pandemic) [37].

4.1 Activation of laboratory response during outbreaks

Hospitals must shift rapidly to emergency response in early outbreaks. This activation enables early detection and containment of epidemics. A coordinated response plan allows diagnostic accuracy, safety, and containment efficiency.

During outbreaks, the potential need for responding laboratories is to (1) rapidly develop novel pathogen-specific diagnostic testing methods, (2) collaboratively develop case definitions and testing criteria based on scientific evidence, (3) integrate public health partners to optimize response capacity, and (4) establish microbiology testing data sharing that support timely outbreak investigation [38].

A rapid laboratory response plan is beneficial for enhancing laboratory preparedness and facilitating effective coordination of responses. The importance of such a plan was demonstrated during national and international outbreak responses, in particular the Ebola virus epidemic (2014–2016) and the Zika virus epidemic (2015–2016). Thus, the rapid laboratory response plan's development should align with national and international guidelines and related regulations/laws of local, national, and international levels to enhance coordinated response capacity to outbreaks, epidemics, and pandemics [39].

The COVID-19 pandemic underscores the essential role of a timely and coordinated laboratory response in supporting outbreak control [40].

4.1.1 Triggers for activation

Outbreak response in medical laboratories is typically initiated by: (1) An unusual increase in positive test results of communicable disease such as measles or a rare disease such as anthrax, or novel pathogens or high-transmission pathogens (e.g., *N. meningitidis*); (2) A cluster of cases, as happened in the 2003 hepatitis A outbreak; (3) Detection of an outbreak from analysis of surveillance data; (4) Notification from infection control or public health authorities [41]. Once activated, medical laboratories must make adjustments to their response plans to support an efficient and timely outbreak response.

4.1.2 Key components of laboratory response

4.1.2.1 Laboratory investigation

Early investigation of a new or emerging pathogen includes creating, assessing, sharing, and adopting testing standards and recommendations with laboratory networks. The priority for supporting consistent case reporting and surveillance is to establish standardized criteria or laboratory procedures for case confirmation [42]. Rapid scaling of testing capability played a major role during the pandemic response.

In the COVID-19 pandemic, the first COVID-19 case in 2020 was confirmed using newly developed molecular diagnostic methods. The healthcare authorities continued to provide confirmatory reference testing and quality assurance to ensure the ongoing accuracy of national case detection [37].

A key challenge during outbreaks, epidemics, or pandemics is the significant increase in testing demand. Medical laboratories should plan to maintain efficiency by: Expanding working hours or adding shifts, establishing more testing sites, collaborating with other medical microbiology laboratories for overflow capacity, and forecasting to manage reagent and consumable shortages. The priority for laboratory investigations and limited resource management is risk-factor-based testing criteria and protocols. This was a key consideration during laboratory response to the Zika epidemic, as it posed significant capacity challenges due to high demand for Zika testing [43]. Likewise, testing criteria were established to prioritize testing within existing laboratory capacities at the beginning of the COVID-19 outbreak. This strategy was carried out to overcome the increasing global demand on supply chains. It enabled the rapid acquisition of laboratory supplies, equipment, reagents, personal protective equipment, specimen collection swabs, transport media, test kits, reagents, and testing platforms [44].

The laboratory response plan regarding investigation should consider: (1) Sample triage and prioritization (procedures for collecting, storing, and safely transporting samples for testing purposes to ensure accurate and timely results); (2) Biosafety protocols (biosafety, biosecurity, and infection control. These protocols must be strictly followed, especially when handling high-risk or unknown pathogens); (3) Applicable laws and regulations; (4) Test selection and verification; (5) Workforce organization (medical staffing may be adjusted through extended working hours, task redistribution, and rapid training or retraining in relevant techniques); (6) Communication and coordination (regular reporting of test results to infection control teams, emergency departments, and public health authorities is essential). Clear communication on testing capacity, turnaround times, and operational constraints allows for an effective outbreak response; and (7) Triage protocols for priority testing, quality control, standardization of testing methods, and result reporting processes are key to all aspects of laboratory response [37].

4.1.2.2 Laboratory response capacity and training

An early consideration for capacity is the availability and validation of high-throughput screening and confirmatory diagnostic test methods for infectious pathogens. National reference laboratories should rapidly develop and validate new test methods for identifying outbreaks early [42]. Public health laboratories may also be required to participate in the standardization and validation of testing protocols, instruments, and reagents to secure uninterrupted supply chains.

Lab response efforts may be limited as workforce capacity is reduced due to government-imposed measures for preventing pathogen spread. Based on experience during the COVID-19 pandemic response, measures may include extended periods of self-isolation due to confirmed disease, potential exposure, or symptomatic illness [45].

Engagement and mobilization of healthcare staff with suitable skills and expertise may play a major role in addressing capacity challenges in clinical microbiology laboratories, as demonstrated by the responses to COVID-19, Zika, and the international

deployment of mobile laboratory response teams to support the 2014–2016 Ebola epidemic in West Africa [46].

Depending on the duration of outbreak response requirements and access to remote or isolated populations, decentralization of front-line laboratory testing and other technology transfer activities may also be prioritized to expand laboratory capabilities on a temporary or long-term basis [47].

During the responses to Ebola, Zika, and the COVID-19 pandemic, national collaboration supported the decentralization of front-line laboratory testing to enhance response capabilities, while sustaining centralized national capacity for reference and confirmatory testing [44].

Flexibility in addressing capacity and capability challenges specific to novel pathogens was critical to response efforts.

The laboratory response plan should explore alternative strategies to improve testing capacity and data sharing. It should also identify surge capacity personnel with in-demand skillsets. These positions may be cross-trained and mobilized to other laboratory facilities within or across hospitals. They may also serve as part of a mobile laboratory response team [37].

4.1.2.3 Laboratory surveillance and data management

Laboratory result data is a critical input to support outbreak investigations [48, 49]. Outbreak investigations rely on the rapid availability of epidemiological information, which guides test triage, confirmatory testing, and the analysis of test outcomes. For example, during the Zika outbreak, epidemiological and clinical data were incorporated into the test process as components (e.g., pregnancy status, travel history, and onset date for symptomatic cases) to facilitate triage and route specimen testing [37].

To ensure timely laboratory surveillance and data management, early response may involve quickly developing a case definition based on consensus laboratory and epidemiological criteria of the current outbreak [47]. The identification of essential data for laboratory analysis, case confirmation, and surveillance is fundamental to this process. Standardizing confirmation rules and data requirements helps ensure uniform detection, reporting, and monitoring across regions, while improving comparability. The ability to rapidly link laboratory findings with case investigations and to associate confirmed cases with an outbreak or its origin is vital for effective surveillance. Linkage and integration of data may be complicated for separate public health authorities [37].

Laboratory surveillance and response are supported and improved by molecular epidemiology tools, such as genomics, to improve outbreak detection, case characterization, and identification of transmission routes. Whole-genome sequencing can also support real-time surveillance of pathogens [50].

Standardized approaches to documenting, monitoring, and reporting laboratory investigation results may be valuable at the start of an emerging infectious disease response. The surveillance platforms, such as current laboratory information management systems, online public health informatics, and other digital tools, are helpful for adaptively supporting pathogen surveillance and response. During the COVID-19 pandemic, early response activities included the timely and secure collection, linkage, and integration of data, as well as laboratory test results and surveillance indicator reporting [51, 52].

To enhance outbreak detection and response capabilities using “omics” approaches, longer-term planning should include operational and infrastructure requirements for data transfer pipelines and bioinformatics tools used to analyze and report results [49, 52].

4.1.2.4 Interjurisdictional engagement and communication

Strengthening intelligence sharing with relevant public health authorities and inter-jurisdictional networks is essential for informing laboratory guidelines, clinical recommendations, and supporting public health surveillance and intervention strategies [53, 54].

Identifying specific communication and reporting structures is crucial for supporting the efficient exchange of information both within and outside the system. Thus, clear and uniform communication through single-window points of contact within the healthcare authorities is crucial. Such considerations are not unique to clinical microbiology laboratory responses. The importance of clearly defined communication structures was also highlighted during the Ebola virus epidemic [53]. The public-facing, web-based Guide to Laboratory Services, a 24-hour emergency contact number, and site-based support are essential to ensure clear communication [55].

Microbiologists may also be among the most in-demand to address information requests from multiple sources that may pose a challenge to response coordination, particularly when an outbreak poses significant public concern, media interest, and political attention [37].

An effective communication method is crucial to ensure consistent messaging from public health agencies that meets the specific needs of targeted audiences. The link between laboratory guidance to public health professionals, the media, and the general public may be enhanced by social media tools and other web-based platforms [37].

4.2 Workflow adaptation and biosafety during hospital outbreaks

Healthcare staff have to adapt workflows and biosafety practices simultaneously during outbreaks. The improved biosafety protection measures and optimized workflow have ensured the safety of staff and the smooth running of daily operations. The biosafety protection measures in clinical microbiology laboratories significantly minimize infection risks for medical staff and support good laboratory practices. This prevents laboratory-acquired infections and sustains diagnostic accuracy under pressure [56].

The microbiologists are at risk of exposure, including aerosols, throughout testing processes. Therefore, adherence to workflows and biosafety practices is essential for effective prevention and control.

4.2.1 Workflow adaptation

Clinical microbiology laboratories must restructure their workflows to meet the increasing demand for tests while maintaining quality and reliability during outbreaks.

Specimens of high-risk pathogens (e.g., *SARS-CoV-2*, *Ebola*) should be handled in segregated areas. These areas should be equipped with negative-pressure systems. Specimens should be handled in biosafety cabinets to reduce cross-contamination [57].

Throughput can be increased via batch testing, automation, or rapid testing. Prioritization protocols should focus on hospitalized patients and healthcare workers.

Critical tasks should be assigned to experienced healthcare staff. Trained backup teams should be in place to maintain continuity. Rotational schedules help to reduce fatigue and allow sustained performance during prolonged responses [58].

4.2.2 Biosafety enhancements

The high risk of exposure to infectious pathogens during outbreaks requires the strict follow-up of biosafety protocols to protect healthcare staff and prevent secondary transmission.

4.2.2.1 Hand hygiene

Proper mastery of correct handwashing techniques is essential. Recall five essential aspects of hand hygiene [56].

4.2.2.2 Personal protective equipment

A suitable level of biosafety protection must be in place to protect the staff. Proper personal protective equipment (PPE), including medical masks, single-use head covers, protective clothing, face shields, gloves, waterproof isolation gowns, and shoe covers, must be used. Healthcare staff should be properly trained on the techniques for donning and doffing to prevent self-contamination [59]. Aerosol-generating protocols must be performed in BSCs with certification to ensure safety. Communicate with the clinic and reduce detection as much as possible [58].

4.2.2.3 Surface and waste decontamination

Work areas must be disinfected with effective agents (e.g., 0.1% sodium hypochlorite and 70% ethanol). All waste must be treated as infectious and disposed of using validated methods (e.g., autoclaving and incineration) [56].

4.2.2.4 Exposure response protocols

In case of exposure or spills, laboratory safety protocols must be followed strictly (immediate reporting, medical evaluation, and prophylaxis method) [58].

4.2.3 Documentation and quality assurance

All workflow and biosafety procedures must be documented and approved by the relevant authorities; strict adherence to these procedures is required.

5. The role of microbiologists in outbreak response

Microbiologists play a key role in outbreak response. They help define intervention and response protocols for the early implementation of response strategies to outbreaks. Adequate laboratory capacity is an essential component of outbreak response and vital to rapidly detect and identify infectious pathogens, outbreak readiness,

monitoring, and control of outbreaks, and providing data to prevent and control outbreaks. Microbiologists, as part of preparedness and response, must be involved in Emergency Operations Centre activities and ensure that healthcare staff and coordination are in place to respond to outbreaks [60].

Microbiologists are at the forefront of infectious disease outbreaks. They conduct critical research to identify contagious pathogens, study the biology of pathogens, and develop and test vaccines and antibiotics, making them available to the broader medical community for treating and preventing infectious diseases.

Clinical microbiologists play a major part in supporting the treatment of patients infected with pathogens. They report laboratory testing results and actively participate with clinicians in the prescription of antibiotics, the management of infectious diseases, and infection control. Microbiologists collaborate with clinical experts to active case discussions, knowledge sharing, diagnostic testing, analysis of drug resistance trends, and rapid outbreak detection. They alert clinicians to antibiotic resistance patterns and the emergence of rare or atypical isolates.

The microbiologists are evaluating the effectiveness of new antimicrobial drugs and conducting in vitro susceptibility testing for novel pathogens. They ensure the proper use of antibiotics and help guide treatment decisions through regular meetings with clinicians to promote antimicrobial stewardship and recommend the most appropriate antibiotics. Empiric therapy may not always be effective for unusual infections, highlighting the importance of collaboration between intensivists, clinicians, and microbiologists in preventing outbreaks. The experience in the pathology of pathogens, laboratory diagnostics, and infection control of clinical microbiologists supports the development of effective strategies for containing outbreaks.

5.1 Diagnostic leadership and interpretation

During outbreaks, clinical microbiologists consult on test selection, specimen collection, and result interpretation to support timely clinical decisions. Clinical microbiologists guided the selection of detection/identification tests, sampling methods, and the interpretation of results during the COVID-19 pandemic. In cases of *M. tuberculosis* and fungal outbreaks, they differentiate between colonization and active infection and recommend confirmatory techniques. By integrating medical microbiological data with clinical data, they guide treatment [61].

5.2 Infection prevention and hospital outbreak management

Key responsibilities of microbiologists include identifying hospital-acquired infections, interpreting resistance patterns, recommending isolation and patient cohorting, supporting patient/environmental sampling, and decontamination methods. Microbiologists enable the early detection of outbreaks, allowing for containment efforts, as demonstrated in outbreaks of *Candida auris* and carbapenemase-producing *Enterobacterales*, as well as the COVID-19 pandemic [62–64].

5.3 Surveillance and data reporting

Microbiologists ensure the timely and accurate reporting of medical microbiology data to relevant authorities. Their roles include: Notifying cases of high-transmission pathogens (e.g., *Neisseria meningitidis*, *Salmonella* spp., SARS-CoV-2); contributing to antimicrobial resistance surveillance; performing molecular typing and genome

sequencing for variant tracking; supporting national and international platforms such as WHONET, WHO GLASS, and local platforms to enable real-time data sharing and coordinated response [65].

5.4 Communication and public health collaboration

Clinical microbiologists serve as the bridge between collaborators, including laboratories, clinicians, and public health agencies. Their roles include responding to outbreaks, contributing to case identification and public health messaging, and advising on how to collect and transport samples, select appropriate tests, and interpret diagnostic results. Their clear communication ensures a coordinated response to outbreaks. Their consultations are beneficial for managing patients with infectious diseases [66].

5.5 Education and training

During outbreaks, healthcare staff should be trained by clinical microbiologists in specimen collection, transport, and handling; biosafety procedures; result interpretation and test limitations; and updates on emerging pathogens, variants, and diagnostic guidance.

Clinical microbiologists enhance the preparedness and safety of healthcare staff through continuous education [67, 68].

6. Collaboration and data sharing among laboratories, hospitals, and public health authorities

6.1 Reporting of data

6.1.1 Internal reporting within hospitals

Laboratory data are shared within hospitals for the following purposes: (1) to inform clinicians of timely patient management, (2) to support infection prevention and control through detection and isolation measures, and (3) to assist outbreak response committees in coordinated mitigation strategies [69].

6.1.2 External reporting to public health authorities

Clinical microbiology laboratories must report the positive cases with highly infectious pathogens, such as *Neisseria meningitidis* and SARS-CoV-2, to relevant public health authorities using:

- Paper-based reports (common in resource-limited settings).
- Electronic platforms, such as the CDC's NNDSS or Europe's TESSy.
- Automated LIS (Laboratory Information Systems).

Timely reporting enables essential outbreak responses, including contact tracing, risk communication, and containment [70].

6.1.3 Public health authorities: Data utilization and responses

Alongside receiving medical microbiology data, public health authorities also provide:

- Epidemiology of circulating pathogens and outbreak hotspots.
- Updated and published testing protocols and case definitions.
- Published reports of prevalence and regional trends.
- Requests for expanded testing during active investigations.

This feedback enables laboratories to align with evolving public health priorities and adapt to support the timely containment of outbreaks [71, 72].

6.1.4 Integration with surveillance networks

Clinical microbiology laboratories contribute to national and international surveillance platforms, such as:

- WHONET (WHO-developed software for AMR surveillance).
- GLASS (Global Antimicrobial Resistance Surveillance System).
- EARS-Net (Europe) and ReLAVRA (Latin America), Regional resistance monitoring networks.

The above platforms provide medical microbiology laboratory data for antibiotic resistance analysis, resistance tracking, and policy development [73, 74].

6.1.5 Challenges in data connectivity

Several challenges affect the integration of medical microbiology laboratory data:

- Lack of standardized data formats across systems.
- Poor interoperability between LIS, EMRs, and public health databases.
- Limited Internet access in low-income countries.
- Delays from manual data entry and verification.

Overcoming these challenges requires investment in digital platforms, training healthcare staff in data management, and fostering cross-sector collaboration. This enables epidemic intelligence, early detection, rapid response, and intervention to mitigate the impact of outbreaks [75].

6.2 Example case of the effectiveness of lab public health integration during epidemics

The importance and effectiveness of linking the laboratory with public health systems became evident in the COVID-19 pandemic. Timely diagnostics, data sharing,

and cross-sector coordination allow earlier outbreak detection, contact tracing, containment, and more targeted interventions.

6.2.1 The COVID-19 pandemic

The integration between clinical laboratories and public health systems worldwide during the COVID-19 pandemic has several advances:

- Early identification of novel pathogens: In December 2019, clinicians in Wuhan, China, have reported an unusual pneumonia; local microbiology laboratories rapidly identified and sequenced a novel virus, namely *SARS-CoV-2*. The whole-genome sequence has been rapidly published via GISAID to support global assay development [16].
- Rapid global response: The WHO published standardized real-time RT-PCR protocols, enabling national reference laboratories to perform testing to identify *SARS-CoV-2* worldwide [76].
- Public health surveillance: Medical microbiology laboratories published daily results on the number of cases, test positivity, and variants. These results directly inform interventions, vaccine strategies, and policy development [71, 72].

6.2.2 Ebola virus disease in West Africa (2014–2016)

The Ebola outbreak that occurred in West Africa from 2014 to 2016 showed the limitations of coordinating laboratory and public health systems for early containment:

- Delayed diagnostics: The absence of integrated laboratory and surveillance systems led to delayed case detection, reducing the chance for early containment and allowing the virus to spread in the community. The limited molecular testing capacity led to slow case confirmation, thereby delaying containment and interventions.
- Lack of technologies to aid in the diagnosis and management of diseases: Without integration, laboratories were not equipped or prioritized within public health planning, resulting in unsafe diagnostic environments that increased transmission risk. Field-based PCR units enabled rapid testing, enhancing contact tracing and containment, allow to rapid prevention and control of outbreaks.
- Cross-sector coordination: Real-time data sharing among the affected countries, governments, and health agencies improved transmission tracing, resource allocation, and outbreak containment. The absence of collaboration infection control regulations between laboratory and front-line care leads to preventable infections and deaths among healthcare workers. The lack of integrated IT and reporting systems between labs and public health authorities posed the negative effect on coordinated response and real-time case tracking, especially in remote areas.

- Insufficient training and workforce preparedness for outbreak diagnostics: The disconnect between laboratory systems and broader health infrastructure meant few personnel were trained in outbreak diagnostics, delaying accurate testing and appropriate response measures [77].

6.2.3 Multidrug-resistant *M. tuberculosis* (MDR-TB) surveillance

The global response to multidrug-resistant *M. tuberculosis* demonstrates the main role of lab public health integration during epidemics:

- Routine reporting: Medical microbiology laboratories have reported multidrug-resistant *M. tuberculosis* data through platforms such as WHO GLASS and national TB databases, enabling global trend analysis [65].
- Genotypic diagnostics: Tools such as Xpert MTB/RIF enable rapid detection of *M. tuberculosis* and its resistance mutations, guiding timely treatment [78]. Xpert MTB/RIF is an automated PCR test that quickly detects TB and rifampicin resistance.
- Targeted interventions: Integrated lab and epidemiological surveillance enables the identification of MDR-TB hotspots and informs risk classification, resource allocation, and containment [79].

6.2.4 Influenza surveillance networks

The Global Influenza Surveillance and Response System (GISRS) shows how connecting microbiology labs helps improve public health response. With institutions in 130 WHO member states, GISRS supports sample collection, testing, and data sharing, which inform influenza vaccine recommendations [80].

During the H1N1 pandemic (2009), GISRS enabled early detection of the novel variant and supported global tracking, underscoring the role of coordinated medical microbiology laboratories in pandemic preparedness [81].

The responses to these four above pandemics highlight the crucial role of global laboratory coordination, investing in laboratory infrastructure, cross-sectoral coordination, standardized digital reporting, and timely data exchange.

7. Challenges and future directions in clinical microbiology for outbreak preparedness

7.1 Overcoming antimicrobial resistance as a hidden pandemic

The antimicrobial resistance progresses slowly, but poses a severe public health concerns. Drug-resistant pathogens have caused rising morbidity, mortality, and healthcare burden globally.

Clinical microbiology laboratories play a main role in reducing antimicrobial resistance rate. They are also providing susceptibility testing profiles and supporting antimicrobial stewardship. However, the global response is impeded by limited and inconsistent diagnostic capacity, disease surveillance infrastructure, and limited cross-sector coordination. These limitations have delayed the identification and

undermine the implementation of effective intervention strategies during outbreaks, epidemics, or pandemics [82, 83].

