

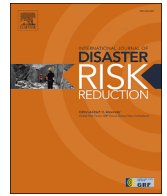


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Need for effective detection and early warnings for epidemic and pandemic preparedness planning in the context of multi-hazards: Lessons from the COVID-19 pandemic

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ABSTRACT

The need for effective early detection and timely surveillance for a robust pandemic and epidemic early warning and preparedness has been widely discussed amidst the Covid-19 pandemic, which suddenly erupted worldwide. This need is further established by various other hazards reported in many countries amidst the COVID-19 pandemic. In addition, the failure of early detection of pathogens and their source of origin has been largely connected with global transmission and severe outbreaks in many contexts. Therefore, effective early detection, timely surveillance and early warning are key aspects of a successful response to an epidemic or pandemic. Hence, this paper aims to identify key elements and stages of an effective epidemic and pandemic early warning (EW) and response system. Further, the paper analyses inter-connections of the elements of the early warning system, focusing on the COVID-19 and multi-hazard context. The systematic literature review method was used to collect data from electronic databases. Results suggest that epidemiological surveillance & detection, primary screening of raw data & information, risk and vulnerability assessments, prediction and decision-making, alerts & early warnings are critical components of epidemic and pandemic EW. In addition, response-control & mitigation, preparedness-preventive strategies, and reducing transmission, elimination and eradication of the disease are integrated components of the early warning and response ecosystem that largely depend on effective early warnings. The significance of integrating epidemic and pandemic EW with other EWs to operate as multi-hazard early warning systems is also analysed.

1. Introduction

The Covid-19 pandemic has stressed the need for an effective early warning system and mechanism for epidemic and pandemic preparedness. Pandemic warning and dissemination are the keys to pandemic response in terms of mitigating risk and vulnerability in any social setting. Effective early detection and warning and dissemination process provides significant guidance and direction to pandemic preparedness, which has been examined as a core pillar of pandemic risk reduction by several previous pandemics, including Ebola, SARS and Influenza Pandemics [1–3].

Early detection of pathogens and timely dissemination is critical as several countries have almost experienced ‘epidemics amidst the pandemic’, triggering the need for better preparedness for multi-hazards. For instance, a fungal infection known as black fungus

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(*mucormycosis*), a highly contagious infection, was reported in India in February 2021 across many populated areas as a concurrent epidemic while the country was severely hit by the Covid-19 outbreak [4]. Similarly, the risk of combined health hazards was triggered by re-emerging Monkey Pox in Wales and a few other places in the UK, with several hospitalized cases during the Covid-19 pandemic [5]. In addition, multiple public health challenges have impacted Sri Lanka due to the rise of dengue and several imported malaria cases reported with the heavy monsoon rain and flooding, mainly in populated urban and suburban areas, amidst the COVID-19 pandemic. Therefore, pandemic and epidemic warnings and dissemination seemed highly critical in terms of multi-hazard preparedness and response planning.

With the unprecedented challenges that emerged during the most challenging pandemic ever witnessed in recent human history, the consequences of effective early warning systems and mechanisms were stressed mainly due to the gradual emergence of new strains of the SARS-CoV-2 virus. In mid-2020, the severity of the pandemic had significantly increased with the sudden emergence of two variants of SARS-CoV-2 known as the B.1.1.7 variant,¹ which was initially detected in the United Kingdom on September 20, 2020, and B.1.351 variant, found in South Africa in Mid-May 2020 [6], known as Beta² [7]. Subsequently, another two strains from Brazil were found amidst the second wave of the Covid-19 outbreak,³ recognized as P.1, which has two similar mutations (E484k and K417T) and started spreading around November 2020. Initially, the Brazil variant was found in Japan, and then the National Institute of Infectious Disease reported the strains to the WHO. This variant rapidly transmitted among 51 countries, including the USA, causing a dramatic increase in infection rate in the USA [8]. Further, in the latter half of October 2020, another strain dominated India, technically identified as B.1.617.2 and reported as the highest virulent variant found since the first outbreak started to spread across all sub-continent [9]. Finally, Omicron (B.1.1.529) was found to be the most transmissible variant ever reported in mid-November from several countries and became the dominant strain in all continents. Therefore, all these five variants have been classified as variants of concern (VOC)⁴ by the WHO, evaluating the severity of transmission and detrimental changes in the Covid-19 outbreak across the countries [10].