7.1.1 Antimicrobial resistance as a global health emergency

Antimicrobial resistance is recognized as a serious global health threat that has resulted in a decline in treatment options. Antimicrobial resistance leads to patients facing prolonged illness, increased rate of complications, and higher healthcare costs. In 2019, antimicrobial resistance bacterial infections caused 1.27 million deaths, excess those from HIV/AIDS and malaria. The World Health Organization (WHO) has identified antimicrobial resistance as a top public health priority [84, 85].

Unlike acute outbreaks, antimicrobial resistance progresses slowly, making early detection and timely response more difficult. Clinical microbiology laboratories are essential to antimicrobial resistance surveillance, routine antibiotic susceptibility testing, and trend monitoring. Integrating medical microbiology laboratory data into national and worldwide surveillance systems is crucial to reduce antimicrobial resistance rate and burden [86].

7.1.2 Role of microbiology laboratories

Clinical microbiology labs play a major role in tracking and controlling antimicrobial resistance. They perform routine antimicrobial susceptibility testing identifies resistance profiles of pathogens, guiding treatment and supporting public health responses [87].

Clinical microbiology laboratories identify resistance mechanisms such as extended-spectrum beta-lactamases, carbapenemases, and methicillin resistance in *Staphylococcus aureus*. The empirical treatment and effectively prevention and control of outbreak may rely on these data. Antibiotic susceptibility testing profiles should be submitted to national and global surveillance systems, such as WHO GLASS, to share data with relevant authorities. Clinical microbiologists guide antimicrobial stewardship and enable timely public health interventions by monitoring resistance trends and sharing data regularly via surveillance systems [88].

7.1.3 Surveillance challenges

Antimicrobial resistance surveillance remains fragmented, mainly in poorer countries. Challenges include outdated and unequal capacity in medical microbiology laboratories, inconsistent antibiotic susceptibility testing methods, weak connectivity between clinical microbiology laboratories and public health databases, and the absence of standardized protocols and quality control systems. These factors undermine the reliability and comparability of the data [88, 89].

These challenges may be overcoming by targeted investments in medical microbiology laboratories. Priorities include facilitate to access to molecular and culture methods, standardized antibiotic susceptibility testing platforms, and integrating laboratory information systems into national surveillance frameworks to enhance AMR detection, reporting, and response coordination [90, 91].

7.1.4 Integration into outbreak preparedness

The outbreak preparedness planning should be included antibiotics resistance profiles. Real-time resistance monitoring is essential during outbreaks/epidemics, particularly

for managing secondary bacterial infections, as seen in hospitalized COVID-19 patients. Outbreaks of resistant organisms, such as *Candida auris* or carbapenem-resistant *Enterobacterales*, require antimicrobial resistance data for effective containment [92].

Incorporating antimicrobial resistance data into emergency treatment protocols improves therapeutic outcomes and supports effective antimicrobial stewardship. This integrated model enhances public health responses to both outbreaks/infections and the threat of antimicrobial resistance [93].

7.1.5 Future directions

Antimicrobial resistance is a “hidden pandemic”; thus, it requires the sustained and strategic involvement of clinical microbiology laboratories. Priorities include expanding rapid molecular diagnostics (e.g., PCR to detect antimicrobial resistance genes) and whole-genome sequencing to monitor the evolution and transmission of resistance [35, 36].

Global data sharing and cross-sectoral coordinated surveillance on antimicrobial resistance are essential for detecting emerging threats and guiding global interventions. Clinical microbiology laboratories should collaborate with antimicrobial stewardship authorities and the clinical care units. To support therapeutic decision-making, the collaboration among clinical microbiology laboratories, antimicrobial stewardship authorities, and the clinical care units is essential. The investment in development of testing methods, in digital infrastructure, and healthcare staff is required to facilitate this collaboration. Antimicrobial resistance surveillance should be integrated into routine diagnostics and outbreak preparedness to support antimicrobial efficacy and preserve treatment options.

7.2 Innovations and future opportunities for microbiology in outbreak preparedness

Advances technology and international collaboration are key to effective outbreak response.

7.2.1 Point-of-care molecular testing

Molecular techniques, like the Xpert MTB/RIF assay, detect *M. tuberculosis* complex and resistance to rifampin under 2 hours. The ID NOW™ COVID-19 test identifies SARS-CoV-2 in less than 15 minutes. These systems are widely used to diagnose infections such as *M. tuberculosis*, *influenza*, and SARS-CoV-2 and help to reduce diagnostic delays. Expanding point-of-care testing to primary care, border control, and remote areas will improve early outbreak detection [94].

7.2.2 Digital health and laboratory information systems

The integration of laboratory testing results with digital platforms is important for real-time surveillance and monitoring of outbreaks, automated monitors for detecting unusual trends, applying artificial intelligence in analytics to interpret resistance patterns and optimize test utilization, and utilizing mobile applications for specimen tracking, result reporting, and communication. These tools enhance rapid reporting and coordination among clinical microbiology laboratories, clinicians, and public health authorities [69, 95, 96].

7.2.3 Genomic surveillance and pathogen discovery

Whole-genome sequencing has enabled tracking of transmission and evolution of infectious pathogens.

- mNGS and WGS are the useful approaches for tracking of transmission and evolution of infectious pathogens. These techniques have enabled the rapid identification of SARS-CoV-2 variants like Alpha, Delta, and Omicron, allowing timely vaccine development and effective public health interventions.
- For *M. tuberculosis* and foodborne outbreaks, genomic typing has helped detect sources of infection and improve outbreak containment.

Metagenomic sequencing facilitates the real-time identification of novel or unusual pathogens, thereby supporting outbreak preparedness [17].

7.2.4 Emerging applications of artificial intelligence in laboratory and public health practice

Artificial intelligence is increasingly applied in healthcare systems and provides critical support for timely outbreak response:

- Using mobility, climate, and population data to forecast outbreak hotspots and inform public health interventions.
- Machine learning models using medical microbiology laboratory databases to identify emerging trends in antimicrobial resistance, enabling early detection and containment.
- Clinical support systems guide clinicians in choosing appropriate diagnostic tests and interpreting results, especially in cases of co-infections or rare pathogens.

These artificial intelligence tools are helpful in low-resource areas. It may improve diagnostics and optimize medical microbiology laboratory resources and testing [97].

7.2.5 Strengthening laboratory systems through long-term investment

Several key supports for the integration of clinical microbiology laboratories into outbreak preparedness and response systems:

- Workforce development: Well-trained and retained laboratory professionals to enable consistent diagnostic capacity during routine and crisis periods.
- Quality assurance systems: Standardized protocols, which are approved by relevant authorities, and participation in external quality assurance programs to enhance accuracy and reliability.
- Regional laboratory networks: These systems provide timely diagnostics, reduce reporting delays, and enable rapid response and containment of outbreaks.
- Public-private partnerships: Collaborations between governments, industry, and regulatory agencies to support the development of new diagnostic technologies.

Africa CDC's tiered lab network (which enhances regional diagnostic resilience) and WHO-FIND collaborations (promote global access to essential diagnostics) are successful examples. Innovation is critical for clinical microbiology laboratories as a core component of global epidemic preparedness and response [98].

8. Conclusion

Clinical microbiology laboratories are crucial to effective outbreak preparedness and response. They allow early outbreak detection, guide diagnostic, surveillance, and containment efforts. Clinical microbiology laboratories contributed to the development of molecular diagnostics, implementation of biosafety practices, and integration into multidisciplinary emergency response systems. Experiences from the outbreaks, epidemics, pandemics, and antibiotics resistance data worldwide underscore the crucial role of real-time data sharing and microbiologist interpretation in informing clinical and public health decisions.

Future efforts must prioritize the expansion of point-of-care diagnostic platforms, digital system integration, and the application of artificial intelligence in clinical microbiology laboratory. Investment in these platforms is essential to building health-care systems capable of early detection and rapid response to outbreaks, epidemics, and pandemics.

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Beyond Resistance: The Virulence Determinants Fueling Hypervirulent *Klebsiella pneumoniae*'s Threat

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Abstract

In recent years, hypervirulent *Klebsiella pneumoniae* (hvKp) has emerged as a major global health threat, known for its ability to cause severe, invasive infections even in healthy individuals. Unlike classical strains of *K. pneumoniae*, hvKp carries a unique set of virulence determinants that extend beyond antimicrobial resistance to enhance its pathogenic potential. This chapter explores key virulence factors driving hvKp's heightened infectivity, including its robust polysaccharide capsule, iron-scavenging siderophores (aerobactin, yersiniabactin), biofilm formation, and specialized adhesins that facilitate tissue colonization and immune evasion. It also examines the role of virulence-regulatory genes in modulating pathogenicity and antibiotic resistance. Understanding these virulence mechanisms is crucial for developing effective diagnostic, preventive, and therapeutic strategies to combat the growing virulence and threat of hvKp infections.

Keywords: hypervirulent *Klebsiella pneumoniae*, virulence determinants, hypermucoviscosity, capsule, aerobactin

1. Introduction

Klebsiella pneumoniae has emerged as a significant public health threat due to its ability to acquire antimicrobial resistance and evolve hypervirulent phenotypes. Among its variants, hypervirulent *Klebsiella pneumoniae* (hvKp) is distinguished by its capacity to cause severe infections even in healthy individuals. In the past decade, hvKp has been associated with invasive syndromes, such as pyogenic liver abscesses, meningitis, and necrotizing fasciitis, with high morbidity and mortality rates [1].

Global surveillance data highlights a rising trend of hvKp cases, particularly in the Asia-Pacific region, which is now spreading to other parts of the world [2, 3]. Factors such as international travel and global trade have facilitated the dissemination of

hvKp to previously unaffected areas [4]. Compounding this threat, hvKp frequently evades traditional diagnostic methods due to overlapping phenotypic traits with classical strains (cKp). For instance, while hypermucoviscosity is a hallmark of hvKp, it is neither universally present nor exclusive to these strains [5, 6]. Recent advances in molecular diagnostics have identified virulence-associated genes such as *iucA*, *rmpA*, and *peg-344* as reliable markers for hvKp identification [7].

The first documented case of hvKp emerged in Taiwan during the 1980s, involving a liver abscess with severe complications such as endophthalmitis [2]. This strain, characterized by enhanced pathogenicity, was subsequently classified as hvKp. Since then, hvKp has gained global attention due to its high virulence and association with severe community-acquired infections [3–5].

Key determinants of hvKp's virulence include its hypermucoviscous capsule, iron-scavenging siderophores (significantly aerobactin), biofilm formation, and specialized adhesins that facilitate immune evasion and tissue colonization [6]. Adding to its complexity, hvKp infections are increasingly linked to multidrug-resistant strains (MDR-hvKp), particularly those harboring carbapenemase genes. These strains represent a dire challenge for healthcare systems worldwide [5, 7, 8]. Despite significant progress in understanding these mechanisms, much remains to be explored regarding their regulation and interaction. This chapter will delve into the primary virulence factors of hvKp and their roles in infection dynamics, highlighting the urgent need for advanced diagnostic, preventive, and therapeutic strategies in the face of this growing global health crisis.

2. Discovery and epidemiology

Klebsiella pneumoniae, a Gram-negative bacterium commonly found in the human gastrointestinal tract, has long been identified as an opportunistic pathogen, particularly in immunocompromised individuals. However, the emergence of hypervirulent strains of *K. pneumoniae* (hvKp) marked a shift in the understanding of this pathogen's potential. In 1986, a notable case emerged in Taiwan involving a *K. pneumoniae* liver abscess (KLA) with severe extrahepatic complications, including purulent meningitis, prostate abscess, and pyogenic ophthalmia. Despite receiving aggressive treatment, the patients ultimately lost their vision [2].

Historically, pyogenic liver abscesses were considered polymicrobial infections, with *Escherichia coli* being the primary causative agent [9, 10]. However, this case revealed that *K. pneumoniae* alone could cause a liver abscess, signaling the emergence of a new invasive syndrome. HvKp is notable for its hypermucoviscosity (HMV) phenotype, which allows the bacteria to produce an unusually thick, sticky capsule that helps the pathogen evade the host immune system. This phenotype is primarily regulated by genes such as *rmpA*, which control the synthesis of the capsular polysaccharides, an important determinant of virulence. Interestingly, concurrent research by Nassif and Sansonetti [11], as well as Nassif et al. [12], identified a ~180-kbp plasmid in *K. pneumoniae* strains. This plasmid harbored genes encoding aerobactin and its receptor, along with *rmpA*, which is associated with a mucoid phenotype. In addition to its virulence factors, hvKp also possesses pathogenicity islands, which are genetic elements that encode virulence determinants such as iron acquisition systems, siderophores, and type III secretion systems. These factors are essential for hvKp's ability to invade tissues, acquire nutrients, and evade the host immune response, further enhancing its pathogenic potential.

The epidemiology of hvKp has evolved significantly in recent decades, with the bacterium emerging as a cause of both healthcare-associated infections and community-acquired infections. Initially, hvKp was reported predominantly in Southeast Asia, where it was associated with liver abscesses and other severe infections [13, 14]. However, the spread of hvKp has become a global concern, with reports of outbreaks in Europe, the United States, and the Middle East [15–23], with the highest prevalence in the Asia-Pacific region [24]. This geographic spread has been accompanied by an increase in community-acquired infections in otherwise healthy individuals, a trend that has complicated clinical management. Colonized individuals may act as reservoirs, facilitating transmission within both healthcare facilities and the broader community. Furthermore, the growing global mobility of populations has contributed to the dissemination of hvKp strains across regions, complicating efforts to control outbreaks [25].

Several factors have contributed to the rise of hvKp, including antibiotic pressure, the global movement of populations, and increasing rates of conditions such as diabetes and chronic liver disease. Antibiotic overuse and misuse, particularly in healthcare settings, have created selective pressures that favor the emergence of more virulent and antibiotic-resistant strains of *K. pneumoniae*. Additionally, the widespread use of broad-spectrum antibiotics has provided an opportunity for hvKp to thrive in hospital environments, where these strains can persist and spread.

The distribution of multidrug-resistant hvKP (MDR-hvKP) follows a similar pattern, primarily in Asia, although cases have been reported globally [26, 27]. The genetic makeup of hvKP varies, with clonal group (CG) 23 being the most dominant [28, 29]. However, new sequence types of hvKP continue to emerge, indicating ongoing evolution [14]. MDR-hvKP strains are predominantly associated with ST11. Carbapenem-resistant *K. pneumoniae* (CR-KP) MDR-hvKP ST11 strains have been reported in China [27, 30]. Both ST11 and ST258 belong to the CG258 clone, with ST11 being a single locus variant of ST258. Although MDR-hvKP strains are common in ST11, ST258 MDR-hvKP strains have not been detected [31].

An infectious disease outbreak requires three key factors: a source, a transmission route, and a susceptible population. *K. pneumoniae* is commonly found in humans, animals, sewage, polluted water, and soil [32, 33]. However, the origin of hvKP remains unclear. Liu et al. [34] recently identified ST23 hvKP in a cucumber sample, along with *E. coli* carrying the *bla*_{NDM} gene, in ready-to-eat vegetables. Additionally, three MDR-hvKP strains were detected in public water sources in Brazil, suggesting that contaminated environments might increase the risk of hvKP spread [35]. These findings indicate that the environment could act as a reservoir for hvKP and MDR-hvKP dissemination.

Unlike cKP, which is typically linked to hospital-acquired infections, hvKP is usually associated with community-acquired infections [36, 37]. However, when hospital strains of cKP acquire hypervirulence plasmids and colonize the intestines, healthcare-associated hvKP infections can occur more widely [25]. A study in Beijing by Liu et al. [38] revealed that more than 90% of hvKP infections were hospital-acquired, indicating that hvKP may have developed into a healthcare-associated pathogen. Retrospective studies demonstrated that hvKP infections are more common in susceptible individuals, especially men over 50 years old and those with diabetes [39]. Jin et al. [40] found that diabetic neutrophil extracellular traps (NETs) have a reduced ability to kill hvKP, which may explain why diabetics are more prone to these infections. A recent study also identified coexisting hepatobiliary disease as an additional risk factor [41]. In-depth studies examining host factors in hvKP infections are

limited, yet this information could play a crucial role in understanding the underlying epidemiology and implementing effective prevention and control strategies.

3. Difference between classical *K. pneumoniae* and hvKP

The key differences between hvKp and classical *K. pneumoniae* (cKp) are outlined in **Table 1**.

According to Shon et al., [42] *K. pneumoniae* exists in two main forms: hvKP and cKp. Each presents distinct challenges for clinicians. cKp infections are typically hospital-acquired and occur mainly in immunocompromised patients, often causing pneumonia or urinary tract infections [53]. In contrast, hvKp is more severe,

Characteristic	Hypervirulent <i>K. pneumoniae</i> (hvKP)	Classical <i>K. pneumoniae</i> (cKP)	References
Populations	Often affects healthy individuals with no underlying conditions	Immunocompromised, older age, chronic diseases like diabetes	[25, 38, 42]
Virulence	Highly virulent, causing severe invasive infections	Less virulent, typically causes opportunistic infections	[25]
Infection type	Community-acquired infections	Nosocomial (hospital-acquired) infections	[37]
Clinical manifestations	Causing invasive, metastatic infections (e.g., liver abscesses, pneumonia, endophthalmitis, meningitis, necrotizing fasciitis)	Primarily causes opportunistic infections (e.g., pneumonia, urinary tract infections, bloodstream infections)	
Mucoviscosity	Typically hypermucoviscous (string test ≥ 5 mm)	Non-mucoid or weakly mucoid (string test < 5 mm)	[43]
Capsular types	K1, K2, K5, K20, K54, K57, KN1	K1–K79	[44, 45]
Siderophore production	• High siderophore production • Enterobactin, yersiniabactin, salmochelin, and aerobactin • Specifically, aerobactin, which enhances virulence	• Lower siderophore production • Enterobactin, yersiniabactin • Typically lacking aerobactin	[46–48]
Resistance to phagocytosis	More resistant to phagocytosis and complement-mediated cytotoxicity	More susceptible to immune responses	[42, 43]
Antibiotic resistance	Often multidrug-resistant (MDR), including carbapenem resistance	Varies, but typically less resistant compared to hvKP strains	[27, 44, 49, 50]
Prevalence	More prevalent in Asia-Pacific regions; emerging globally	Common worldwide, especially in hospital settings	[51]
Plasmids	Carries hypervirulence plasmids (e.g., rmpA, iucA, rmpA2)	Typically lacks hypervirulence plasmids	[44, 52]
Virulence mechanisms	Increased capsule production, siderophore-mediated iron acquisition	Standard virulence factors, including lipopolysaccharide (LPS) and fimbriae	[4, 42, 51]

Table 1.
Main differences between hvKp and cKp.

community-acquired, and can lead to invasive infections even in healthy individuals [54]. hvKp can infect almost any part of the body, causing conditions such as pneumonia, liver abscesses, endophthalmitis, meningitis, and necrotizing fasciitis [25, 51].

The string test, which detects the hypermucoviscous phenotype (string ≥ 5 mm), is commonly used to identify hvKp, with an accuracy of about 90% for clinical strains [43]. However, this semi-qualitative method can be affected by colony conditions and the operator's technique [55]. Recent studies indicate that not all hvKp strains exhibit the hypermucoviscous phenotype, and some cKp strains can also show hypermucoviscosity [43, 54]. This creates confusion when defining hvKp based solely on this characteristic. Therefore, identifying biomarkers on virulence plasmids linked to infection in *in vivo* models is a more reliable approach for differentiation, diagnosis, and management. Key biomarkers include *iucA* (involved in aerobactin siderophore biosynthesis), plasmid-borne *rmpA* and *rmpA2* (regulators of the mucoid phenotype through increased capsule production), chromosomal *rmpA* (*c-rmpA*), and *peg-344* (a putative transporter). These biomarkers can accurately identify hvKp strains with a precision of over 95% [43]. The specific genes and biomarkers of hvKp will be discussed in detail in the following sections.

Another mucoviscosity assay involves measuring the absorbance of supernatants obtained through low-speed centrifugation. Since hypermucoviscous strains do not sediment well, the supernatants remain turbid, which can be quantified as an indicator of mucoviscosity [51, 56].

Capsular types such as K1, K2, K5, K20, K54, and K57 have also been used to help differentiate hvKP strains [42, 57]. Moreover, total siderophore production is strongly correlated with hvKP subtypes, with aerobactin playing a key role in virulence [46]. Immunological studies have demonstrated that hvKP strains are more resistant to phagocytosis and complement-mediated cytotoxicity compared to cKP pathogens [58, 59].

4. Virulence-associated factors and genes

4.1 Capsule

The primary virulence factor of hvKp is its capsule (**Figure 1**), which plays an essential role in immune evasion and pathogenicity. The capsule is composed of polysaccharides that form a thick, gel-like layer around the bacterial cell. This phenotype is characterized by an unusually sticky, viscous capsule that enhances adherence to epithelial cells, increases resistance to phagocytosis, and allows the bacteria to persist in tissues more effectively [1].

In an intranasal infection model, mice infected with non-capsulated strains survived longer and had lower bacterial levels in their lungs and blood compared to those infected with capsulated strains. This indicates that the capsule likely protects the bacteria from the immune system [60–63]. *K. pneumoniae* uses its capsule for protection, not aggression. It evades the immune system by resisting phagocytosis and blocking complement, antimicrobial peptides, and antibodies (**Figure 2**). The capsule rarely directly targets or suppresses immune cells [61, 64–66]. Moreover, the capsule of hvKP strains is typically larger than that of cKP (**Figure 1**). In strains isolated from cerebrospinal fluid, the capsule often exceeds 2 μ m, contributing to their hypermucoviscous nature and likely improving survival [67]. However, this thick capsule may block DNA uptake, limiting horizontal gene transfer. This could explain why hvKP strains generally have fewer antibiotic resistance genes compared to cKP strains [68].

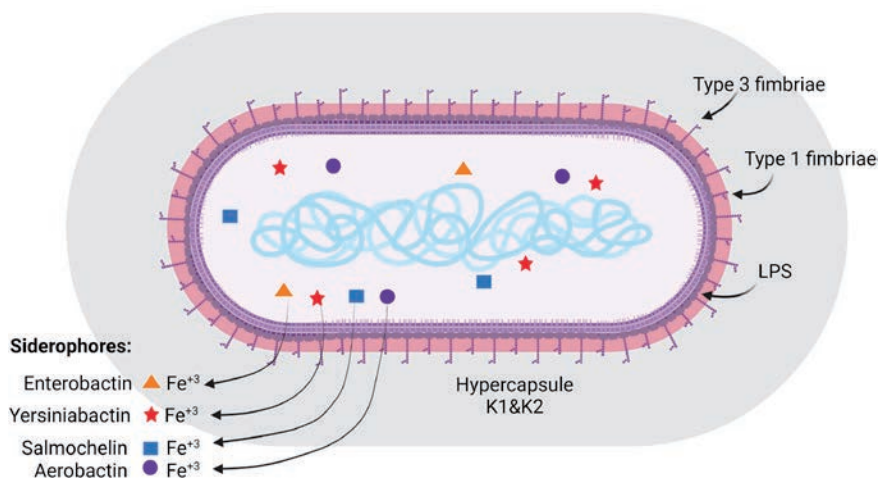


Figure 1.

The four key virulence factors in hvKP; (1) hypercapsule, (2) lipopolysaccharide, (3) siderophores, and (4) type 1 and 2 fimbriae. Created with BioRender.

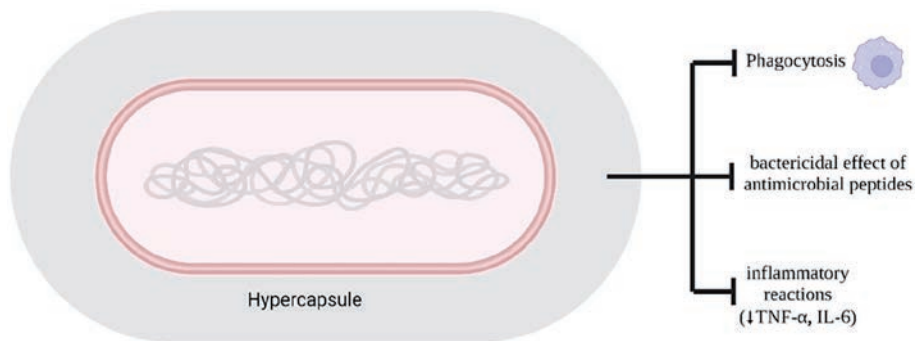


Figure 2.

Role of hypercapsule in hvKP. It has a role in inhibiting phagocytosis, the bactericidal effect of antimicrobial peptides and drugs, and some inflammatory reactions. Created with BioRender.

K. pneumoniae can be divided into at least 79 serotypes based on the differences in its capsule's polysaccharide composition and antigenic structures [69]. In hvKP strains, eight kinds have been identified: K1, K2, K5, K16, K20, K54, K57, and KN1 [45, 70]. K1 and K2 are the most common types and are detected in 70% of strains [42, 43], and several research have revealed that K1 and K2 strains are more virulent than other serotypes' strains [58, 71]. The K2 serotype has greater sequence-type (ST) variety than the K1 serotype, according to multilocus sequence typing (MLST). K1 was significantly associated with ST23, but K2 was linked to ST25, ST86, ST375, and ST380 [70, 72].

Several factors have been proposed to explain the increased virulence of K1 and K2 strains compared to others. One key factor is that both K1 and K2 strains lack specific mannose residue repeats, which are typically recognized by host molecules such as the macrophage mannose-binding receptor and the lung-secreted surfactant protein A (SP-A) [73]. Secondly, the surfaces of K1 and K2 strains contain sialic acid, a host-specific monosaccharide that mimics host cell surfaces, helping the bacteria

evade immune detection [74]. Thirdly, K1 and K2 strains lead to a lower production of reactive oxygen species (ROS) by neutrophils compared to other serotypes, allowing them to persist longer in human tissues [66]. Fourth, K1 and K2 strains have a greater diversity of O serotypes compared to other K serotypes, which may help them evade the host immune system [75]. This information does not indicate that all K1 and K2 serotypes exhibit the same level of hypervirulence. K1/K2 cKP strains lacking increased viscosity and additional virulence factors typically do not show a hypervirulent phenotype. However, serotyping, especially in cases of pyogenic liver abscess, is useful and can help inform preventive measures to reduce the risk of future infections [76].

The genes responsible for capsule production are located in the capsular polysaccharide synthesis (*cps*) region of the chromosome. This *cps* cluster, from *galF* to *ugd*, contains over 20 genes regulated by three promoters: *galF*, *wzi*, and *manC*. Among these, the *wbaP* gene encodes a protein that mediates the first step of capsule biosynthesis, and its deletion impairs capsule production. Notably, a new study found that mutations in *wbaP* can enhance pathogenicity by promoting biofilm formation and increasing the ability of *K. pneumoniae* to invade bladder epithelial cells during urinary tract infections [31]. The *wzx* gene in capsule biosynthesis is responsible for transferring the polymer from the cytoplasm to the periplasm across the inner membrane. The Wzy protein plays a role in polymerization through a catch-and-release process [77]. The *wza* and *wzc* genes encode proteins that form a complex to assemble and transport the capsular polysaccharides from the periplasm to the bacterial surface [78]. Wzb, a phosphatase that works with Wzc, binds to Wzc's catalytic domain and dephosphorylates it. In this regard, Niu et al. [79] found that a knockout of *wza* impairs polysaccharide transport, reduces the expression of *wzb*, *wzc*, and *wzi* genes, and prevents polysaccharide buildup, resulting in capsule deficiency. The *wzi* gene, which is specific to each serotype, encodes an outer membrane protein that helps anchor capsular polysaccharides to the outer membrane, playing a key role in capsule formation. A deficiency in *wzi* results in an acapsular phenotype, where the bacterium lacks a capsule [80, 81]. The *wzy* gene is often used as a serotype-specific marker to classify different *cps* types. Interestingly, the mucoviscosity-associated gene A (*magA*), identified in 2004, was later found to be the *wzy* gene in the K1 locus (K1_*wzy*) [82, 83]. *MagA* (K1_*wzy*) is crucial for the synthesis of capsular polysaccharides and contributes to the hypermucoviscous phenotype and resistance to complement-mediated lysis. Mutants lacking *magA* ($\Delta magA$) lose these traits, suggesting that *magA* is a virulence factor specific to K1 strains [84].

In addition to the genes in the *cps* cluster, several other virulence genes contribute to high capsule production. These include the capsule synthesis regulator B (RcsB), which regulates capsule synthesis, as well as the mucoid phenotype regulators A and A2 (*rmpA* and *rmpA2*). Other important virulence factors include *Klebsiella* virulence regulators (*kvrA* and *kvrB*), which also play a role in enhancing capsule production and the overall virulence of the bacterium [85, 86]. These genes act as positive transcriptional regulators of the *cps* locus, promoting the expression of genes involved in capsule synthesis. RmpA requires RcsB to initiate capsular polysaccharide production. Strains with either *rmpA*⁺ but lacking *rscB*, or *rmpA*⁻ with active RcsB, fail to surge capsule synthesis [87]. This suggests that RcsB is essential for baseline capsule expression, while RmpA boosts capsule production beyond this level [88].

Furthermore, RmpA and RmpA2 are key regulators linked to the hypermucoviscous phenotype in hvKP strains. Unlike chromosomal genes such as *RcsA*, *RcsB*, and *RcsC*, both *rmpA* and *rmpA2* can be located on either the plasmid or chromosome.

Chromosomal *rmpA* (*c-rmpA*) is embedded within an integrative and conjugative element (ICEKp1), while the plasmid-borne form (*p-rmpA*) is more commonly found [89]. *c-rmpA* has been identified in hvKP strains. Whole-genome sequencing of approximately 30 hvKP strains from different regions revealed the presence of the *rmpA* gene [72]. Additionally, several studies from China reported that 92–100% of tested hvKP samples carried the *rmpA* gene, regardless of the infection site [90, 91].

Interestingly, a hypercapsule alone does not fully explain the hypermucoviscous phenotype. Early studies suggested that the processes generating hypercapsule and hypermucoviscosity differ [11, 12]. Hypermucoviscosity may result from variations in capsule composition rather than capsule thickness alone. For instance, *Klebsiella* liver abscess (KLA) isolates contain fucose, produced by genes such as *wcaG* and *gmd*, which are absent in classical strains causing urinary tract infections [92]. Pan et al. [93] disrupted the fucose synthesis gene in KLA isolates and found the mutants were less mucoid than the wild type, although capsules were still present. This suggests that while a hypercapsule is essential for virulence, additional factors or uncharacterized gene functions may contribute to hypermucoviscosity, warranting further investigation.

4.2 Siderophores

Another critical virulence factor in hvKp is its ability to acquire iron, a vital nutrient that is typically sequestered by the host's immune defenses. hvKp produces siderophores (iron-binding proteins) such as aerobactin and yersiniabactin, which have a high affinity for iron and facilitate its uptake [94, 95]. The ability to scavenge iron allows hvKp to thrive in nutrient-limited environments, promoting bacterial growth, tissue damage, and overall virulence [96]. Once secreted, siderophores bind to environmental iron and transport it back to the bacterial cells. The iron-siderophore complex is then recognized by specific outer membrane receptors, which facilitate its transport into the periplasm. There, siderophores interact with periplasmic proteins to deliver the complex to the inner membrane. Finally, an ABC transporter channels the iron into the cytoplasm, where ferric iron (Fe^{3+}) is reduced to ferrous iron (Fe^{2+}), making it available for bacterial use [97, 98].

Siderophores can steal and scavenge iron from host iron-binding proteins because they have a higher affinity for iron than host-binding proteins. The siderophore molecules are subsequently absorbed by the bacterial cell via specific receptors (YbtQ, IutA, FepA, and IroN) (**Figure 3, Table 2**) [101].

Yersiniabactin (Ybt), enterobactin (Ent), Salmochelin (Iro), and aerobactin (Iuc) are the four types of siderophore molecules produced by hvKP. Those last two are apparent in cKP and specific to hvKP. A crucial component of virulence in cKP is yersiniabactin, but no evidence of its importance in hvKP has been discovered [43, 102, 103]. Aerobactin (Iuc) is the most significant hvKP siderophore system for systemic infection [104], and in laboratory trials, it accounts for nearly 90% of siderophore activity [46]. The host's natural immunity has the power to reduce their action. For instance, aerobactin can be bound by the antimicrobial peptide LL-37 [105]. Lipocalin-2 protein, another innate immunity component, effectively binds enterobactin, blocking its reuptake by the cell and, therefore, protecting the microorganism [106]. As a result, *K. pneumoniae* produces more than one siderophore to optimize the colonization of different tissues and/or avoid the neutralization of one siderophore by the host [101, 107].

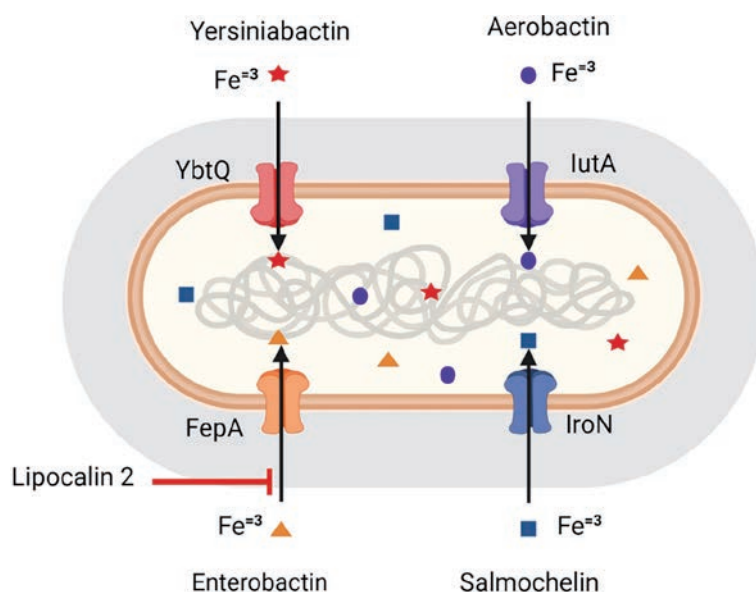


Figure 3.
 Siderophore production in hvKP. Siderophores can steal and scavenge iron from host iron-binding proteins, as they have a higher affinity for iron than host-binding proteins, and then the siderophore molecules are subsequently absorbed by the bacterial cell via specific receptors. Created with BioRender.

In hvKP, approximately 90% of the total siderophore production is attributed to aerobactin, which plays a dominant role in its hypervirulence. Research has shown that hvKP mutants lacking aerobactin, but not those missing enterobactin, salmochelin, or yersiniabactin, exhibit reduced virulence in mice following pneumonic or subcutaneous infections [46, 108]. This specificity suggests that aerobactin could serve as a reliable biomarker for identifying hvKP [43, 66]. Additionally, aerobactin is considered a more sensitive indicator of hvKP than hypermucoviscosity [109, 110].

The *iucABCD* operon is responsible for encoding aerobactin, while the *iutA* gene encodes its corresponding receptor [108]. Studies by Ye et al. [111], Zhang et al. [109], Zhao et al. [112], Wu et al. [91], and Zhan et al. [113] have consistently shown that hvKP strains possess the *iucABCD* and *iutA* genes more frequently than cKP strains.

4.3 Lipopolysaccharide (LPS)

The lipopolysaccharide (LPS) layer of hvKp also plays a key role in its immune evasion strategies. LPS, also known as endotoxin, is present in all Gram-negative bacteria, so it is present in both cKP and hvKP strains. It is made up of three layers: lipid A, oligosaccharide core, and O-antigen. O-antigen is the pathogen's outermost layer, which is attacked by the host's innate immunity and protects the pathogens from complement-mediated killing and phagocytosis. As O-antigen binds a C3b component in the complement system and prevents drilling and disruption of the bacterial membrane [99]. There are eight known O serotypes, with the O1 antigen being the most frequent among clinical *K. pneumoniae* strains [75, 114].

In a previous investigation, it was discovered that *K. pneumoniae* strains lacking the O1 antigen were less virulent than those containing the antigen [115]. However, its

Virulence factor	Function	Mechanism of action	Impact on pathogenesis	References
Capsule (hypermucoviscosity phenotype)	Increased adherence, immune evasion, and biofilm formation	The hypermucoviscous phenotype (via <i>rmpA</i> expression) enhances bacterial aggregation and resistance to phagocytosis	Facilitates persistence in tissues, especially during chronic infections	[42]
Siderophores	Iron acquisition	Siderophores like aerobactin bind to iron and allow hvKp to obtain this vital nutrient from the host	Essential for bacterial growth, survival in iron-limited environments, and promoting virulence	[47]
Lipopolysaccharide (LPS)	Immune modulation, protection from antimicrobial peptides	LPS is involved in immune evasion by altering its structure (e.g., longer O-antigen chains) to resist complement-mediated killing	Facilitates bacterial survival and persistence in the host	[99]
Fimbriae	Tissue adhesion	Fimbriae bind to specific receptors on host epithelial cells, aiding in colonization	Critical for initial infection, biofilm formation, and resistance to host defenses	[25]
Proteases and toxins (Colibactin)	Tissue damage, immune evasion	Proteases and toxins degrade host tissues and immune molecules, helping bacteria evade detection	Contributes to tissue destruction and bacterial survival in the host	[100]
Type 6 secretion system (T6SS)	Host cell manipulation, bacterial competition, and immune evasion	The T6SS delivers effector proteins directly into eukaryotic cells or bacterial competitors through a needle-like structure. These effector proteins can induce cell death or manipulate host immune responses to the benefit of the pathogen	Assists in evading immune responses, competing with other microbes, and promoting infection establishment	

Table 2.
Summary of key virulence factors of hvKp.

role in K1 hvKP strains, where the O1 antigen is hidden by the K1 capsule, has not yet been clearly established [115, 116].

4.4 Fimbriae

Fimbriae, hair-like structures on the surface of hvKp, are critical for initial adhesion to host tissues. By binding to specific receptors on epithelial cells in the respiratory and urinary tracts, fimbriae enable the bacteria to establish infection and resist host clearance mechanisms. This adhesion is vital for the persistence of the bacteria in chronic infections and biofilm formation [25].

Type 1 (mannose-sensitive) and type 3 (mannose-resistant) fimbriae were characterized experimentally for *K. pneumoniae*. Type 3 fimbriae enhance biofilm formation on abiotic surfaces, but its role on hvKP strains is not clear [117]. Seven unique fimbrial clusters of bacterial genes, *kpa*, *kpb*, *kpc*, *kpd*, *kpe*, *kpf*, and *kfg*, were discovered, with the *Kpc* fimbriae being the most common in the K1 serotype hvKP [118]. It was demonstrated that biofilm production in *K. pneumoniae* CG43 and activities of type 3 fimbriae are influenced by iron supply and positively regulated by *Fur*, suggesting that type 3 fimbriae may be less important for hvKP infection *in vivo* under iron-limited settings [42].

4.5 Colibactin

It is a genotoxin created by hvKP and produced by non-ribosomal peptide synthetases, polyketide synthases, and other enzymes encoded by the *pks* gene as part of secondary metabolism [100]. The majority of K1 serotype isolates analyzed, the *pks* locus was found (66–100%) [119]. Colibactin is thought to facilitate hvKP colonization and dissemination within the body, although the exact mechanisms contributing to hvKP pathogenesis remain unclear [120].

4.6 Peg-344

A widely distributed gene among hvKP strains that promotes the virulence of hvKP. The *peg-344* gene functions as an inner membrane transporter, but its exact role in virulence is unknown. The *peg-344* gene is involved in achieving maximum virulence in *in vivo* models, but it has no effect on systemic infection [43, 121]. Interestingly, a study by Bulger et al. [121] showed that PEG344 is crucial for high virulence in lung infections but not in skin infections.

4.7 Type 6 secretion system (T6SS)

It was identified in recent decades in hvKP strains. The T6SS acts like a nano-syringe, injecting effector proteins into target cells. This allows it to damage eukaryotic cells or compete with other prokaryotic cells [122].

5. Conclusion

HvKP strains, initially reported in Asia, have now spread globally, causing both community-acquired and hospital-associated infections. The combination of hypervirulence and antimicrobial resistance in these strains worsens the public health threat and complicates treatment. While the exact source and transmission of hvKP infections remain unclear, intestinal colonization seems to be an important step in infection. Risk factors include diabetes, male gender, and Asian ethnicity. The capsule and siderophores are key virulence factors that contribute to the hypermucoviscosity phenotype of hvKP. However, the exact molecular mechanisms behind this phenotype are still being studied as some hypervirulent strains do not exhibit hypermucoviscosity. The current definition of hvKP includes clinical features, phenotypes, and genotypes. However, identifying hvKP strains in clinical laboratories remains challenging. Other virulence factors, such as LPS, fimbriae, the *peg-344* gene, and T6SS, require further investigation to understand their roles in hvKP. These factors work together in

a coordinated manner to facilitate infection. Additionally, with the rise of MDR-hvKP, there is a need for the development of non-antimicrobial treatments targeting these virulence factors. Overall, more research on hvKP is essential to improve prevention, diagnosis, and treatment strategies for infections caused by these strains.

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Early Warning through Genomic Surveillance in Epidemic Management

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Abstract

Public health surveillance is essential for detecting outbreaks and ensuring health security worldwide. Civilization has faced outbreaks of varying scales and impacts throughout history, highlighting the importance of disease surveillance to spot outbreaks early and respond correctly. By implementing real-time surveillance, local outbreaks can be controlled before they escalate, possibly preventing a pandemic. Disease-causing organisms can be tracked genetically through genomic surveillance, enabling the detection of their evolution, spread patterns, and outbreaks. Researchers and public health officials can use genome sequencing and bioinformatics analysis to identify emerging threats and develop effective countermeasures, such as vaccines or treatments, against pathogens such as viruses, bacteria, and fungus. This chapter highlights the role of metagenomics and artificial intelligence in genomic surveillance, emphasizing their potential as early warning systems for epidemic management. Furthermore, it discusses key technologies, implementation frameworks, and data sharing platforms as well as current methods and tools for genomic surveillance. In addition, it highlights infrastructure gaps, ethical concerns, and challenges to international cooperation. In order to improve epidemic preparedness and global health security, the chapter emphasizes the need for genomics and artificial intelligence into public health policies.