Grave risks of the pandemic are still there. The severity of the pandemic increased with the rapid spreading of new variants across many regions showcasing the devastating impact and violent nature of the Covid-19 pandemic. For instance, WHO and SARS-CoV-2 Virus Evolution Working Group have identified 7 SARS-CoV-2 strains such as Epsilon, Zeta, Eta, Theta, Iota, Kappa and Lambda, which have been classified under variants of interest (VOI) by health authorities [7]. Nevertheless, many of the above strains have been omitted from the WHO variants list, *Lambda* and *Mu* are known to be potential variants that listed under VOI [10]. This unexpected and unprecedented global challenge has highlighted the need for scaling up sustainable and effective early warning systems to combat severe infectious disease outbreaks and mitigate challenges caused by combined hazards during a pandemic. Furthermore, the COVID-19 pandemic stressed the fragility of the existing response capabilities for a massive public health emergency and the weaknesses of EW systems to cater for pandemics, as many EWS have been developed to capture single hazards or dedicated several. On the other hand, this pandemic provides significant insights into understanding future challenges and constraints that could be caused by unexpected biological hazards that are likely to happen [11].

Several countries have been severely affected by compound hazards during the COVID-19 pandemic. The multi-hazard situations have doubled the pandemic risks and increased the cascading impacts creating dual challenges in the preparedness and response activities [12]. For example, the Pacific Islands and the North Pacific Islands, especially Vanuatu and Palau, were hit by the Harald cyclone amidst the pandemic. In contrast, Indonesia was severely impacted by heavy rain and flooding during the peak of the Covid-19 outbreak [13]. The Congo also experienced similar challenges due to the concurrent Ebola outbreak during the COVID-19 pandemic [14]. According to Ref. [15]; Guinea has reported a similar scenario due to the concurrent amplification of Ebola and COVID-19 infection. After that, in 2021, several European countries were brutally affected by massive floods, while Malaysia evacuated 30,000 people due to monsoon floods amidst the COVID-19 pandemic [16]. In the case of Sri Lanka, many areas were severely affected by heavy winds, landslides and floods during monsoon seasons amid the COVID-19 pandemic in 2021 [17]. Nearly 245,212 people in 10 districts were affected due to heavy monsoon showers in May 2021, and again in late October, about 62,247 people in 17 districts were severely impacted by heavy showers and landslides [18]. This evidence emphasizes the need for global and domestic preparedness planning to combat multiple challenges caused by multi-hazards.

Considering the lessons learnt from the COVID-19 pandemic and other hazards, strengthening existing EW and dissemination systems and enhancing their capacity to perform better within the globally connected surveillance systems, platforms, and initiatives seemed vital. Therefore, identifying gaps in the current EWS to improve the capabilities seems essential in response to unforeseen challenges of biological hazards in both domestic and global scenarios. In this context, this study aims to explore the essential elements and critical stages of epidemic and pandemic early warning systems and analyse the interconnectedness of the identified key elements focusing on the multi-hazard situation.

¹ This variant is scientifically known as Alpha under the lineage GRV (formally GR/501Y-V). But in many initial publications, the variant has been quoted as UK variant.

² Beta strain was classified under GH/501Y-V2.

³ The strain is known as Gamma was classified under GR/501Y-V3 lineage. This also commonly identified as Brazil variant in early stages WHO. (2021b). Tracking SARS-CoV-2 variants: 26/06/2021. <https://www.who.int/en/activities/tracking-SARS-CoV-2-variants/>.