Keywords: surveillance, outbreaks, epidemic, pandemic, public health, infectious disease, metagenomics, artificial intelligence

1. Introduction

The rapid emergence and spread of infectious diseases through bacterial, viral, and fungal infections pose significant threats to global health, economies, and societies [1]. Over the past two decades, viral outbreaks such as SARS-CoV-2, Dengue, Zika, Ebola, Chikungunya, Swine Flu, and Oropouche have triggered widespread epidemics and pandemics across the globe [1]. Human-animal interaction is shaped by climate change, urbanization, travel, and increased zoonotic disease risk [2]. The recent SARS-CoV-2 pandemic highlighted the need for robust surveillance, rapid

diagnostics, skilled personnel, and immediate communication among clinicians, scientists, and policymakers. However, the traditional methods of epidemiological surveillance, such as clinical reporting, case counts, and laboratory diagnostics, fail to provide timely alerts during the early stages of outbreaks. Recently, genomic surveillance has transformed epidemic management by enabling real-time monitoring of pathogen genomes. Sequencing pathogen genomes (e.g., viral, bacterial, or fungal) during outbreaks allows bioinformatics and genomics scientists to detect novel variants, trace transmission pathways, and anticipate changes in pathogen behavior, serving as a vital early warning system for public health surveillance. It involves collecting, analyzing, and interpreting patient data to plan, implement, and evaluate public health practices, along with the timely broadcasting of information. One of the best examples of sequencing-based surveillance is metagenomics-based diagnostic support systems for infectious disease monitoring, which has been widely implemented in healthcare systems worldwide [3]. A number of surveillance and prediction systems have been developed during the COVID-19 pandemic, including outbreak.info [4], nextstrain.org [5], ERVISS [6], cov-spectrum.org [7], sarscoverage.org [8], and CovRadar [9]. To forecast risks from emerging disease variants, predictive tools such as IRAT [10], VASIL [11], VirPreNet [12], ViPal [13], and VarEPS [14] may be utilized to assess virulence, epidemiological impact, and host immunity interactions, thereby supporting disease surveillance efforts.

Furthermore, antimicrobial resistance (AMR), which causes approximately 700,000 deaths annually, is a serious global health threat that requires early detection, robust surveillance, accurate prediction, and health policy making. Early warning through AMR surveillance widely utilizes whole genome sequencing (WGS)-based-16S rRNA gene profiling, shotgun metagenomics, followed by bioinformatics analysis to detect emerging resistance threats and enable timely interventions. Surveillance enables the early detection of changes in microbial populations, including the emergence of resistance genes and mechanisms, allowing scientist and health officials to respond before resistance becomes widespread. A recent publication on AMR surveillance in hospitals highlights their importance and outlines methodologies for epidemic management [15–18]. There are national policies on epidemic management in most countries, which provide a framework for preparedness, early detection, rapid response, and recovery during outbreaks of infectious diseases [19]. These policies include surveillance systems, laboratory networks, emergency response protocols, coordination among healthcare and government agencies, and public communication strategies, tailored for disease burden, population needs, and national budgets.

In this chapter, we discuss how genomic data is integrated into surveillance systems for early warning, and the ethical, legal, health policy and data sharing challenges that affect global implementation. The chapter concludes with a discussion of future directions, including the increasing role of machine learning and cloud-based platforms in enabling scalable, responsive surveillance systems.

2. Genomic surveillance as a tool for early detection and response

Genomic surveillance, which involves the systematic collection, sequencing, and analysis of pathogen genetic material to track their evolution, diversity, and spread, is vital for public health and infectious disease control [20]. Scientists across health institutes use this approach to study pathogens' genetic makeup and identify mutations that may affect their behavior, transmissibility, or severity. Genomic

surveillance allows early detection and timely response to outbreaks by tracking the emergence and spread of new variants [21]. In addition, vaccines, neutralizing antibodies, and diagnostic tools are evaluated to ensure their effectiveness against emerging variants. Genomics information can be used to inform vaccination strategies, travel policies, and resource allocation in public health. It helps researchers understand how pathogens spread within and between populations, enabling more effective containment and prevention measures [22]. A proactive, data-driven response to infectious diseases is enabled by genomic surveillance, ultimately protecting public health.

In recent years, genomic surveillance has evolved from PCR-based methods to NGS-driven metagenomics, supported by advanced bioinformatics and AI-based machine learning (ML) and deep learning (DL) techniques, enabling high-resolution and timely detection of pathogens. Early warnings, outbreak predictions, and tracking of AMR can be achieved with these tools/methods. To meet the public health needs, global genomic surveillance must be integrated, driven by innovation, collaboration, and equitable access. Polymerase chain reaction (PCR) is used for specific mutation detection and screening, whereas next-generation sequencing (NGS) allows rapid, high-throughput sequencing of entire genomes, crucial for real-time outbreak analysis. NGS-based techniques enable molecular-level detection and tracking of infectious diseases (caused by viruses, bacteria, fungi, and parasites), offering insights into pathogen behavior and evolution. Based on pathogen type, sample size, and data requirements, NGS-based genomic surveillance offers benefits and challenges. For example, metagenomics *via* next-generation sequencing (mNGS) enables comprehensive, culture-independent detection of pathogens, resistance genes, and virulence factors across the human body. An mNGS-based diagnostic support system enhances clinical decision-making at the point of care by identifying microbial differences between health and disease [3]. With clinical metagenomics, infectious diseases can be diagnosed quickly and comprehensively, and antimicrobial treatment can be informed by a broad understanding of pathogens.

Furthermore, AMR surveillance is undergoing a transformation driven by the integration of artificial intelligence (AI), including machine learning (ML) and deep learning (DL), with the potential to revolutionize microbial research, diagnostics, and therapeutic strategies [23]. AI-based ML/DL has revolutionized AMR surveillance by enhancing microbial classification, functional annotation, and pathogen detection. Advances in sequencing and data processing, combined with the integration of multi-omics data, have greatly enhanced scientists' ability to understand microbial functions in both health and disease [24–25]. AI-driven algorithms now decode complex microbial interactions, uncover disease-associated signatures, and accelerate genomic research, with deep learning playing a pivotal role in advancing precision medicine and therapeutic development [25–27].

Bioinformatics tools have enabled large-scale genomic data analysis with unprecedented precision, advancing pathogen research. However, the increasing complexity and volume of data from major projects like the Cancer Genome Atlas and the Human Microbiome Project demand more sophisticated computational approaches for accurate interpretation and meaningful biological insights. Genomic surveillance using bioinformatics tools enables detailed pathogen characterization, variant tracking, and assessment of treatment effectiveness. These insights support informed public health decisions and reveal transmission dynamics. Using tools like Nextstrain, GISAID, CDC dashboards, Pathogenwatch play vital roles in guiding responses to infectious disease threats through real-time genomic data analysis (**Table 1**).

Surveillance	Application	Toolkits	Website
COVID	Understand genetic makeup, track variants, evaluate treatment impact, inform public health policies, and study transmission patterns.	NCBI Virus, GISAID, Nextstrain, Pangolin, CoVariants, Outbreak.info, WHO GISRS, CDC, Dashboard, and Microreact	https://www.ncbi.nlm.nih.gov/genbank/ ; https://www.gisaid.org/ ; https://nextstrain.org/ ; https://cov-lineages.org/ ; https://covariants.org/ ; https://outbreak.info/ ; https://www.who.int/initiatives/global-influenza-surveillance-and-response-system ; https://www.cdc.gov/respiratory-viruses/data/genomic-surveillance/index.html ; https://microreact.org/
AMR	Identify antimicrobial resistance genes, track pathogen evolution, and support surveillance by analyzing genomic data from clinical isolate	Pathogenwatch, Resfinder, CARD and NCBI pathogen database	https://pathogen.watch/ ; http://genepi.food.dtu.dk/resfinder ; https://card.mcmaster.ca/ ; https://www.ncbi.nlm.nih.gov/pathogens/
Fungal	Support fungal surveillance by providing taxonomy, genomic data, and interaction networks, enabling identification, and monitoring of fungal pathogens in clinical and environmental settings	Mycobank, FungiDB, and FungiNet	https://www.mycobank.org/ ; https://fungidb.org/ ; https://www.funginet.de/home.html

Table 1.
Bioinformatics tools used in genomic surveillance.

3. The genomic edge in epidemic management

Genomic data provide insights into how pathogens arise, transmit, and evolve, which is crucial for epidemic management. It is essential to have this information in order to develop effective diagnostics, therapeutics, and vaccines, as well as to implement the targeted public health interventions. Genomic data can be valuable in epidemic management in the following ways:

3.1 Understanding pathogen features

It is crucial to understand pathogen behavior using genomic data, as it aids in epidemic management in a number of ways. It allows for the tracking of a pathogen's origin, evolution, and mutations, helping to identify how an outbreak begins and how the pathogen adapts over time [28]. This is crucial for tracking emerging variants, as seen with Delta and Omicron during the SARS-CoV-2 pandemic. The early detection of these variants allows public health authorities/organizations to assess potential risks and adjust interventions accordingly, including developing vaccines based on the circulating strains. Advances in nucleic acid sequencing have significantly enhanced the ability to identify, characterize, and monitor disease-causing agents in real time [29]. Furthermore, analysis of pathogen genomes from different individuals can reveal transmission patterns and chains, offering insights into how diseases spread within populations. Genomic data also provides critical information

about a pathogen’s virulence and drug resistance [30]. By monitoring genetic changes, researchers can detect mutations associated with increased transmissibility, immune escape, or reduced sensitivity to available treatments. As a result of this comprehensive understanding, timely and targeted public health interventions are possible, improving epidemic preparedness and control.

3.2 Developing effective interventions

Genomic information plays a vital role in developing effective interventions by informing diagnostics, therapeutics, and vaccines [31]. This allows the development of highly specific diagnostic tests that can accurately identify pathogens and distinguish them from closely related organisms, ensuring rapid and precise detection critical for timely treatment and public health responses. A deep understanding of a pathogen’s genome also aids in identifying potential drug targets, thereby guiding the development of new antiviral therapies and enhancing existing treatments [32]. Moreover, genomic data is crucial for vaccine development, as it allows researchers to identify the most effective antigens (the parts of the pathogen that trigger a strong immune response), which can be used to develop vaccines that provide robust and targeted protection against disease.

3.3 Supporting public health actions

To promote well-being, prevent disease, and protect communities, public health actions need to be coordinated. Health education, preventive measures including vaccinations and screenings, and strategies that address environmental and infectious risks combine to build stronger, healthier populations. Genomic surveillance programs in various countries support public health by identifying high-risk populations and regions, enabling targeted interventions such as testing and vaccination (Table 2).

Region	Organization	Tasks
Global	World Health Organization (WHO)	Coordinates international health efforts and provides guidelines for genomic surveillance.
India	Indian Council of Medical Research (ICMR), Department of Biotechnology (DBT), Indian Biological Data Center (IBDC), Indian SARS-CoV-2 Genomics Consortium (INSACOG), and Genome India Project (GIP)	Leads national genomic research and surveillance, particularly for diseases like COVID-19 and AMR.
Asia	China CDC, Japan National Institute of Infectious Diseases, Korea Disease Control and Prevention Agency (KDCA)	National public health institutes conducting pathogen surveillance and genomic tracking.
America	Centers for Disease Control and Prevention (CDC), and Pan American Health Organization (PAHO)	CDC leads genomic monitoring in the U.S.; PAHO coordinates regional epidemic preparedness and response.
Europe	European Centre for Disease Prevention and Control (ECDC), UK Health Security Agency, and Robert Koch Institute (Germany)	Agencies responsible for genomic surveillance, data sharing, and epidemic response across Europe.

Table 2.
Governmental and regional agencies supporting early warning and genomic surveillance for epidemic management across various regions.

Analysis of pathogen genomes during outbreaks helps assess the effectiveness of ongoing control measures, and informs timely adjustments to intervention strategies. Effective public health strategies require strengthening healthcare systems, engaging communities, and developing evidence-based policies. Genomic data provide valuable evidence for public health policies, including travel restrictions and quarantine protocols [33]. The broad scope and impact of these actions can be seen in real-world examples such as TB control, chronic disease prevention, and emergency preparedness such as hemovigilance program in India during the COVID-19 pandemic [19].

3.4 Implementation of early warning systems

Effective implementation of early warning systems (EWS) is critical for timely detection, preparedness, and response to both health-related and environmental threats (**Figure 1**). Public health EWS involve the integration of surveillance networks between laboratories, health agencies, and international organizations [34]. Data-sharing platforms like GISAID and Nextstrain facilitate real-time, global collaboration in tracking pathogen evolution and spread, while networks such as WHO's GOARN support coordinated responses across borders. The use of real-time data analysis tools, such as automated pipelines and interactive dashboards, enables health authorities and scientist to monitor transmission trends and emerging variants in real time. More broadly, early warning systems are built upon four foundational pillars: risk knowledge, detection and forecasting, warning dissemination, as well as preparedness and response [35]. A structured approach starts with identifying

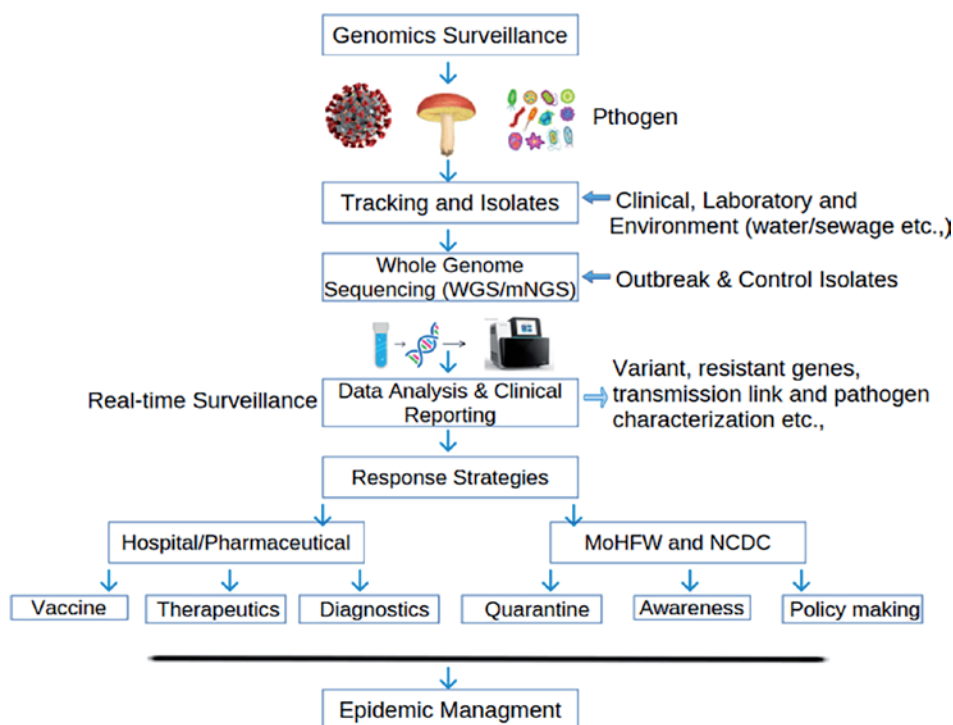


Figure 1.
Flowchart of genome surveillance within the context of epidemic management.

potential hazards, such as disease outbreaks, and assessing susceptibility within affected populations. Technological advancements, including satellite monitoring, sensor networks, and predictive modeling, significantly enhance the ability to detect threats early and accurately [36–37]. Preparedness activities, including emergency drills, public education, and resource mobilization, are essential to strengthen readiness. To be effective, genomic surveillance-based early warning systems (EWS) must be community-engaged, institutionally integrated, and funded sustainably. For these systems to remain responsive and effective in a rapidly changing global health landscape, they require ongoing evaluation and adaptation. According to the World Health Organization (WHO), robust EWS are vital for saving lives, protecting livelihoods, and strengthening resilience against infectious disease outbreaks.

4. Barriers to effective epidemic management through genomic surveillance

4.1 Resource and infrastructure constraints

Many low- and middle-income countries lack the necessary laboratory infrastructure, sequencing capacity, and bioinformatics expertise required for real-time genomic analysis and reporting. Inadequate funding and limited access to reagents and equipment further constrain implementation. Governments must invest strategically, collaborate regionally, and develop centralized genomic facilities at minimal or no cost to users to address these infrastructure gaps. Developing laboratory capacity, expanding hands-on training in genomics and bioinformatics, and ensuring sustainable funding and supply chains are essential. Public-private partnerships and international support can further enhance resilience and enable timely, effective genomic surveillance for epidemic preparedness and response.

4.2 Data sharing and integration

Data sharing and integration are major obstacles to effective genomic surveillance for epidemic early warning. Delayed data exchange, fragmented systems, and poor integration hinder timely detection and response. Legal and ethical concerns, including data privacy and unclear governance, further complicate progress. Standardized systems, clear policies, legal reforms, infrastructure investment, and international collaboration are essential to address these challenges. In order to manage future epidemics more effectively, these steps will improve real-time data use, enhance surveillance capabilities, and support timely, coordinated public health actions.

4.3 Complexities in genomic data analysis

It is challenging to assess the significance of variants, and complex data requires interdisciplinary expertise, thus hindering genomic surveillance's effectiveness. It is essential to invest in advanced computational tools, IT infrastructure, foster collaboration among experts, and develop clear guidelines for interpreting genomic data in order to resolve these issues. These solutions will improve the accuracy and reliability of insights, minimize misinterpretation, and enhance the ability to respond swiftly and appropriately to emerging public health threats.

4.4 Surveillance coverage gaps

Surveillance coverage gaps, driven by uneven global sequencing efforts and sampling bias, hinder early detection of emerging variants. In order to overcome this issue, policies should ensure that resources are distributed equally, surveillance is expanded to underserved regions, and sampling strategies are inclusive. Strengthening global collaboration and funding can ensure more representative and comprehensive genomic data for timely and effective epidemic response.

4.5 Delays in policy implementation

Slow responses and weak preparedness protocols weaken the impact of genomic surveillance. Policy decisions must be made in a timely manner based on genomic insights in order to resolve this problem. Strengthening coordination between scientists and policymakers ensures timely responses and maximizes the public health benefits of genomic surveillance data.

4.6 Financial barriers to genomic surveillance

Financial and sustainability issues, such as high operational costs and reliance on short-term funding, undermine the continuity of genomic surveillance. To ensure the long-term impact, policies must prioritize sustained investment through integrated health budgets and international support. Establishing dedicated funding mechanisms will promote stable, proactive surveillance systems that remain functional beyond outbreak periods, enhancing epidemic preparedness.

4.7 Technical limitations

The accuracy of genomic surveillance can be compromised by technical limitations, such as sequencing errors and challenges in detecting rare genetic events. Investments in advanced sequencing technologies, quality control protocols, HPC infrastructure, bioinformatics software, and workforce training are essential to address these challenges. Enhancing laboratory standards and adopting long-read/hybrid sequencing methods will improve data reliability and enable more precise detection of complex genomic changes during epidemics.

4.8 Political and institutional barriers

The lack of coordination and political interference hamper effective genomic surveillance due to political and institutional barriers. The best way to overcome these challenges is to promote transparent governance, strengthen collaboration across all levels of health authorities, and protect scientific data from politicization. In order to combat emerging health threats, we need to build trust through accountability and clear communication.

5. 2025 and beyond: Future perspectives in genomic surveillance

The future of genomic surveillance holds immense promise for strengthening early warning systems and managing epidemics more effectively. Technological innovations

such as portable sequencing devices, artificial intelligence (AI)-driven analytics, and the development of inclusive and resilient surveillance networks are set to revolutionize how we detect and respond to emerging infectious threats. These advancements can significantly enhance the speed, accuracy, and reach of outbreak monitoring, especially in low-resource and geographically underserved regions. These methods will improve outcomes and save lives with strategic investments and global cooperation. A future surveillance strategy must integrate genomic data into the one health framework, which acknowledges the close connections between humans, animals, and the environment. With this approach, it is possible to predict pathogen evolution, zoonotic spillover, and antimicrobial resistance (AMR). Surveillance systems can provide high-resolution insights into pathogen transmission dynamics and AMR development, both clinically and environmentally, by combining WGS data with epidemiological and ecological information. The experience gained from tracking SARS-CoV-2 variants during the COVID-19 pandemic has demonstrated the value of WGS as a critical tool for real-time surveillance and public health decision-making. Consequently, WGS has become a widely used tool for monitoring infectious diseases and AMR throughout the world. Effective pandemic preparedness through genomic surveillance depends on global collaboration, ethical data sharing, and standardized practices, enabling all nations to promptly detect, monitor, and respond to emerging health threats.

6. Conclusion

The use of genomic surveillance in epidemic management can enable early detection, tracking, and response to infectious threats. Metagenomics, AI-based ML/DL, and bioinformatics are integrated to enhance real-time monitoring, support targeted interventions, and inform diagnostics, therapeutics, and public health policies. The current gap between infrastructure, finances, and data sharing can be bridged with strategic investments, international collaboration, and equitable access. The future will focus on portable sequencing, cloud platforms, and one health integration in order to address zoonoses and antimicrobial resistance. In order for genomic surveillance to reach its full potential, it must be woven into global health systems through ethical collaboration, standardized frameworks, and a sustainable support system for coordinating, and preparing for epidemics.

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Chapter 9

Effectively Using PPE to Mitigate the Spread of Pathogens

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Abstract

Infectious respiratory pathogens spread through activities such as coughing and sneezing. Airborne virus-laden respiratory secretions can spread when the infected person does not use personal protective equipment (PPE) such as face masks or shields. PPE can help mitigate the spread of airborne viruses during a pandemic, however, the concentration and transmission of pathogens indoors depends on the fabric and fit of a face mask or orientation of a face shield. Using computational fluid dynamics, we evaluate the performance of various face masks and face shield configurations in indoor environments. The analysis explores how differences in fit, size, orientation, and other design characteristics of face masks and shields influence the movement of airborne pathogens and the level of protection provided. The scenario considered is an enclosed space with two children standing 0.91 m apart and one child is infected, spreading pathogens by coughing. Four face shields with varying sizes, fits and orientations, and two types of face masks, are examined to assess the flow and pathogen transport around the PPE to determine the source control and protection offered by them. The findings indicate that a social distance of 1 m is sufficient to reasonably control pathogen transmission when at least one person is wearing a face covering. The study also shows that the design and orientation of a face shield can provide excellent protection, especially when a face mask cannot be used. These strategies are extremely relevant to the next pandemic.

Keywords: airborne transmission, computational fluid dynamics, face shield, personal protective equipment, source control

1. Introduction

The COVID-19 pandemic was an eye-opening experience for the world, exposing vulnerabilities in how we protect ourselves from airborne pathogens. Personal protective equipment, such as face masks, face shields, medical gowns and gloves, proved essential in controlling the spread of infectious secretions to their surroundings [1]. The use of PPE along with social distancing practices helped save lives. Yet, years later, the use of PPE outside of medical settings like hospitals and doctor offices has lessened. The vigilance of individuals to use PPE when they are sick and in public is evident by continued transmission of COVID-19 and the flu. This study revisits the

importance of PPE and demonstrates how thoughtful design and proper usage can help manage and mitigate risks in future outbreaks.

Airborne pathogens have a detrimental impact on the health and well-being of people especially indoors. Transmission of pathogens that originate in the respiratory tract of an infected person are expelled during activities such as breathing, talking, coughing, and sneezing [2, 3]. Pathogens are carried by respiratory secretions of varying velocities depending on the activity, and can be categorized based on size, where aerosols are less than 5 microns and droplets are greater than 5 microns [2, 4]. Studies have shown that aerosols, being lighter, linger in air for prolonged periods, increasing the infection risk of individuals in the room.

Many researchers have investigated respiratory fluids using different methods [2, 4–6] and have reported that aerosol and droplet secretions have diameters distributed in a wide size range mostly between 0.1 and 500 μm . Several experimental studies have investigated the transport of droplets for different diameter distributions [7, 8] and have reported the settling distance of particles in different diameter ranges. Yan et al. [9] used computational fluid dynamics (CFD) to examine the thermal effect of human body on the cough droplet transmission for a human in a sitting position. Feng et al. [10] studied the influence of wind and relative humidity on airborne transmission to predict social distancing required in the given conditions. However, these papers do not consider the effect of face protection in the transmission of pathogens.

Face protection equipment, in particular masks and shields, potentially prevents pathogens from entering the respiratory tracts of exposed persons. Masks and shields also control the spread of pathogens from the source (infected person) to the surrounding. Studies have shown that face masks provide better personal protection and source control than face shields as they fit close to the mouth and the nose and have smaller gaps through which pathogens can escape [11–14]. However, the use of masks can be particularly challenging for some populations, including those who experience respiratory difficulties, sensory discomfort, or communicate by reading lips. Children may also have difficulty continuously wearing face masks in school or while playing with others. Children often respond to mask related discomfort or agitation by touching their hands to their face, which further contributes to the spread of pathogens. Alternate forms of personal protective equipment that address these challenges, while providing reasonable protection to at risk individuals are highly valuable.

Face shields may not always be a suitable alternative to face masks, but they are highly effective in many situations. The design of face shields may be more comfortable, especially in warm and humid weather. They also provide a protective barrier over the eyes as well shield them from potential infections. Most face shields are transparent, making it easier for children with special needs, learning disorders, and hearing impairments, to communicate while wearing them. Comfortable face shields also do not require frequent adjustments, which means less direct contact with the face.

Verma et al. [15] examined face masks and face shields qualitatively by examining the dispersion of cough secretion visually but did not quantify source control for face shields. Fischer et al. [12] proposed low-cost measurement techniques to determine the efficacy of face masks and mask alternatives like bandanas and neck gaiters. Three recent studies on face shields and face masks evaluated the behavior of aerosols and droplets [5, 13, 14]. Lindsley et al. examined cough aerosols and the collection efficiency of face shields and an ASTM level 3 face mask [13]. Lindsley et al. [13] conducted an experimental study to determine the source control provided by N-95 respirators, medical procedure masks, and 3-ply cloth masks,

and reported the collection efficiency percent for separately for six size fractions between 0 and 7 μm . Their findings [13] are used as a benchmark for comparing and validating the results of this study.

It is therefore important to analyze the efficacy for different face shields to understand how size and fit impact personal protection and source control offered. Several experimental [7, 8] and computational [9, 16] studies have investigated the transport of respiratory droplets in ambient indoor conditions. Li et al. [16] examined droplet transport in static ambient conditions to show that evaporation caused droplet sizes to decrease, increasing the concentration of inhalable pathogens, resulting in higher infection risks. Akagi et al. [17] used CFD to examine the flow around a face mask when an individual sneezed. Verma et al. [15] conducted experiments to visualize the flow around a face mask and shield and determined their performance when a person coughs or sneezes. Lindsley et al. [5, 14] experimentally evaluated the collection efficiency of face shields for aerosols in different diameter ranges.

The study herein presents a quantitative and qualitative investigation of source control (collection efficiency) using PPE worn by two children interacting in an indoor environment. The room has no ventilation and can be considered the worst-case scenario during a pandemic. The PPE selected includes comparisons of a cloth mask and an ASTM level 3 mask, and two types of face shields. CFD simulations are used to predict the flow dynamics and transport of cough secretions in the enclosed space with ambient conditions. The study focuses on examining the transport of aerosols because of their ability to remain airborne for prolonged periods. The findings of this study will show that the fabric and fit of the face mask as well as the size and orientation of the face shield has a significant impact on the source control. The results will also show the benefits of wearing a face shield over a face mask to significantly reduce the spread of pathogens. Additionally, a face shield with an inch-thick foam along the top (in contact with the forehead) can further reduce the spread of pathogens. Given the threat of future pandemics and seasonal outbreaks persists, this work offers timely insights to guide public health strategies and improve community resilience through improved PPE design.

2. Methodology

This study focuses on examining the role of face shields and face masks in mitigating the spread of pathogens released when an infected person coughs. The efficacy of the face shield and mask is evaluated by calculating the collection efficiency, also known as source control. Source control refers to the use of PPE to cover a person's mouth and nose to reduce the spread of respiratory secretions to others when the person talks, sneezes or coughs.

2.1 Modeling of cough droplets

The respiratory activity considered for the purpose of this study is coughing, where fluid is expelled horizontally at a speed of 12 m/s [4, 18]. The respiratory secretions (i.e., fluid) are assumed to be composed of spherical particles and modeled as water droplets containing a 25% non-volatile nucleus [16]; see also Joshi [19] for detailed modeling parameters. The particle size distribution varies for different diseases and depends on an individual's health. **Figure 1** shows the initial cough-particle distribution (count-based size distribution) to elucidate the number (frequency) of

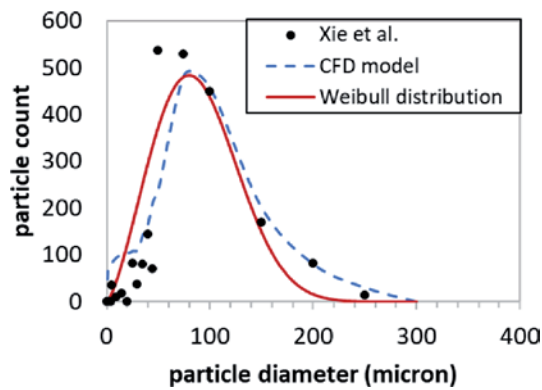


Figure 1.
Initial respiratory particle size distribution expelled during a cough based on data by [6].

aerosols and droplets relative to particle diameter. The particle size distribution for the cough is based on published data by Xie et al. [6] with a mean particle diameter of $85\text{ }\mu\text{m}$, shown as circles. The frequency of each particle size can be represented closely to a Weibull distribution (solid line). To be as accurate as possible for the simulations, the cough was modeled to ensure capturing the range of aerosols (dashed line).

2.2 Geometry and computational domain

The domain of interest for this study is a room with two children (a boy and a girl) standing 0.91 m apart with approximate heights of 1.22 m , as shown in **Figure 2**. The setup was adapted from the computational domain described in [19]. The boy is shown with a face shield (**Figure 2 (a)**) and both a shield and face mask (**Figure 2 (b)**) as examples for the case studies. One scenario assumes the boy is infectious and the effectiveness of source control is examined as respiratory particles are released. Another scenario assumes the girl is infectious and the effectiveness of the PPE providing a barrier from the pathogens is examined. The use of children as models connects to anecdotal accounts that children are often uncomfortable

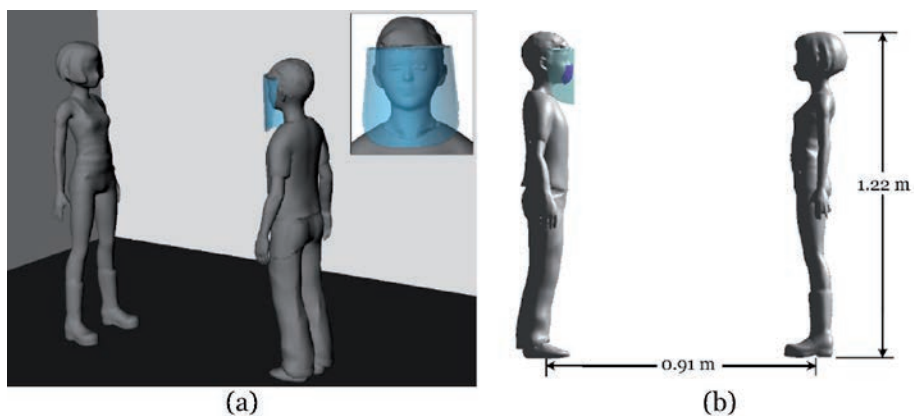


Figure 2.
Schematic of the computational model of two children standing 1.22 m apart in a room: (a) boy is wearing a face shield and (b) boy is wearing a face mask and shield.

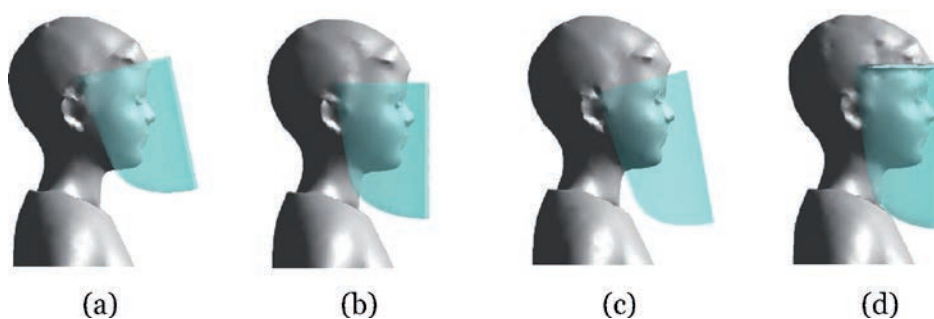


Figure 3.
 Side view of four face shields examined: (a) short shield with a tilted fit; (b) short shield with a straight fit; (c) long shield with a tilted fit; (d) long shield with a straight fit and thick foam along on the top.

with face masks but respond better to face shields. **Figure 3** (a-d) presents different views showing the four case studies of face shields. **Figure 3** (a) is a common shield, herein referred to as a short-shield, and is 16.1 cm in length and titled to represent improper wear and shown in **Figure 3** (b) is the properly worn short-shield. **Figure 3** (c) is a long shield, 19.8 cm in length, also commonly used. **Figure 3** (d) models the

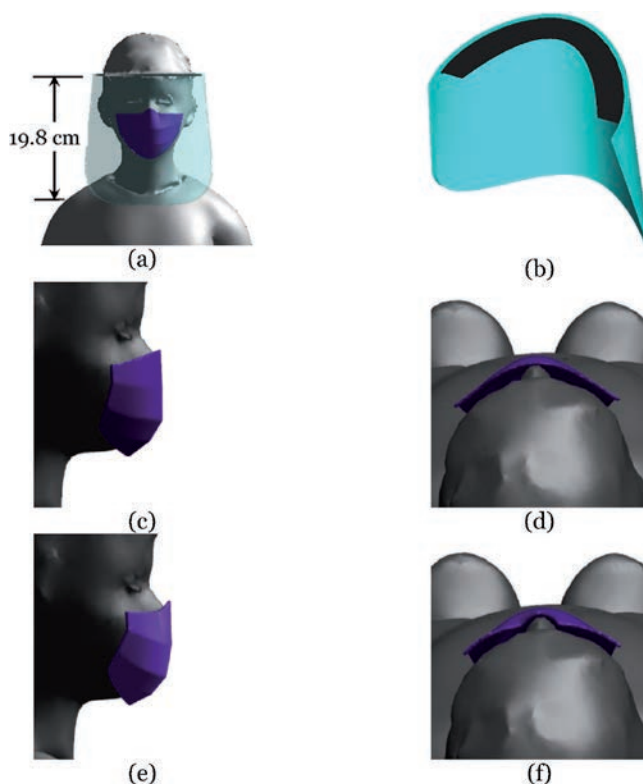


Figure 4.
 (a) Front view of the long face shield; (b) perspective view of the foam along the top of the long face shield; (c) side view of a generic cloth mask showing a loose fitting near the nose; (d) top view of the cloth mask showing large gaps created by the loose fit; (e) side view of the ASTM level 3 mask showing how the wired frame fits near the nose; (f) top view of the ASTM level 3 mask showing the reduced gap between the face and the mask.

Little Lives PPE face shield, 19.8 cm in length with a one-inch-thick piece of foam at the top to provide a comfortable fit and to seal the gap between the forehead and the shield (also see **Figure 4(a)-(b)**). The foam prevents respiratory particles from spreading upward and can be easily washed and reused. Each occupant has a mouth opening to create respiratory particle expulsion to model the airflow and particles released during respiratory activities. **Figure 4(c-d)** presents the side view and top view of a generic cloth mask. **Figure 4(e-f)** shows the side and top view of an ASTM level 3 face mask that fits tightly from the sides and the bottom (near the chin) but has small gaps near the nose region. The wired frame surrounding the mask provides a perfect fit even for different face morphologies.

2.3 Numerical methods

The computational fluid dynamics (CFD) software ANSYS Fluent [20] is used to model and simulate the respiratory action of occupants in an enclosed space. The computational domain is discretized using an unstructured mesh and was inspired from the mesh used in Jazizadeh et al. [21] and further developed in [19] for PPE simulation scenarios. The computational domain utilized 1.76 million polyhedral cells to discretize a total volume of 19.45 m³. The mesh included refinements near the mouth, mask and shield region.

A two-way coupled Eulerian-Lagrangian approach is used where the flow field in the room is predicted by the Eulerian method and the concentration and transport of cough particles is computed by the Lagrangian approach [22]. Turbulence is predicted using the k - ϵ realizable model and a user-defined function controls the passage of particles through the mask medium. The simulations are performed using 16 parallel processors that require approximately 36 hours to compute 15 seconds of flow time.

3. Results and discussion

3.1 Assessment of face shields

CFD simulations for two different scenarios are conducted to determine source control, i.e., collection efficiency, provided by the shields modeled in **Figure 3(a-d)** with different fits. These computations assume that one of the two children is coughing and releasing infectious respiratory particles of different size and mass. The expelled particles are categorized as aerosol (particles smaller than 7 μm) and droplets (particles greater than 7 μm) based on their diameters. The droplets tend to deposit on surfaces under the influence of gravity and do not remain airborne for very long. Aerosols, being lighter, have the propensity to remain airborne for prolonged periods, hence, are a primary source of viral transmission.

The collection efficiency is calculated as the volume fraction of cough aerosols captured by a face protection device. The aerosols expelled by the cough are categorized into six bins based on the particle diameter and the collection efficiency for each size bin is separately calculated to investigate the airborne transmission with increasing aerosol diameter. The following results will use images from the simulations to show how pathogens spread and quantitative calculations of collection efficiency to benchmark the importance of face shield fit.

3.1.1 Scenario 1: Size and fit of the face shield

The first scenario considers the transport of respiratory cough particles from the boy who is infectious. The boy expels cough particles, which include aerosols and droplets, at a speed of 12 m/s. To begin, the short shield is considered with a loose fit because it is tilted away from the face, shown in **Figure 5(a-b)**. The aerosol diameters are very small and would not be visible; therefore, they are magnified for visualization purposes in the figure. The shield covers the region between the forehead and the neck although large gaps form at the top and the bottom of the shield. **Figure 5(a-b)** show the cough, which forms a jet of air that hits the shield and spreads along its surface, dispersing the particles along with it. It is seen that a plume of particles escapes from the top of the shield and a significant number of particles are directed downwards. The shield succeeds in capturing only 25.70% of aerosols by mass as most the smaller, lighter particles escape through the gaps at the top and the bottom of the shield. Most of the droplet, which are larger particles are captured by the shield. The tilt of the shield creates a larger gap at the bottom and allows more particles to escape.

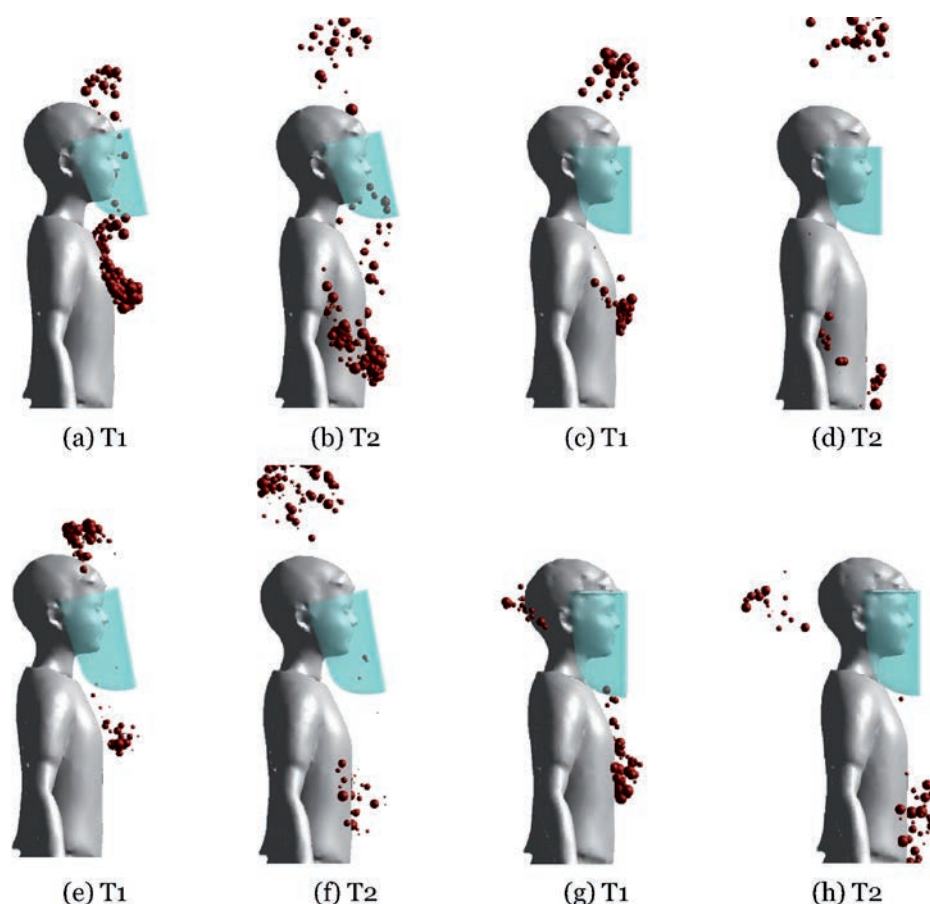


Figure 5.
 Scenario 1: Cough aerosols escaping the (a-b) short face shield with a tilted fit, (c-d) short face shield with proper fit, (e-f) long face shield with a tilted fit and (g-h) long face shield with foam. Each pair of images are for two instances in time.

Additionally, the angle allows particles to travel longer distances from the source of infection, that being the boy.

To examine the importance of fit and possible improvement with source control, the second case assumes the short shield aligns with the boy's face. The transport of cough particles at two instances is shown in **Figure 5(c-d)**, where particles still escape from the top and bottom of the shield. The particles escaping from the bottom are directed downwards and eventually deposit on the floor or on the boy's body limiting the spread to long distances. Aligning the shield reduces the gap at the bottom and captures more particles, providing a source control of 30.63%. Therefore, improving the alignment of the shield, increases the source control from 25.70 to 30.63%.

The next case examines source control of a generic face shield that is long and fits at an angle as shown in **Figure 5(e-f)** at two instants in time. The long shield protects the region between the forehead and the shoulder. The jet of air released during the cough hits the shield in front of the mouth and the impact splits the flow in two directions. One part of the jet containing the cough particles is deflected upwards and the other is deflected downwards. Most of the droplets are captured by the shield, however 63.15% cough aerosols escape from the top and bottom. The long generic face shield slightly improves source control to 36.85% compared with the short shield.