⁴ WHO in consultation with the WHO SARS-CoV-2 Virus Evolution Working Group has been reporting and publishing the diagnosed new strains of the Covid-19 virus under a few categories: ex; Variants of concern (VOC); Variants of interest (VOI). Strains detected under the VOI are highly cause community transmission, multiple Covid-19 cases, and has been detected in various countries, or assessed to be a VOI by the WHO virus evolution working group. In contrast, increase of transmissibility or detrimental change in Covid-19 epidemiology, increase in virulence or change in clinical disease presentation and decrease in effectiveness of public health and social measures or available diagnostics, vaccines, therapeutics are the determinants of including a strain under VOC. Ibid.

2. Material and methods

A comprehensive desk review was conducted to accumulate the existing research literature on the epidemic and pandemic warning and dissemination and to design a comprehensive conceptual framework to understand how various elements and processes are contextually interconnected within the EW and response ecosystem. A systematic literature review was conducted to gather data using three electronic databases: PubMed, Scopus, and ScienceDirect.

The research literature mining was initiated once the keywords were derived from the research question: what are the key elements and processes of an effective early warning and response system dedicated to epidemics and pandemics? The syntax used for the Boolean operator was Detection OR Early warning OR Dissemination OR Epidemic OR Pandemic OR Covid-19 OR Multi-hazards. The literature mining was restricted to published peer-reviewed articles and disregarded unpublished works, working papers, abstracts, books, chapters, reports, theses, meta-analyses, etc. Further, the literature search was confined to the research articles that were published between 2010 and 2022 to identify recent pandemic and epidemic-related research papers. Potential papers were picked from broader themes of public health, epidemiology, social sciences, environmental science, technology and media, and information management.

Once the literature mining process was completed, 48 papers, including 40 from selected databases and 08 from other sources, were finally extracted based on the relevance to the themes of the research question. Further, selected grey literature sources were also used, including reports and webpages published by public health and disaster management agencies. Once the sources were finalized after the full paper reading, selected research articles and grey literature sources were imported into the citation manager (EndNote X9). The review adopted the standard literature mining and filtering procedure. The following floor chart (Fig. 1) was obtained using PRISMA to elaborate on each stage of the literature mining process.

Collected data was then analysed using the thematic analysis method, focusing on the synthesis approach. The below sections summarise the key findings under each sub-theme.

3. Results

3.1. Warning and dissemination for epidemic and pandemic

Effective early warning systems are comprised of four interconnected elements: (1) disaster risk knowledge based on the systematic collection of data and disaster risk assessments; (2) detection, monitoring, analysis and forecasting of the hazards and possible consequences; (3) dissemination and communication, by an official source, of authoritative, timely, accurate and actionable warnings