The fourth case is the boy wearing the Little Lives PPE face shield and coughing. The Little Lives PPE face shield has the same dimensions as the generic face shield, however, there is one-inch-thick piece of foam along the top of the shield that seals the gap between the forehead and the shield and keeps the shield vertically aligned. The movement of cough aerosols from the boy at two instances in time is shown in **Figure 5(g-h)**. Similar to the generic face shield, the jet of air carrying the cough particle redirects after hitting the shield. **Figure 5(g-h)** shows some particles escape from the bottom (chin region) and few aerosols escape from the side of the shield and move backwards. The foam along the top fits restricts the flow of air and cough particles upward, reducing spread of the aerosols. The collection efficiency increases from 36.85% for the generic long shield to 51.50% for the Little Lives PPE shield. The majority of the escaping aerosols descend vertically and eventually deposit on the floor or on the boy. The straight fit of the shield restricts the aerosols in the space surrounding the boy and it is found that no aerosols reach the girl.

3.1.2 Scenario 2: Deflection characteristics of the face shield

The second scenario models the girl who is infectious and coughs in the direction of the boy wearing the Little Lives PPE face shield. **Figure 6** presents the transmission of cough aerosols expelled by the girl at two instances in time, T1 and T2. **Figure 6** clearly shows particles of different diameters begin to disperse as they move towards the boy. Approximately 96% particles are blocked by and adhere to the Little Lives PPE face shield and some are deflected. The foam along the top of the shield prevents and captures aerosols providing addition protection. The long shield prevents contaminants from reaching the face and the neck area and significantly reduces exposure. To visualize and contrast the transmission of pathogens, Video 1 (available from: <https://tinyurl.com/Joshi-video-01>) presents (i) children talking without PPE and the girl coughs, (ii) boy wearing a shield and the girl coughs, and (iii) boy wearing a shield and the boy coughs. The blue particles are emitted from the boy, pink particles from the girl and yellow are pathogens.

Figure 7 compares the collection efficiency of different face protection device for six size bins for particle diameters of: 0.0–0.6, 0.6–1.1, 1.1–2.1, 2.1–3.3, 3.3–4.7,

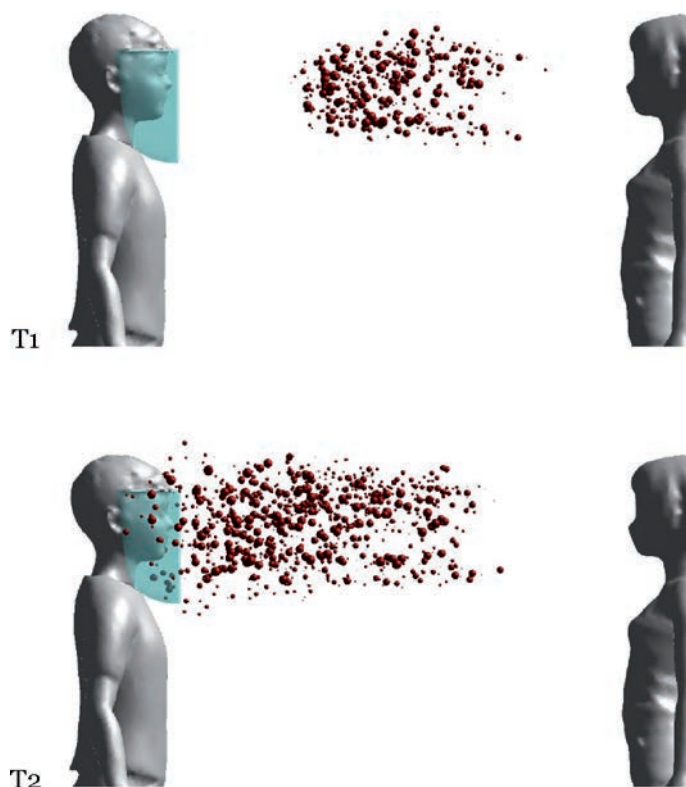


Figure 6.
 Scenario 2: Time sequence for personal protection provided by the Little Lives face shield for cough particles released by the girl.

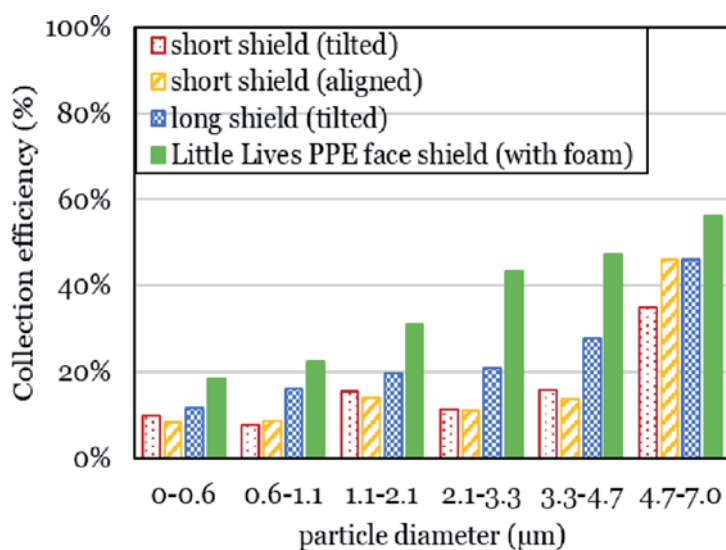


Figure 7.
 Volume fraction of aerosols captured in each size bin for the scenario when the boy coughs for each shield case: short shield tilted, short shield aligned, long shield tilted, and long shield aligned with foam.

Face protection device	Collection efficiency
short shield (tilted)	25.70%
short shield (aligned)	30.63%
long shield (tilted)	36.85%
Little Lives PPE face shield (with foam)	51.50%

Table 1.
Collection efficiency/source control provided by the different face shields.

and 4.7–7.0 μm . The bins for each shield case are different colors and patterns. A notable feature is that the long shield with foam collects the most aerosols within each bin. Aerosols smaller than 0.6 microns are very difficult to capture irrespective of the shield. With increasing particle diameters, each shield captures more aerosols, however, for particles greater than 2 μm , the long shield with foam starts to outperform the other shields, capturing larger particles. For aerosol diameters between 4.7 and 7.0 μm , the collection efficiency is comparable for each shield. The total collection efficiency is shown in **Table 1**, demonstrating that wearing a Little Lives face shield provides maximum protection. The three shields with no foam capture less aerosols as many escape from the gaps formed by the size and fit of the shields. Overall, the Little Lives PPE face shield is shown to have very good efficacy features. One of the unique attributes is that the thick foam at the top prevents respiratory particles from escaping upwards, especially from a violent action such as a cough. The thickness and curvature of the foam facilitates proper positioning and vertical alignment of the shield with the face, thus redirecting respiratory particles downward.

3.2 Assessment of face masks

CFD simulations for different cases are conducted to determine the source control provided by the shield, mask, and a combination of both. These computations assume that the boy coughs expelling infectious respiratory particles categorized as aerosols and droplets. The scenarios include investing source control provided by cloth mask, an ASTM level 3 mask and the additional protection offered when a face shield and an ASTM level mask are used together.

3.2.1 Scenario 3: Boy wears a cloth mask and coughs

The scenario for source control models a boy wearing a generic cloth mask and coughing. The cloth mask uses a fabric that captures respiratory particles larger than 2.5 μm . The mask has a loose fit and leaves a gap near the nose region and small gaps on the sides. **Figure 8(a-b)** shows the transport of cough particles at two instances in time; the size of the particles are enlarged by the same scaling factor for visualization purposes. Particles smaller than 2.5 μm pass through the fabric of the mask and are released to the surrounding. The mask reduces the speed of the very small aerosols and restricts them from traveling long distances.

The cloth mask successfully captured most of the droplets, however, only 48.95% aerosols (by mass) are captured. A considerable portion of aerosols that are not captured escape from the gaps near the nose and on the sides. To improve the source control, it is necessary to improve the fit of the mask in addition to the improving

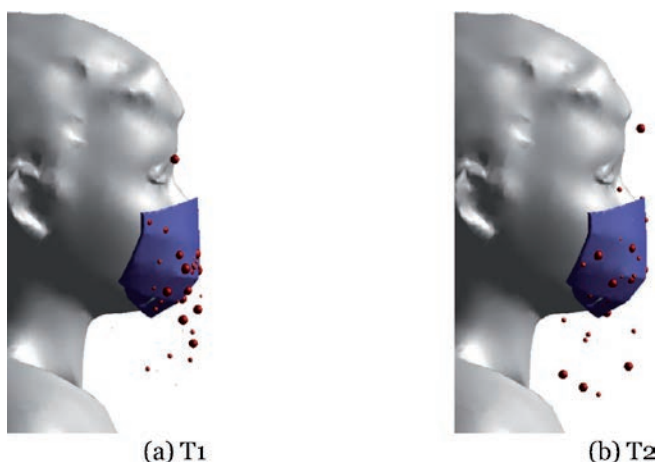


Figure 8.
Scenario 3: Snapshots showing small cough aerosols escaping through the fabric of the cloth mask. Some particles escape through the gap between the mask and the face.

the filtering efficiency of the fabric, which will capture even smaller particles and minimize the spread of infectious pathogens.

3.2.2 Scenario 4: Boy wears ASTM level 3 mask and coughs

Scenario 4 models a boy wearing an ASTM level 3 mask and coughs, shown in **Figure 9**. The ASTM level 3 mask has a wired frame along its edges which allows for a tight fit on the face and minimizes the gaps on the sides and near the nose. The porosity of the ASTM level 3 mask captures respiratory particles larger than $0.3\ \mu\text{m}$. The initial cough distribution has aerosols smaller than $0.3\ \mu\text{m}$ that pass through the fabric of the mask. Some aerosols that escape as an infectious fluid reach speeds of $12\ \text{m/s}$. The ASTM level 3 mask captures 66.56% aerosols but is very effective

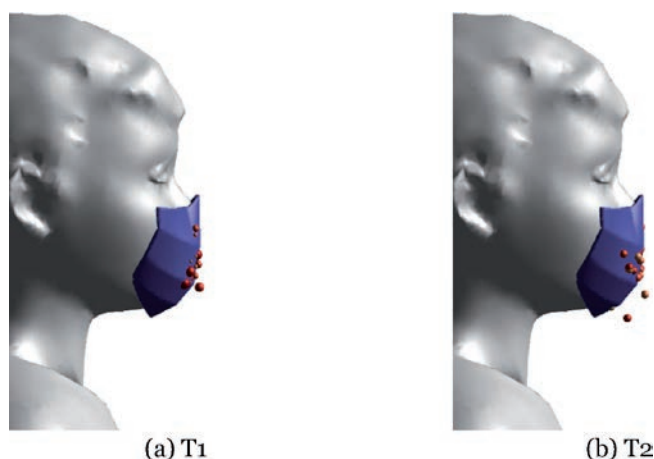


Figure 9.
Scenario 4: Snapshots showing small cough aerosols escaping through the ASTM level 3 mask.

controlling the spread of droplets, capturing 99%. **Figures 8 and 9** elucidate that more aerosols pass through the cloth mask as compared to the ASTM level 3 mask.

3.2.3 Scenario 5: Boy wears ASTM level 3 mask and long face shield and coughs

Approximately 33% cough aerosols escape through the ASTM mask fabric as discussed in Scenario 4. These escaping aerosols can be captured by adding an extra layer of protection like a face shield in combination with the face mask. The improvement in source control using the long face shield with the ASTM level 3 face mask is examined in this scenario. **Figure 10(a-b)** shows the aerosols just leaving the mask at time T1, and the particles deflected downwards escaping the shield at time T2. Most of the aerosols that pass through the mask are captured by the shield in front of the mask. Some aerosols are carried upwards by the stream of air deflected by the shield, which are then captured by the foam along the top. The additional protection provided by the shield improves the source control from 66.56% to 70.07% when boy wears the Little Lives face mask and shield together. The aerosol speeds reduce due to the mask fabric and the elongated face shield, ensuring that the aerosols remain in a confined space. It was observed that most of the escaping particles deposit on the boy's body and the floor further reducing the risk of airborne transmission in the indoor space.

3.3 Effective source control

The transmission of cough aerosols is examined by quantifying collection efficiency for a cloth face mask, the ASTM level 3 face mask alone and with the Little Lives face shield. **Figure 11** compares the collection efficiency of the different face protection devices for each size bin and **Table 2** reports the overall source control for the simulations. The experiments of Lindsley et al. are used to benchmark the source control findings for a cloth mask and ASTM level 3 mask, as shown in **Table 2**.

Figure 11 shows that the cloth mask allows aerosols smaller than $2.5\ \mu\text{m}$ to escape, hence the collection efficiency of the cloth mask for the first three bins is zero.

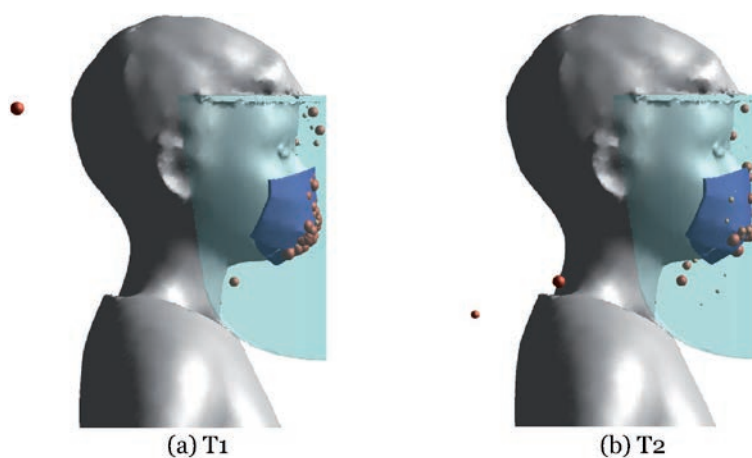


Figure 10.

Scenario 5: Snapshots showing small cough aerosols escaping through the gaps between the fabric of the Little Lives ASTM level 3 mask and are captured by the face shield. Some particles escape through the gap between the mask and the face.

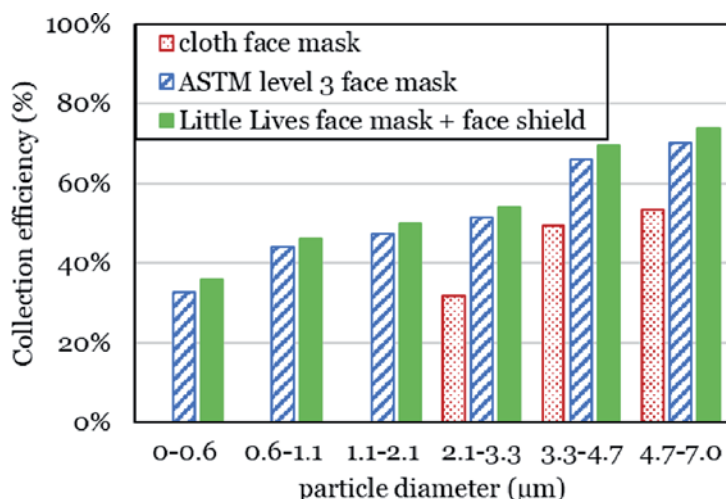


Figure 11.
 Volume fraction of aerosols captured in each size bin for the scenario when the boy coughs for each case: generic cloth mask, Little Lives ASTM level 3 face mask and a combination of Little Lives Face mask and shield.

Face Protection Device	Source control (simulations)	Source control (experiments) [13]
Cloth face mask	48.95%	50.90%
ASTM Level 3 face mask	66.56%	58.50%
Little Lives ASTM Level 3 face mask + face shield	70.07%	—

Table 2.
 Overall source control for cough aerosols expelled.

Lindsley et al. reported a source control of 50.90% for a cloth mask, which is comparable to 48.95% achieved using CFD simulations. The difference in the source control values is attributed to differences in the porosity of the cloth mask.

The ASTM level 3 mask captures significantly more aerosols that are 2.1 μm and smaller (first three bins in **Figure 11**) and has a source control of 66.56%. A source control of 58.50% was achieved in the experiments by Lindsley et al., which used an ASTM level 3 mask. Differences may be attributed to the fit used for this study. A general trend seen is that as the aerosol diameter increases the collection efficiency for each scenario increases, indicating that more aerosols are captured.

As a final comparison, the ASTM level 3 mask in conjunction with the Little Lives face shield is assessed and the collection efficiency increases, but not dramatically. Clearly the ASTM level 3 mask is sufficient on its own as the best PPE to control the source of infection (i.e., a sick person) as well as reduce transmission of pathogens to a healthy person wearing the mask.

To demonstrate the viability of a properly worn face shield, **Figure 12** presents a time sequence of the two children and Video 2 (available from: <https://tinyurl.com/Joshi-video-02>) is the corresponding animation. The simulation models the boy breathing, shown as blue dots, and coughing shown as yellow dots in frames T2 and T3. The particle distribution was modeled using [2, 4] with a velocity

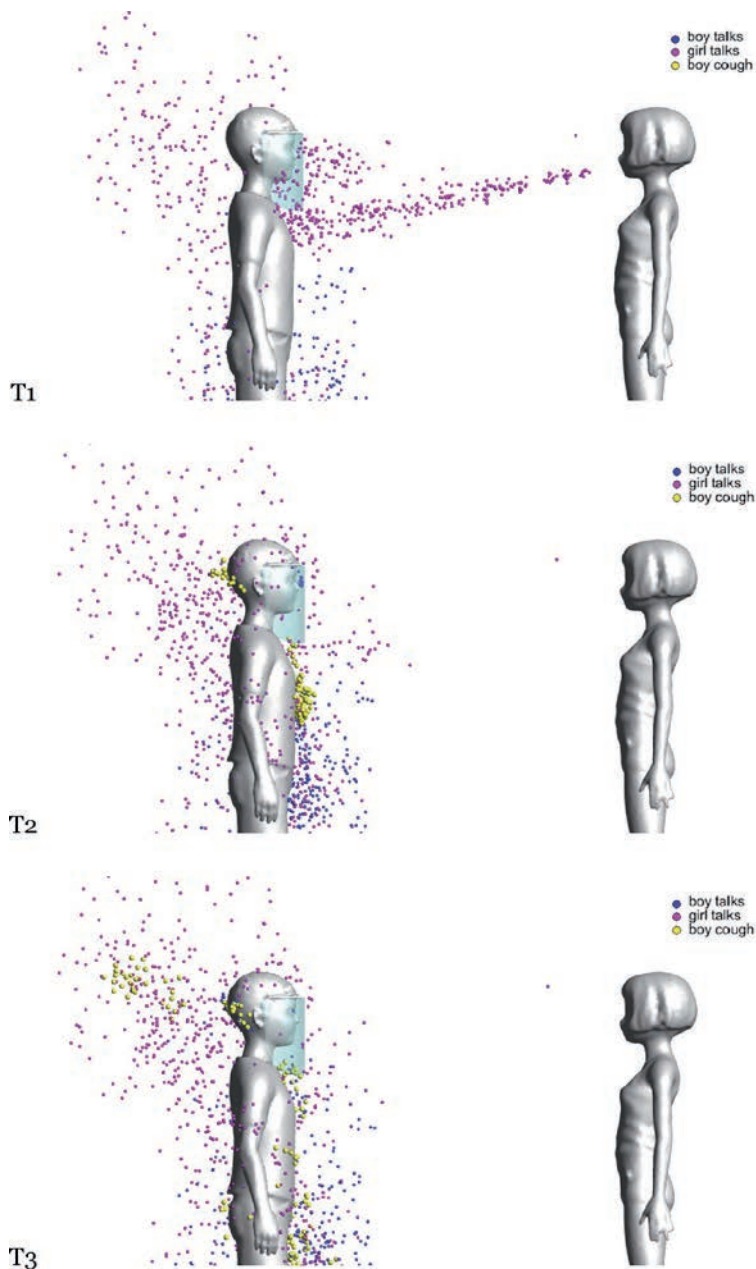


Figure 12.

Time sequence with the girl talking (pink) and the boy breathing (blue) and coughing (yellow).

of 0.4 m/s. The shield redirects his breathing downward and does not travel towards the girl. More importantly, the cough is not only directed downward, but the force of the cough hitting inside the shield directs escaping fluid to move behind the boy, thus preventing transmission to the girl. The face shield was reported to have a collection efficiency of 51.5% in **Table 1**. Also shown is the girl talking excitedly and the air stream distribution was modeled using [4] with a velocity of 0.8 m/s [23]. Frame T1

shows the air stream impact the boy's chest and shield while the girl talks. The shield deflects most of the air stream and would protect the boy if the girl was infectious.

4. Summary and conclusions

An assessment of face shields and face masks was analyzed using computational fluid dynamics. The scenarios assumed that there was no ventilation and that two children were in a room. We know that ventilation is very important, [24] but this scenario is considered the worst case when there is risk for transmission of infectious particles. Results of the study showed that size, orientation, and enhanced features like foam along the top edge of the shield is extremely important for source control. A long face shield would provide at least 30% source control but the Little Lives PPE™ face shield provided superior performance. This was due to the foam that eliminated aerosols from escaping upward in front of the person. Also, wearing the shield so the front was vertically aligned with the face also improved source control. It was also shown that the mask material is an important factor for source control and personal protection. The ASTM level 3 mask was extremely effective in reducing the transmission of aerosols, capturing approximately 66%. Wearing the Little Lives face shield with the face mask provided addition protection thus further reducing the transmission of aerosols.

The importance of properly using PPE cannot be underscored and the world observed the ramifications during the COVID-19 pandemic. In March 11, 2020, when the World Health Organization announced the pandemic, PPE for the face was not required. As a result, over 500 million deaths worldwide in March and April. Once face masks were required, the type of masks that were initially recommended included simple cloth masks, gaiter masks and paper-type masks, but N-95 masks were recommended only in medical settings. These actions contributed to the continual spread of the coronavirus because non-N95 masks did not sufficiently protect the individual or control the spread of aerosol pathogens to others.