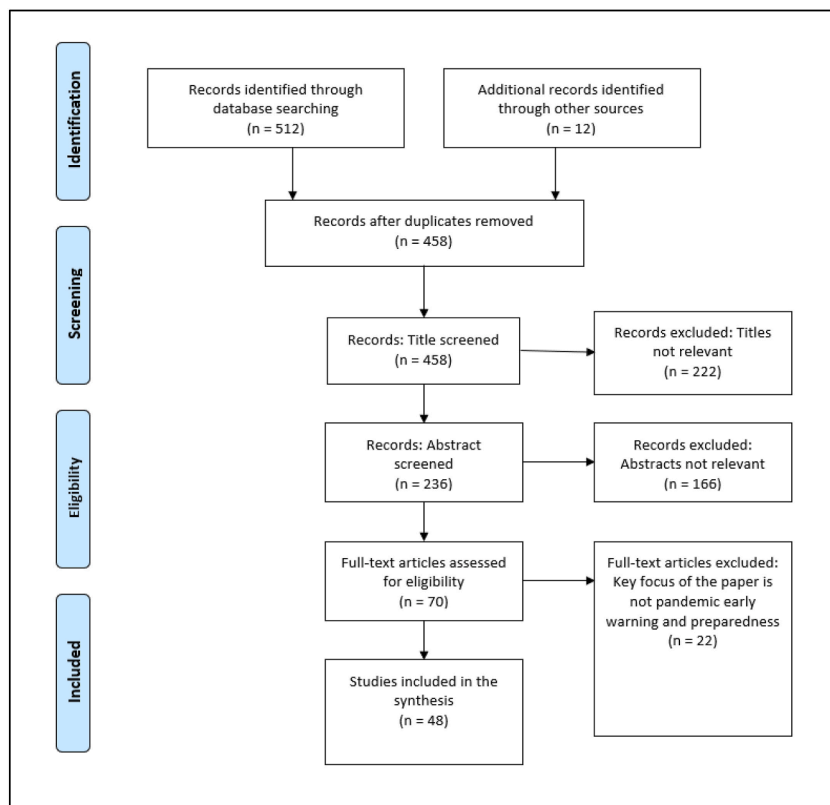


Fig. 1. Floor diagram for the literature mining process.

and associated information on likelihood and impact; and (4) preparedness at all levels to respond to the warnings received [19]. However, warning and dissemination are the critical and dynamic processes that interconnect all relevant stakeholders interchangeably between upstream (policy initiative) and downstream (implementation level-response and recovery) [20]. Risk governance in a pandemic context relies on adequate warning and dissemination, as highlighted by several recent research studies during the COVID-19 pandemic [21–23]. Furthermore, a strong warning and dissemination process expedites the response activities with a sharp direction and regulates proper communication platforms, avoiding misinformation and rumours that complicate the pandemic response [24].

The COVID-19 outbreak stimulates the need for an effective, sectorial-interconnected and timely-initiated pandemic warning and dissemination process by networking all regional and global networks to accelerate the response activities. Although several public health emergencies, including many severe epidemics, have emerged during the previous decades, pandemic warning and dissemination discourse has not yet been adequately reflected until the COVID-19 pandemic brutally hit the world. The WHO (2018a) suggested that some of these diseases, such as Cholera, Plague, and Yellow fever, have and can be repetitively emerged in a more significant number of instances. For example, the unending catastrophe of Cholera has been reported in more than 40 outbreaks each year from different regions worldwide.

Over a thousand epidemics have been reported only during the previous decade [25]. Previous records about epidemics show the complexity of EW and response efforts regarding many epidemics reported in various regions. For example, severe acute respiratory syndrome, commonly known as SARS, has hit several regions, mainly in Asia, after 2003, showing the gravity of a severe epidemic which concurrently transmitted to many sub-continent, resulting in more than 8000 confirmed cases. In addition, H1N1, a novel influenza virus in 2009, and another pneumonic disease called Middle East respiratory syndrome (MERS) were transmitted in 2012–13 across Middle-East countries. In this milieu, many agencies have spotted the significance of global initiatives connected globally and timely-run EW systems for preparing and responding to global biological hazards. For example, the Ebola epidemic in 2014 badly impacted the West African region, including Guinea, Liberia and Sierra Leone, then spread to the other three continents by sparking the global alert for epidemics and pandemics response as a Public Health Emergency of International Concern (PHEIC) [26].

Further, another severe epidemic experienced by many parts of the world was reported due to the Zika virus in 2015. Initially, Zika was reported being emerged in Brazil and then started spreading over more than 70 countries [27]. The Zika virus, however, was believed to be first found in Uganda in 1947 [28]. The most recent epidemic occurred due to a severe outbreak of the Plague in Madagascar in 2017, which lasted a long time, and 2417 confirmed cases were reported, including 200 deaths. An infectious disease transmitted by rodents also caused this epidemic. Nine other countries and territorials have declared travel restrictions since the public health threats caused by this bubonic plague. According to the WHO data, 1307 epidemic events were reported only between 2011 and 2017 caused by twenty transmissible infectious diseases [2,25]. Therefore, local and international EW and dissemination mechanisms should be effectively incorporated, as some infectious diseases produce more significant epidemic outbreaks with pandemic potential.

Data illustrated in Table 1 shows the frequent re-emergence of infectious diseases from 2011 to 2017. In addition, some epidemic events such as Zika virus, Meningitis, Monkeypox, Influenza A and Crimean-Congo haemorrhagic fever have dramatically increased during the period compared to other prevalent pathogens. This trend indicates that the probability of re-emergence of early pathogens in future occurrences would be exceptionally high. Hence, strengthening EW systems across the globe to detect and dis-

Table 1
Epidemic events reported from 2011 to 2017.

Epidemic event	2011	2012	2013	2014	2015	2016	2017	Total
Yellow fever	17	12	8	2	4	10	4	57
Chikungunya	8	10	3	29	27	14	4	95
Viral haemorrhagic fever						6	4	10
Ebola	1	2		11	4	3	1	22
Marburg virus disease		1		1			2	4
Crimean-Congo haemorrhagic fever	3	5	6	8	7	7	13	49
Rift valley fever	1	1	1	1	1	4	5	14
Cholera	62	51	47	37	44	42	25	308
Typhoid fever	20	23	5	2	8	3	14	75
Shigellosis	25	24	28	29	4	2	1	113
Plague	8	7	6	10	7	6	3	47
Lasa fever	2	1	2	3	2	7	6	23
West Nile fever	11	15	15	11	11	18	10	91
Zika virus disease			5	7	19	54	52	137
Meningitis	14	20	19	19	19	23	23	137
MERS-CoV		3	10	17	12	7	8	57
Influenza A	5	6	7	9	10	5	9	51
Monkeypox					2	2	5	10
Nodding syndrome		1	1					2
Nipah virus infection	1	1	1	1	1			5

Source [25].

seminate warnings on new pathogens and re-emerging infections would allow local and global partners to act immediately and respond strategically.

Taking early actions based on early warnings and alerts during any epidemic or pandemic outbreak is very common in responding to infectious disease outbreaks [29]. However, the failures of timely or inadequate response measures have mainly been interconnected with the lack of attention to disease surveillance and detection when an outbreak is started local transmission [30]. For example [31], highlight the time gap between detection and response based on several critical infectious diseases in the human-animal interface. Further, the research has analysed the onset date, official reporting date and actions taken by regional and global actors who play a crucial role in warning and dissemination. There is a considerable gap between the primary detection of the infections and official reporting, which is the official call for immediate response. Therefore, lessons from early biological hazards replicated in recent history have produced empirical insights on current gaps in the existing EW systems and the repercussions of such implications, which need filling immediately.

Detection of pathogens and timely dissemination of EWs become challenging and complicated when an epidemic or pandemic overlaps and the transmissibility is considerably high. Further, epidemics and pandemics arise from various origins and drivers, making prevention and preparedness complex. The Global Catastrophic Biological Risk (GCBR) is a concept used to understand the gravity and scope of infectious disease outbreaks caused by any pathogen capable of developing a severe transboundary human transmission [32]. Potential – microorganisms that constitute a GCBR are identified to maintain several common attributes to generate a severe or massive outbreak.

1. Respiratory Transmission
2. Spreading during the incubation time
3. Lack of host immunity
4. Lack of medical countermeasures [32].

Pathogens that have pandemic potential efficiently transmit respiratorily between humans. Lack of pre-existing immunity among the people and the lack of medical countermeasures, such as vaccines/prophylaxes, cause rapid virus spreading. Also, pathogens with GCBR potential are believed to spread during incubation before the onset of solid symptoms [32].

In terms of origin, most human infectious diseases (58–65%), including COVID-19, are zoonotic pathogens, and many of the pathogens that cause severe amplifications in epidemics are vector-born [31]. However, large outbreaks reported from several countries during previous decades have been primarily caused by viruses (including COVID-19, HIV/AIDS, Ebola, Zika and pandemic influenza). As per the evidence, Bacteria cause most emerging infectious disease outbreaks (e.g., plague, anthrax, Cholera, Q fever, typhus, rickettsia diseases), fungi or helminths [32]. Therefore, domestic-level disease surveillance and response strategies must be systematically aligned with regional and global platforms and initiatives to better correspond to global outbreaks like COVID-19 [30]. Also, empirical research evidence and scientific diagnosis methods developed during previous outbreaks can positively be shared and used to understand the nature of growing pathogens and the dynamics of outbreaks, which is believed to be inadequate [25,33].