The PPE choices that we make during the next pandemic can significantly impact outcomes. Individuals need access to N-95 masks and to wear them properly, ensuring that the flexible metal ridge on the nose fits in order to reduce gaps along the face mask. The study herein showed that important feature. In addition, this study shows that for individuals with unique needs who do not tolerate masks, a face shield can help with protection. Our preparedness relies on immediate communication of best practices and economical (or free) availability of face PPE. While face masks and shields are not the only important PPE to reduce spread of pathogens, they can contribute significantly as scientists develop vaccines.

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Rebuilding Domestic Outbreak Readiness: Partnerships, Perception, and Public Health in Crisis

Summyr Burton, Savannah Baus and Stephen Murphy

Abstract

This chapter critically examines the state of domestic outbreak preparedness in the United States, focusing on three interdependent domains essential to effective infectious disease response: partnerships and collaboration, public risk perception, and the outbreak response workforce. Drawing on case examples, especially the COVID-19 pandemic, it discusses key systemic and structural challenges that undermine readiness. Through evidence-based analysis, the chapter offers recommendations for building cross-sectoral partnerships, improving public trust and risk communication, and strengthening workforce competence and capacity. Emphasizing the urgency of proactive and sustainable investment in infrastructure, planning, and collaboration, this chapter provides a framework for ensuring a more cohesive, equitable, and resilient response to future epidemics and pandemics.

Keywords: pandemic preparedness, cross-sectoral collaboration, multidisciplinary partnerships, risk perception, health belief model, risk communication, information exchange, workforce competency, burnout

1. Introduction

Biological threats are in the air we breathe, the food we eat, the water we consume and use for bathing, and the people we encounter every day. Infectious disease outbreaks, and their ever-increasing risk of escalating into epidemics or pandemics, pose persistent and evolving threats to public health systems. While scientific and technological advancements have enhanced our ability to detect and manage outbreaks, operational readiness is contingent upon a network of interdependent domains, each uniquely susceptible to systemic vulnerabilities.

This chapter analyzes the current state of readiness within the United States, analyzing the roles, prevailing shortfalls, and key contributing factors within three critical domains: collaborative partnerships, public risk perception, and the public health preparedness and response workforce. The chapter culminates with a set of key recommendations to inform strategic improvements to our domestic infrastructure,

aiming to ensure a heightened state of readiness for, and optimal response to, the next inevitable biological threat in our communities.

2. Overview of epidemics and pandemics

The domestic health security infrastructure has been shaped and refined over decades of response to various historical outbreaks which provided valuable insights, such as recurring system failures and key achievements in successful mitigation. The well-known 1918 influenza pandemic showed critical shortfalls in public compliance and use of non-medical countermeasures, while the 2009 H1N1 influenza pandemic underscored challenges in large-scale vaccine development and distribution. Given the fluid and dynamic context of the domestic infrastructure, we will discuss key mitigation strategies and provide a basic overview of the domestic health security infrastructure in place to execute them.

2.1 Key mitigation strategies

Controlling community spread of contagious pathogens relies on preventive measures that work to a) reduce or inhibit human-to-human spread of disease and/or b) rapidly detect the pathogenic threat before escalation into an epidemic or pandemic. Numerous mitigation strategies are available for jurisdictions to employ for outbreak management and control.

2.1.1 Surveillance

Infectious disease surveillance is the primary means by which outbreaks are detected. Surveillance is defined as “the ongoing, systematic collection, analysis, and interpretation of health data” for use in planning, implementation, and evaluation of infection control activities [1]. Three goals of surveillance include a) to provide a baseline presence and burden of disease, b) to monitor trends over time, and c) to detect emerging pathogens and outbreaks [2]. Pandemic-specific information, such as the incidence of hospitalized cases, case-fatality rates, and mapping data to visualize current and project future hot spots, provides situational awareness for jurisdictions and decision makers. Passive disease surveillance for both infectious and chronic diseases occur across many STLT jurisdictions, including wastewater surveillance and healthcare facility mandatory reporting mechanisms, with diseases of concern reported to federal entities.

2.1.2 Risk communication

When a crisis such as an epidemic or pandemic occurs, jurisdictions’ primary responsibility is to manage uncertainty within the at-risk communities and follow best practices when communicating health and outbreak messaging [3]. Risk communication is pertinent to managing uncertainty, as it encompasses sharing information with at-risk communities about a hazard, including potential outcomes and recommended actions and behaviors to adopt to protect oneself and their loved ones [3, 4]. The CDC’s Crisis and Emergency Risk Communication (CERC) framework provides a foundational model for developing health messages and conducting risk communication [4]. **Table 1** describes CERC’s six core principles outlined in the framework.

Core Principle	Meaning
Be First	Early communication shapes public perception and reduces risk of misinformation.
Be Right	Accuracy is critical to establish credibility and instill public trust.
Be Credible	Maintain honesty, transparency, and consistency to foster and sustain trust.
Express Empathy	Acknowledge public fear and uncertainty in times of crisis strengthens relationship between institutions and the public.
Promote Action	Always provide action cues with clear, simple instructions to help reduce anxiety and increase public compliance.
Show Respect	Respectful and culturally-competent messaging promotes cooperation and builds rapport with the public.

Note: Adapted from [4].

Table 1.
CDC’s Crisis and emergency risk communication core principles.

2.1.3 Non-medical countermeasures

When an outbreak begins to propagate throughout a community, particularly in the case of an emerging, or novel, pathogen where there are often no known treatment or vaccine, there is a heavy reliance on non-medical countermeasures to curb transmission. Non-medical countermeasures, also known as non-pharmaceutical interventions, are critical first-line responses that community members and local decision-makers may enact. These countermeasures include personal protective measures, such as hand hygiene and wearing face masks, environmental measures, including disinfection practices and ventilation, and social and physical distancing measures, including travel restrictions and school and workplace closures [5].

2.1.4 Medical countermeasures

Medical countermeasures (MCMs) are central to the public health response to mitigate the impact of influenza pandemics. While vaccinations remain the most effective MCM for mitigating the impact of an infectious disease pandemic, the specific pathogen is unknown before the incident itself. Therefore, other MCMs must be available through localized stockpiles and the centralized, federally supported Strategic National Stockpile (SNS). A formalized and ideally exercised distribution strategy for deployment once these MCMs, including a developed vaccine, are made available is also standard practice for jurisdictional entities. Stockpiles of MCMs typically include vaccines, antivirals, antibiotics, diagnostics, ventilators, and respiratory protection devices.

Surveillance and risk communication are standard practices and should be consistently maintained regardless of the presence of an outbreak. Strategic decision-making for other medical and non-medical countermeasures, including which to deploy and for how long, are largely dependent on pathogen characteristics such as how quickly the pathogen is spread through the community (transmissibility) and the severity of clinical symptoms of those who fall ill (clinical severity) [6]. With this understanding we can discuss the domestic outbreak response system used to develop, implement, and employ them.

2.2 Domestic outbreak response system

The domestic response mantra suggests that all disaster response is locally executed, state-managed, and federally supported. Domestic public health authority operates within a decentralized framework where primary authority during infectious disease outbreaks rests with state, and sometimes local, governments [7]. Key U.S. policies such as the Public Health Service Act, National Response Framework, and the U.S. Constitution's 10th amendment, provide a solid foundational structure and clearly delineates roles and responsibilities for agencies, departments, and individuals working at all levels from local to federal.

The federal outbreak response structure includes specialized personnel within agencies such as the CDC, FEMA, and the Administration for Strategic Preparedness and Response (ASPR). These entities are primarily responsible for strategic oversight, guidance, technical assistance, and surge support. In recent decades and due to lessons learned from other epidemics and disasters, federal initiatives have advanced our infrastructure for more rapid, efficient outbreak response.

Examples of key initiatives include the Public Health Emergency Preparedness (PHEP) cooperative agreement, the Hospital Preparedness Program (HPP), the National Syndromic Surveillance Program (NSSP). These structures lay the groundwork for improved coordination and operational capacity prior to, during, and after outbreak for continuous improvement of the domestic infrastructure.

Each state maintains its own public health laws, regulatory authorities, and operational systems that may or may not be based on federal guidance. As such, significant

Function/ power	Federal (e.g., CDC, HHS, President)	State governments (e.g., Governors, State Health Depts)	Local/Tribal Authorities
Isolation & Quarantine	CDC can detain individuals at ports of entry or between states under the Public Health Service Act	States can impose mandatory quarantine/ isolation under state police powers	Local HDs enforce (& sometimes impose) isolation/quarantine locally
Deploying Medical Counter- measures (MCMs) (e.g., vaccines)	FDA issues Emergency Use Authorizations (EUAs) Federal gov. deploys supplies from Strategic National Stockpile or other MCMs (e.g., vaccines)	States allocate and distribute SNS supplies; manage local prioritization	Local health systems execute distribution of countermeasures; coordinate outreach
Surveillance & Reporting	CDC oversees national surveillance (NNDSS, BioSense); mandates reporting of notifiable diseases	States collect and report surveillance data to CDC; may expand contact tracing and reporting	Local HDs do case investigations, contact tracing, and local reporting
Risk Commun- ication	CDC, HHS, and White House coordinate national messaging campaigns	Governors and state health officers lead statewide risk communications	Local public health agencies communicate with communities

Table 2.
Outbreak activities of federal, state, local, and tribal authorities.

variabilities exist in terms of public health governance and capacities across local and state jurisdictions and limits the ability for cross-jurisdictional cohesion and unified national response during epidemics and pandemics.

Local health departments (HDs), including those serving county, city, and tribal areas, have a lead role in the execution of public health interventions, surveillance, risk communication, and community engagement activities providing the strategic, operational, and tactical readiness plans and responses, including the distribution of MCMs across the jurisdiction and often have the authority to enact and enforce non-pharmaceutical interventions. **Table 2** provides a basic overview of key functions of outbreak mitigation and responsibilities of federal, state, and local/tribal entities.

In the post-COVID-19 context, like the 1918 and 2009 influenza pandemics, the current system and infrastructure is likely to change. The rest of this chapter will explore the ways by which the current system is challenged during large-scale outbreaks such as epidemics and pandemics.

3. Factors impacting domestic outbreak readiness

It is nearly impossible to consistently provide optimal response against pathogens of pandemic-level risk, particularly emerging and zoonotic threats and the highly complex contexts by which they spread. However, some factors, including effective collaboration through partnerships, community risk perception, and reduced outbreak response work-force, continuously challenge response and thus warrant attention and improvement.

3.1 Partnership and collaboration

Infectious disease outbreaks, particularly those caused by emerging zoonotic pathogens, demand a level of coordination that no single sector or institution can achieve alone. Public health emergencies are not only biomedical events but also complex socio-ecological crises that require multi-sectoral engagement. Effective response requires the integration of human, animal, and environmental health services, along with the participation of emergency management agencies, law enforcement, private sector partners, and local communities [8]. These partnerships facilitate surveillance data exchange, coordinated response activities, mutual aid deployment, resource mobilization, and many, many other benefits for effective response. Although the importance of collaboration is widely acknowledged, its execution is often undermined by systemic, logistical, and political challenges.

3.1.1 Lack of cross-sectoral and multi-disciplinary partnerships

Standardized structures such as NIMS and Incident Command System (ICS) are the primary means by which jurisdictions are trained to collaboratively operate during any crisis. Key federal initiatives such as the PHEP cooperative agreement and HPP additionally support collaboration at all jurisdictional levels. However, cross-sectoral collaboration is often undermined in practice by institutional silos, fragmented funding streams, and inconsistent mandates across government agencies.

As aforementioned, effective infection control must rely on early detection and mounting a rapid response and mobilization of resources. This not only requires robust plans and protocols to outline roles and expectations for each group, but it also further requires cross-sectoral motivation to trigger a strong response. For example, political

refusal to mobilize resources once an outbreak is detected significantly delayed response during the 2009 H1N1 influenza pandemic, 2014 West Africa Ebola Virus Disease epidemic, and 2016 Zika virus epidemic [9]. These differences in legal authorities, organizational mandates, and operational protocols hinder coordination across jurisdictions.

One adverse outcome of these systemic complexities reflects STLT jurisdictions' continued reliance on pre-existing relationships, trust, and informal networks. These informal relationships, while beneficial in many ways, are not as effective or secure as formal agreements and arrangements which offer structure and clarity on partner expectations, responsibilities, and decision-making processes [10]. Another outcome describes local and territorial jurisdictions who face challenges aligning their response strategies with federal priorities when guidance or funding criteria are ambiguous. Tribal sovereignty adds additional layers of complexity to coordination with state governments, particularly when mutual aid or resource sharing is needed.

3.1.2 Reactive, not proactive, relationship building

A lack of joint operational planning and clearly delineated responsibilities can lead to duplication of efforts, supply chain inefficiencies, and inconsistent service delivery. Federal funding and support mechanisms, based primarily on jurisdictional threat assessments and national priority areas, often prioritize large states and urban centers, inadvertently marginalizing smaller and resource-limited jurisdictions in rural and tribal areas. Pre-outbreak collaboration is further threatened by fluctuating political will, finite attention spans, and the media and donor landscapes, impacting funding streams necessary to engage in partnership building [11].

Partnerships established during outbreaks are often unsustainable in the long-term. The 2014 West Africa Ebolavirus Disease epidemic offers a comparative example of reactive and proactive partnerships on epidemic mitigation. Systems and infrastructures developed during this epidemic were not institutionalized. In the post-epidemic months, as donor attention waned, funding was cut off, and resources such as laboratory equipment and medical supplies were removed from the affected areas, creating an environment similar to the fragile, unprepared pre-epidemic context.

Nigeria's response during the 2014 Ebola epidemic, in comparison, was effective at mitigating transmission within their country, in large part due to an existing outbreak response infrastructure established for prior polio eradication campaigns. This included a multisectoral and cross-disciplinary network which rapidly mobilized to engage in mitigation strategies, such as private sector actors contributing logistical resources and local community leaders working with the formal response to implement culturally appropriate and safe burial protocols [12]. The same infrastructure, now bolstered from continued relationship building during the Ebola epidemic, was instrumental during the COVID-19 pandemic. These insights show the clear utility of pre-outbreak efforts to build strong relationships and their ongoing effectiveness for future outbreaks.

3.1.3 Data siloes and information exchange

Data is central to any disaster response as it provides the common operating picture (COP) by which decision-makers form the situational awareness that informs strategies, legislation, and action plans to mitigate the spread of contagion. Robust information sharing practices and structures are widely supported in policies, initiatives, and frameworks such as the Pandemic and All-Hazards Preparedness

and Advancing Innovation Act (PAHPAIA), the PHEP Cooperative Agreement, and Emergency Management Assistance Compact (EMAC).

Ongoing challenges related to data collection and sharing across sectors include data siloes, poor data standardization, and inadequate systems in place to facilitate information exchange. Information siloes arise when poor collaboration and a lack of formal partnerships impede understanding of what data is being collected, where the data is stored, and who to coordinate with to obtain collected data. By example, surveillance and health information systems are often fragmented and externally incompatible. This requires staff at a local HD to locate and connect with staff at a local healthcare facility to gain an understanding of current bed capacity and case counts, significantly slowing down decision making processes. Siloes are further exacerbated by strict data sharing policies and cybersecurity measures that do not provide ability to share across jurisdictional and organizational lines. Inadequate data standards and data collection practices, such as reporting timelines, inhibit comparisons across jurisdictions and time.

These challenges are further impacted by ineffective or a lack of plans and protocols to facilitate information exchange and decision-making across sectors. Improving on these challenges will take immense time, effort, and funding resources that currently are not available to all outbreak response sectors and geographic regions. Tribal and territorial entities, in particular, may encounter barriers to data access due to historical mistrust, restrictive policies, or inadequate infrastructure.

3.2 Community risk perception

Risk perception, defined as the perceived personal vulnerability or likelihood of a disease or health threat, has long been recognized as an important influence on an individual's intention and motivation to utilize protective behaviors [13]. As mentioned earlier, in the absence of medical countermeasures to diagnose and treat infection, outbreak mitigation relies heavily on community trust and compliance with recommended protective actions.

The health belief model (HBM) posits that an individual's perception of a threat is based on their perceptions of susceptibility (or risk) to and severity of the disease [14]. The HBM also includes the efficacy of protective actions as influencers of health behavior and elucidates on the psychological underpinnings of health behavior adoption. Indeed, for an individual to engage in health behaviors against a perceived health threat, one must account for a) the perceived benefits of the behavior, b) perceived self-efficacy to successfully adopt the behavior, and c) the perceived barriers impeding access to successful adoption of the behavior. Interestingly, large-scale meta-analyses have identified perceived barriers as consistently the most significant predictor, and perceived severity the least significant predictor, of health behavior action [15]. Public risk perception is impacted by ineffective risk communication practices and media-fueled misinformation.

3.2.1 Ineffective risk communication

Managing uncertainty requires communicators to remain consistent, provide accurate information, and share current and future risk projections. Within the U.S., best practices for risk communication include the CDC's CERC core principles, referenced in **Table 1**. Unexpectedly, these responsibilities are challenged by the overwhelming complexities and rapidly changing contexts during an outbreak, particularly an epidemic or pandemic caused by an emerging pathogen.

A recurring hurdle in recent outbreaks has been the lack of message consistency across risk communicators within differing jurisdictional levels and sectors, due in large part to decentralized authority for public health actions. While federal agencies such as CDC and ASPR often lead on national messaging and media briefings, the actual delivery and tailoring of messages fall largely to STLT HDs. These departments are best positioned to interpret and adapt national messages for local contexts, yet they often lack specialized staff, training, or budgetary flexibility to mount effective communication campaigns.

Conflicting messages between federal and local leaders, or elected politicians and leading health experts, especially in politicized environments, undermine public confidence and lead to widespread uncertainty, fear, and confusion [16]. Ineffectual risk communication bears immense risk of losing public trust and buy-in to adopt protective behaviors to curb transmission of the infectious disease.

Social resistance was suggested to be a critical challenge to the control of the 2018 Ebolavirus disease outbreak in the Democratic Republic of Congo [17]. During this outbreak, resistance was caused by issues such as mistrust of the government, disbelief in public health messages, and proposed protective behaviors contradicting cultural norms (e.g., burial practices) [17].

3.2.2 Media and misinformation

Rumors, misinformation, and conspiracy theories are not new to infectious disease outbreaks. During epidemics and pandemics, false information most often relates to the origins of disease, cures, and vaccine safety and has led to deeply adverse consequences such as stigmatization of community groups and vaccine hesitancy. Though the behavior is hardly new, technological advancements and social media have greatly increased the velocity at which misinformation and disinformation is able to spread.

Social media and its resultant “infodemic” have fundamentally challenged traditional public health messaging approaches and vetting processes, drastically reducing the reach and accessibility to accurate outbreak information and evidence-based protective actions. Media ecosystems, particularly digital platforms, significantly mediate how messages are received, distorted, or amplified. One example of innovative media advancements is the use of algorithms which provide each user with tailored content according to their interests and beliefs. Research has found algorithms prioritize high-engagement, sensationalized content that can create emotional and irrational responses [18].

In recent years, the U.S. media environment has become increasingly fragmented and digitized, further challenging jurisdictional risk communication messages. Conflicting health information from risk communicators and a wealth of harmful health rumors circulating on traditional and social media platforms has eroded public trust in jurisdictional entities and outbreak responders. Without public trust, awareness and educational campaigns on outbreak dynamics and protective behaviors are largely ineffective and, in some cases, dangerous.

3.3 Outbreak response workforce

An effective domestic outbreak response hinges upon the availability, competence, and sustainability of a dedicated workforce to engage in public health surveillance, contact tracing, case investigation, infection prevention and control, vaccination campaigns, and community outreach activities.

3.3.1 Burnout, attrition, and workforce capacity

Burnout, defined by the World Health Organization as “a syndrome resulting from chronic workplace stress that has not been successfully managed,” has become a global occupational issue in the post-COVID-19 era [19]. Within the U.S., research has indicated burnout is impacting 46% of healthcare workers and 54% of environmental health professionals (e.g., disaster responders, infection control) [20, 21]. This phenomenon is marked by emotional exhaustion, depersonalization, and a diminished sense of accomplishment, undermining productivity, decreasing morale, and compromising public service quality [22].

Numerous factors contribute to the development of burnout, but organizational and systemic-level variables are often implicated due to their widespread adverse impacts across workforces. In public sector settings, organizational demands are deeply shaped by broad structural forces, including chronic budget constraints, restrictive policy mandates, and political interference. These systemic conditions increase job strain without corresponding increases in resources or autonomy, leading to chronic work overload and staff shortages, primary causes of burnout and attrition [23–25]. This “doing more with less” mentality is persistent in entities lacking advanced structure and resources seen in federal entities such as CDC and FEMA, leading to local contexts suffering disproportionately from the effects of burnout.

Additional contributors to burnout include issues such as weak support for responder wellness and mental health, rigid bureaucratic oversight, unsupportive leadership, bullying and harassment from the community, and a lack of digital and technological tool integration as major contributors to burnout [26, 27]. Expectedly, employees feel unsupported by leadership and frustrated by institutional policies, poor communication, and leadership inaction [28].

Aside from burnout, organizational factors that fuel attrition include inadequate benefits, particularly salary, and lack of professional advancement opportunities, particularly among younger and short-tenured workers [29]. Attrition, if left unabated, is a vicious cycle that will continue to burnout the remaining workforce while reducing quality of public service and continuing to drain resources and funding.