3.2. Multi-hazard perspective for pandemic response: global lessons from COVID-19

COVID-19 was an eye-opener for many governments to revisit their policies on health hazards. It has led to improving domestic technical infrastructure, hazard governance strategies, and transforming policies to prepare and respond to epidemics and pandemics, especially in multi-hazard scenarios [13,34,35]. Recent research studies suggest that countries with weaker economies and inadequate technical infrastructure face grave risks, most often during combined hazards, due to cascading effects [12,36,37]. Research conducted in the African region [38], including in Nigeria [39], Guinea [15], Congo [40] and several parts of South Asia [41,42] and South East Asia [43] emphasized the disaster risks and vulnerability among developing nations often fatal due to lack of technical infrastructure, deprivation of resources, social inequality, fragile economies and inadequate public health capacities.

Generally, hazards are identified as natural, anthropogenic or human-induced, socio-natural, or a hybrid version of human and environmental factors (ex, climate changes and land degradation). Multi-hazards can be defined in two ways: a) The selection of multiple significant hazards that the country faces, and b) the specific contexts where hazardous events may occur simultaneously, cascadingly or cumulatively over time, and taking into account the potential interrelated effects [19].

A combined or multi-hazard is caused by two or several of the following types of hazards arising together.

1. Biological hazards
2. Environmental hazards,
3. Geological or geophysical hazards,
4. Hydrometeorological hazard
5. Technical hazards

Substantial evidence demonstrates how cascading impacts in a combined hazard scenario are more critical and generate multiple risks among affected people than a single hazard [12]. Several countries faced challenges due to concurrent hazards, including multiple health hazards, amidst the COVID-19 pandemic. For example, Congo has been affected by two health hazards due to simultaneous outbreaks of Covid-19 and Ebola [40]. In contrast, tropical Cyclone Harold devastated some Pacific islands during the COVID-19 pandemic [13]. In addition, a range of cascading impacts was reported from Sri Lanka due to a prolonged drought in dry-zone areas, which devastated over a half million people's livelihoods, and the surge of dengue and malaria epidemics following monsoon rains during the Covid-19 outbreak [17,44]. Similarly, many countries reported compound hazards due to natural hazards during the pandemic. For example, the USA faced a set of lethal Tornadoes [12]. At the same time, Indonesia was hit by devastating floods and the

eruption of the Anak Krakatau volcano (Ye et al., 2020). Likewise, Croatia was impacted by an earthquake during the COVID-19 pandemic [45],

Multiple impacts caused by multi-hazards are deemed more prominent as many countries have unexpectedly faced a range of natural and biological hazards during the devastating COVID-19 pandemic. Thus, risks and vulnerabilities have often been reported to be severe and cascading [13,14]. On the other hand, concurrent hazards invade the capacity and effectiveness of disease surveillance, detection, and early warning dissemination. Therefore, integrated early warning systems, especially climate and public health, have been widely discussed as vital in reducing multiple and cascading impacts [46]. Also, the lack of adaptive and integrated early warning systems has been identified as a significant gap during the COVID-19 pandemic, which needs further strengthening for better public health preparedness planning [23]. In this context, scientific investigations could guide policy transformations toward developing integrated early warning and dissemination systems, which need the capacity to bridge public support and trust [47].

According to Ref. [48]; “MHEWS is designed to cope with multiple hazards occurring simultaneously or cumulatively over time, and any potential cascading impacts and provides relevant impact and risk information to enable individuals, communities and organizations threatened by a hazard to prepare and act appropriately and in sufficient time to reduce the possibility of harm or loss”. The concept of MHEWS has evolved and been established over time, accumulating several approaches and initiations associated with the early warning discourse, such as people-centred, end-to-end, and impact-based warnings [49]. The interconnectedness of hazards, for example, changes in weather patterns and increasing risks of floods, heat waves and epidemics, is a significant motivator for establishing a common approach for MHEWS [35]. Also, pandemics must be an integral component of MHEWS since long-run pandemics double the risk and vulnerabilities of hazards, where health-bearing capacity and socio-economic stability becomes fragile and critical.