3.3.2 Inadequate knowledge, competency, and experience

Competency expectations across all response levels include proficiency in core domains such as applied epidemiology, emergency management principles, risk communication, cultural competence, data interpretation, and ethical decision-making. Significant variabilities exist in these competency areas, disproportionately impacting readiness in some areas more than others. For example, the federal workforce is more likely to benefit from specialized training and robust support structures, whereas STLT personnel may lack access to such resources and be required to learn on the job or through limited, grant-funded initiatives. In many rural areas, it is common to expect one HD staff member to have working knowledge in all competency areas and embody expertise in all areas during active response.

This disparity not only contributes to variability in workforce readiness, but also to a lack of professional advancement opportunities, a poor sense of accomplishment, and high stress when accomplishing tasks. This unsustainable current practice not only impacts individual-level job strain but the entire outbreak response system as it impedes abilities to form and maintain partnerships [30].

Many STLT HDs operate with limited personnel and rely heavily on cross-trained staff from other non-emergency response staff, volunteers, and other formal and informal partners to assist during active outbreak mitigation. Many of these “surge staff” brought on to assist in these critical times had limited to no knowledge in these core competency areas and, sometimes, of infectious diseases in general. These norms are disproportionately distributed in rural, tribal, and territorial jurisdictions, often contending with geographic isolation, limited access to training, and inconsistent funding streams that impede workforce development and retention capacity. Unexpectedly, an in-experienced workforce with limited knowledge and skills related to outbreak response significantly reduces the jurisdictional capacity to effectively operate and curb disease transmission.

Formal education is also insufficient among many in the domestic outbreak response workforce, limiting core knowledge and skills in areas such as public health (e.g., social determinants of health, ethics), policy and legislation, and data analytics. The 2021 PH WINS report that showed that just over one-third (37%) of the governmental public health workforce held advanced degrees and only 14% held a specialized degree in public health [31]. We can expect the current outbreak response workforce to show even less educational attainment as have backgrounds in law enforcement and military. This data highlights significant need to develop, standardize, and institutionalize training and educational opportunities that foster skillsets in public health, data analytics, and decision-making to advance individual-level readiness within the actual and surge workforces.

4. Case study: The COVID-19 pandemic

The COVID-19 pandemic highlighted stark shortcomings in domestic response, particularly as it relates to partnerships and collaboration, public risk perception, and the nationwide outbreak response network.

Substantial challenges in partnerships and collaboration caused delays in resource mobilization, implementation of risk mitigation, and risk communication to the general public. Bureaucratic, supply chain, and jurisdictional resource challenges led to inaccessibility of critical resources, such as data and information, personal protective equipment, and diagnostics to curb viral transmission, often for substantial periods of time [32]. Across the board, jurisdictions were faced with the consequences of poor investments in building relationships in the pre-pandemic period.

One key achievement relates to the implementation of dashboards to highlight the evolving data elements for decision-makers. These situational reports, or SITREPs, showcased highly effectual cross-sectoral coordination using evidence-based information sharing processes. However, many of these relationships were formed out of necessity and thus were not immediately available in the chaotic early weeks of the first pandemic wave. Some were not formed at all, leaving many jurisdictions without the tools or political climate to monitor, compile, and share COVID-19 case counts and related information.

Arguably one of the most challenging hurdles was the poor collaboration, and as a result, poor risk communication, between medical and scientific research experts and political actors. Early in the pandemic’s initial wave, all states enforced some level of mass quarantine via societal lockdowns and school closures. However, in subsequent waves, political will to maintain mitigation measures largely depended on partisan belief systems, as opposed to available science supported by surveillance

and research. This resulted in conflicting health messages from risk communicators, sometimes within the same press conference, causing substantial uncertainty on exposure risk, case counts, and efficacy of protective behaviors and treatments, was rampant at the height of the pandemic.

The public health consequences of the politicization of the pandemic were immense. Indeed, Democratic-led states promoted vaccinations, mask mandates, and school closures while Republican-led states across the country, governors stopped promoting the vaccine and supported efforts to end lockdowns and school closures by specified target dates rather than reduced transmission rates or herd immunity from vaccinations.

Mass confusion surrounding mitigation strategies and their efficacy was widespread, with nearly one in five U.S. adults unsure of quarantine and isolation protocols following viral exposure or positive test results nearly 2 years after the pandemic began [32]. Adults also showed low rates of risk perception and confidence in countermeasures, including risk of COVID-19 impact on personal lives, COVID-19 booster vaccines, and accuracy of at-home COVID-19 testing kits [32]. Coordination challenges such as supply chain issues further added to reduced confidence rates, impacting community buy-in and willingness to adopt mitigation measures. The lack of science-based decision-making resulted in a 43% higher excess death rate among Republican voters compared to Democratic voters [33]. The public health workforce suffered from moral injury and guilt due to unnecessary morbidity and mortality, further contributing to adverse psychosocial consequences.

The mental and psychosocial impacts of the pandemic have been well-documented in both the responder workforce and general public. Stress, anxiety, and depression were pervasive emotions across the globe due to the far-reaching impact of the pandemic and mitigation strategies. These adverse psychosocial impacts and dearth of mental health support have had long-term and widely pervasive negative consequences, with national calls to action reporting a “mental health crisis” and “epidemic” of loneliness and isolation [34, 35].

For the responder workforce, poor mental and psychosocial health has intensified burnout and attrition, further stretching the available workforce and impacting capacity to meaningfully engage with multi-sectoral partners [36]. By example, a 2017 survey projected approximately half of the most vulnerable local and state public health workers shared intentions to vacate their positions by 2021 [29]. Approximately 75% of this cohort actually left by 2021, showing the substantial pandemic impacts on the workforce.

In sum, the COVID-19 pandemic uncovered the shortcomings of our domestic pandemic infrastructure. These include:

- i. Preparedness must be ongoing, not reactive.
- ii. Coordination and consensus among decision makers is essential.
- iii. Data systems must be modernized.
- iv. Risk communication must be clear, proactive, and trustworthy.
- v. Community engagement is indispensable.
- vi. A strong, competent workforce must be prioritized.
- vii. Burnout and attrition must be addressed at all levels.

5. Recommendations for future domestic outbreak readiness

5.1 Partnership and collaboration strategies

During the COVID-19 pandemic, one clear achievement was the unprecedented global collaboration to develop and share global databases on the SARS-CoV-2 viral genome to enable research efforts for epidemiologic and therapeutic development purposes [37]. Similar successes were seen in vaccine research and development activities, whereby partnerships such as the Oxford-AstraZeneca collaboration and BioNTech-Pfizer alliance substantially reduced typical development timelines. Political influence further provided the legislative support to move ahead with rapid development, authorization, and distribution. It is perhaps no surprise that this sector was capable of this remarkable achievement, given its substantial and consistent flow of funding and clear efficacy as a pandemic mitigation measure.

This example shows the importance and effectiveness of cross-sectoral collaborative partnerships, yet, interestingly, remains rare for many jurisdictions. We recommend prioritizing proactive partnership building activities and investing in centralized data systems and mechanisms to improve cross-sectoral information exchange.

5.1.1 Prioritize pre-outbreak partnership building

Many of the readiness and response shortfalls discussed in this chapter can be substantially reduced, if not eliminated altogether, through the establishment and sustainability of robust, multi-sectoral partnerships. Successful workforce surge capacity strategies, including task shifting, redeployment, and expanded scopes of practice, depend on pre-existing collaborative frameworks [36].

Best practice has consistently denoted the importance of including a diverse array of sectors, disciplines, and communities at all phases of the disaster cycle, particularly the planning phase as it is often overlooked. In non-outbreak times, consistent communication, formal agreements, and inclusion into routine exercises and preparedness activities can have substantial impact towards building the readiness infrastructure. Each jurisdiction should, at a minimum, maintain points of contact at local hospitals and healthcare facilities to rapidly generate a SITREP or COP to future threats. These partnerships can facilitate a stronger COP at the state levels which in turn informs local-level operations and provides checks and balances for national level operations.

The decentralized domestic infrastructure set the stage for conflicting risk communication from public health leadership and elected officials at local, state, and federal levels. This dichotomy persists in 2025, 5 years post-pandemic, with the current domestic readiness system hyper-politicized along partisan lines, exacerbating a dearth of consensus on effective countermeasures and strategies to curb outbreak transmission, such as vaccines, facemasks, and mass quarantine. Thus, building consensus across sectors and jurisdictions, though a complex and time-consuming process, is essential to rebuild domestic readiness for future emerging pathogens.

To build consensus, the system must rely on the advanced scientific foundation housed domestically and globally within institutions of higher education (IHEs), government research institutions, and all other non-profit, community-based, and private organizations. In the post-pandemic era, the hyper-polarized topic of public health and infectious disease outbreaks has fragmented these sectors and fostered

significant levels of distrust. Engagement and achievement of the partnership and collaboration recommendations discussed above will assist in building cohesion and trust between these sectors. Ongoing and concerted efforts to bridge these intersectoral collaboration gaps are required by all partners to overcome the immense challenges seen during the COVID-19 pandemic.

Additionally, jurisdictions should strive to diversify their collaborators to include individuals within their communities, local leaders, private sector partners, and IHEs. Arguably the most important collaborative partner, regardless of pathogen or outbreak context, are local community members and community leaders. Inclusion of community engagement practices within existing response frameworks can aid in community empowerment, uptake of protective behaviors against pathogen transmission, ensure effective communications, and build upon existing cultural and contextual values of the community [38, 39].

Evidence has long-supported collaborations with local community leaders who have garnered strong trust among local communities, such as Nigeria's success in promoting safe and culturally sensitive burial ceremonies during the 2014 West African Ebola epidemic. Programs that integrate local knowledge and address social drivers of mistrust perform better and sustain higher compliance [12, 30]. Community engagement should be viewed as a collaborative partnership rather than a top-down communication exercise, recognizing local expertise and addressing historical inequities that undermine trust in health authorities.

Legal and logistical frameworks must be institutionalized to enable private sector actors to contribute to emergency response with clear, pre-established roles and expectations [12]. Pre-negotiated partnership agreements should be established before crises occur, addressing intellectual property concerns, resource allocation protocols, and accountability mechanisms. These partnerships might include local pharmacies and pharmacists, local healthcare facilities and experts, convention centers, or school boards to utilize large spaces for high throughput testing or vaccination strategies.

Partnerships with local IHEs with expertise to contribute to infectious diseases and outbreak response from multiple perspectives, including research, translational, communications, and applied perspectives. Students, particularly graduate students studying medicine, nursing, public health, environmental health, and health security/emergency management, were also leveraged during the pandemic to act as force-multipliers in critical activities such as contact tracing, testing, vaccination, and other research and response roles.

Partnerships can be leveraged for far more than simply active response responsibilities. IHEs may be called on to develop and/or provide education and training for local HDs in critical areas such as surveillance mechanisms, data collection and analysis, epidemiology basics (e.g., transmission mechanics), risk communication, and response operations. Environmental health professionals and veterinarians may be called on to discuss current and future risk of emerging or re-emerging pathogens. Utilizing these often overlooked partnerships offer a wealth of resources for jurisdictions to improve their capacity and plan a robust infrastructure to combat, even prevent, future outbreaks.

5.1.2 Invest in centralized data systems and information exchange mechanisms

All jurisdictions, particularly the federal government, must support permanent integration of human, animal, and environmental surveillance systems. This includes

the establishment of shared laboratories, co-located EOCs, and formalized joint risk assessment frameworks [11, 37]. Rather than creating collaborative mechanisms during crises, preparedness investments should focus on maintaining functional partnerships during inter-pandemic periods.

Additionally, real-time data sharing through centralized databases should be integrated into jurisdictional practice. Case counts, hospitalized cases, and hospital capacities are all critical in pandemic response and should be included in centralized databases and routinely updated. Critical success in this area was seen during the COVID-19 pandemic in the development of the U.S. COVID-19 Forecast Hub to aid jurisdictional decision-making via predictive modeling [40]. These tools must be maintained and improved upon ahead of future outbreaks, namely by improving scalability and the ability to integrate localized contexts for more robust forecasting [41]. Further, pre-established health information systems allowed for immediate and sustained data governance, surveillance, and preventive education during the COVID-19 pandemic [42].

It cannot be understated that these mechanisms should not be implemented during active outbreaks, but thoroughly planned, established, and tested for gaps and shortfalls to ensure reliability and effectiveness. In tandem, legal and regulatory frameworks that hindered rapid data sharing during the COVID-19 pandemic must be reformed to balance sovereignty concerns with public health emergency needs [37].

To champion proactive outbreak detection capabilities, investments into population-based surveillance methods like strategic wastewater surveillance must be adopted and integrated into centralized databases. Such systems can detect emerging threats before they escalate, by identifying the presence of pathogen in human waste rather than reliance on infected individuals presenting at healthcare facilities, all while maintaining continuous monitoring of other pathogens of concern. Surveillance must continue to expand beyond clinical case detection to include continuous environmental monitoring, pathogen-agnostic sampling, and wildlife virome studies [11, 37]. Performing active surveillance may be possible through partnerships external to jurisdictional authority, including research-based universities.

However, as the goal is to strengthen operational readiness, simply providing local public health agencies with access to a centralized database or optimized information exchange process is insufficient. As discussed earlier, workforce competency is lacking in many key areas; data analytics and epidemiology are two such content areas for many outbreak response practitioners. Strong, diverse partnerships and encouraging collaboration and cross-training in these areas will be critical in ensuring centralized data systems and robust information exchange mechanisms are functional and practical to advance readiness. Partnerships between key data and technical partners, such as IHEs and private sector partners, may provide the ancillary support and technical guidance to bridge local entities' critical knowledge gaps and stretched capacities.

5.2 Community risk perception strategies

Critical risk communication shortfalls during the pandemic were instrumental in the breakdown of public trust and curtailing efforts to mitigate community transmission. Therefore, strategies for risk perception must work to a) improve and embed risk communication plans into preparedness, and b) invest in ways to monitor and identify misinformation and implement strategies to combat them.

5.2.1 Improve risk communication and embed into preparedness

Effective risk communication via awareness raising activities significantly improves response efforts through increased public buy-in and adoption of protective actions. Educational initiatives show promise in promoting behavior change and reducing mortality [43, 44]. Culturally tailored messages and use of two-way communication via multiple channels are vital to effective risk communication. Two-way communication should include multiple channels, provide “transparent, accurate, and consistent information,” and have a built-in feedback mechanism to mold messaging to better serve community needs [45].

Dissemination of risk messages via multiple channels, such as radio, television, verbal, or social media, reduces risk of unintentional marginalization of certain communities who lack access to certain communication channels [46]. A thorough understanding of the cultural and contextual factors of what channels are utilized by all members of a community, including historically vulnerable or marginalized populations, is vital to optimal ID outbreak response [46, 47].

Cultivating an understanding of which communication methods, cultural contexts, and channels utilized by the diverse community groups within any geographical context is far too complex an endeavor to complete during any outbreak, small-scale or large. These activities must be integrated into readiness activities, such as jurisdictional risk assessments, where the planners may take time to engage all members of the local context to ensure marginalized and vulnerable communities are not left out of risk communication during active outbreaks. In much the same way, risk communicators should work to pre-establish and standardize messaging templates and communication protocols as well as integrate them into existing exercises that test jurisdictional pandemic plans.

5.2.2 Invest in infrastructure to proactively monitor and combat misinformation

Integrating two-way communication offers a low-cost, high-reward method to monitor and combat misinformation in real-time. This method establishes a feedback loop which allows community members to voice their fears, suspicions, and questions to risk communicators. Not only does this collect a rich dataset on risk perception, beliefs, and attitudes, it allows risk communicators to combat misinformation in real-time. This method inherently builds and strengthens relationships between jurisdictions and their communities, improving institutional trust and likely compliance with recommended protective actions and population mitigation strategies.

It is now well-understood the negative consequences social media and its use of algorithms play on transmission mitigation and institutional trust [18]. National initiatives have been established to combat some effects of social media on youth, such as the National Center of Excellence on Social Media and Mental Wellness [48]. Far more research is required to better understand algorithms and explore strategies to control and combat misinformation during pandemic periods.

Innovative technologies that analyze “big data” from social media to analyze trends and identify misinformation in real-time offers massive potential to strengthen response. However, these technologies are expensive and require specialized staff with knowledge and capacity to engage with them, gaps that are apparent within the current workforce. One solution to this could include federal initiatives to create and institutionalize national-level monitoring and surveillance mechanisms to identify and disseminate trends. The centralized process would limit the applicability to

localized contexts yet provides rich information by which to tailor local risk communication messages.

To combat misinformation in real-time will require overwhelming systemic support and proactive involvement of a vast array of sectors, including social media developers, policymakers, academic researchers, local community leaders, and STLT HDs. For example, coordination between policymakers, elected officials, and social media companies is vital to implementation of misinformation control measures.

5.3 Outbreak response workforce strategies

The current state of the outbreak response workforce is at crisis levels with few investments focused on educating the existing workforce, improving burnout, or increasing staff levels. We therefore recommend that jurisdictions a) improve workforce competency through comprehensive training programs and b) reduce burnout through organizational and system-level change.

5.3.1 Develop and implement comprehensive training programs

A comprehensive training curriculum based on core competencies must be nationally standardized and institutionalized, preferably as part of required onboarding or annual trainings. These training programs should be required for all staff who may play a role in outbreak response activities. Asynchronous trainings are not sufficient, scenario-based exercises such as tabletop and functional exercises will improve retention and skills on these competencies.

Other critical knowledge and competency gaps that require intervention include mental health, leadership, and transdisciplinary skillsets. Trainings related to responder wellness, mental health, and burnout can provide education, tools, and techniques to prepare, identify, manage, and rapidly overcome burnout and negative experiences from outbreak responses. Research has found that providing education and training prior to outbreak response improves coping ability and awareness to detect psychological symptoms within themselves and their colleagues [49, 50]. More research is needed to understand optimal format and core content, delivery methods, and specific educational initiatives [49, 50]. Organizational culture shifts around mental health, particularly stigmatization, is instrumental to increasing access to mental healthcare [51–53].

Public health and clinical education must be restructured to prioritize transdisciplinary training on systems thinking, leadership, crisis communication, and ethical collaboration [30]. Professional development programs should emphasize collaborative skills alongside technical expertise, preparing health workers to function effectively within multisectoral partnerships.

Jurisdictions with funding and capacity constraints should consider leveraging IHEs for training content generation, standardization, and facilitation. Colleges and universities provide ample resources such as building curricula based on adult learning principles, adapting existing training curricula to localized contexts, and hosting training programs on learning management systems for sustainable, long-term training access.

5.3.2 Organizational and system-level change to reduce burnout

A robust pandemic response requires an immense workforce that is highly competent and has capacity to oversee and implement long-term outbreak response

activities. Long before the COVID-19 pandemic began, this sector dealt with little attention and support from leadership, ever-decreasing budget and funding cuts, and increasing numbers of hazards and crises requiring response. Global calls have urged governments to treat burnout prevention as a workforce planning priority, calling for investment in well-being, job design, and digital adaptability in civil service settings [26]. As such, the need for organizational and systemic change is a clear requirement to strengthen readiness.

As previously discussed, widespread adoption of mental health programs and education within the workplace is lacking due to stigmatization, low prioritization and buy-in, and reliance on reactive, as opposed to proactive, implementation of training and education tools [50, 51]. Leadership at all levels, from middle management to federally elected politicians, must consider their roles in contributing to this ongoing crisis and focus their efforts on systemic transformation.

This chapter discussed several structural flaws, including rigid hierarchies, inadequate support systems, and inadequate data and information systems that drastically hinder operational capacity and streamlined processes. It is important to note that top-down approaches to organizational and systemic change often fail at improving processes at the individual and department-levels. Leaders should ensure all efforts to implement change should be developed alongside and supported by the workers to ensure strategies are impactful and effectively reduce factors contributing to burnout and attrition.

Modernizing operational models such as adopting flexible staffing structures, streamlining administrative procedures, and integrating public health emergency functions into core institutional operations are a small subset of opportunities leaders may utilize to improve work processes and reduce job strain on employees. Leadership must prioritize and provide the infrastructure for workers to develop, refine, and exercise plans and protocols for outbreak response, risk communication, and data sharing. Flexible staffing structures may be a challenge in jurisdictions where staffing is critically low. Innovative strategies such as creating surge capacity registries with specialized staff across jurisdictions and disciplines (e.g., IHEs, private sector technology services) may be employed to offset work overload. If left unaddressed, workforce attrition and institutional decline will continue, leaving the domestic readiness system unprepared and overwhelmed for the next epidemic.

6. Conclusion

In summary, our current state of domestic readiness is undermined by fragmented partnerships, misaligned risk communication, and a stretched workforce. Lessons learned from the COVID-19 pandemic reveal that readiness is not a single event but an ongoing process that requires substantial commitment and sustained investment into these core areas by leadership in all jurisdictions, sectors, and disciplines. Future strategies must be inclusive, well-resourced, and institutionalized across all levels of governance to effectively anticipate, detect, and respond to the next biological threat.

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Humanity has experienced multiple biological threats; most recently, the COVID-19 pandemic highlighted the lack of planning for preparation, mitigation, and recovery from these events, resulting in millions of infections and a large number of deaths. The book focuses on ensuring that communities have plans to address and mitigate these threats.

José Antonio Mirón Canelo, Public Health Series Editor

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