3.3. Main elements and phases of epidemic and pandemic EW and response ecosystem

Data analysis suggests that an effective pandemic and epidemic EW and response system must have a set of fundamental elements interconnected with several response phases. Further, necessary interlinks between identified elements must be analysed to understand the response strategies under different epidemic and pandemic phases established by the international health actors. Therefore, several strategic EW and dissemination points were identified with response interventions to highlight certain critical stages of the response ecosystem. In addition, a set of elements associated with preparedness planning were also used to analyse significant interconnections between different pandemic phases and strategies.

In general, four components of an effective early warning system (EWS) are combined with a set of interventions: (1) Risk knowledge (hazard, exposure, vulnerability); (2) Response capability (plans, practice, resources); (3) Monitoring and warning (observation, analysis, trigger); (4) Dissemination and communication (access, understanding, actions) [50,51]. In addition, effective governance and institutional arrangements, a multi-hazard approach, local community involvement, and consideration of gender perspective and cultural diversity are also identified as vital components of an EWS [50]. [31] have identified the following key pillars of a functional early warning system that highlights how the early warning and dissemination process interlinks with EWS focusing human-animal disease interface.

1. Screening of raw data and information
2. Triage of relevant information and risk assessment
3. Alert/early warning
4. Effective response
5. Preparedness

The early warning process and elements highlighted by Ref. [31] include the early warning process and key elements focused on responding to public health emergencies caused by animal diseases. However, these elements are also relevant in understanding critical components of early warning systems for human disease outbreaks. The reason is that many epidemics have emerged due to zoonotic origins, which have caused a more significant number of infectious disease transmissions in the human-animal interface during the previous two decades [25]. Therefore, The WHO, World Organization for Animal Health (OIE),⁵ and Food and Agriculture Organization (FAO), operated under the United Nations, have been set to be mandatory to involve in disease surveillance, detection, dissemination of alerts and early warnings as well as recommend necessary response strategies, in responding to growing pathogens in the human-animal interface [30].

Even though the orthodox disaster management circle for natural hazards includes response, recovery, prevention and mitigation, and preparedness, phases of biological hazards seem complex and dynamic [52]. propose that the pandemic circle composites four main phases: a) the pandemic phase, which is the alert phase, b) the transitional phase, c) the post-pandemic phase, and d) inter-pandemic phase. However, by advocating lessons learnt from past epidemics and pandemics, the WHO proposes a linear model to analyse the critical stages of epidemic or pandemic management, which consists of four fundamental phases [25].

1. Introduction or the emergence of the infectious disease,
2. Outbreak with localized transmission,
3. Amplification stage, which is caused by severe transmission from human to human,
4. Reduced transmission due to acquired immunity or positive impact of health interventions.

⁵ formerly the Office International des Epizooties (OIE).

Also, this model suggests a set of response interventions under each epidemic phase [25]. Therefore, the WHO has presented the following model to analyse epidemic phases and response interventions, which has been used to recognize key response phases and interventions in formulating the final framework of the study.

Adopted from [25].

As emphasized in Fig. 2, the first epidemic phase is the introduction or emergence of the pathogens, where anticipation and early detection are critical in epidemic response. After that, the localized transmission phase appears, where human transmission gradually increases in local territories. In the third phase, the outbreak amplifies with a high transmission rate causing an epidemic or pandemic - the pathogen can transmit from human to human, which causes a sustained outbreak in the community. In this stage, transmission grows beyond the territories. Finally, the fourth phase is reduced transmission, which happens when human-to-human transmission of the pathogen decreases, possibly due to acquired population immunity or effective interventions, including vaccination [25]. These phases and stages were used to develop this study's framework to reflect essential pandemic and epidemic response stages, as depicted in Fig. 3.

Following are the key elements identified through the systematic literature review. Similar and combined elements have been identified in particular to several stages. However, these similar or combined elements connected with the same response intervention have been amalgamated to present in smaller compartments in the framework to reflect their interlinks better.

1. Epidemiological Surveillance & Detection
2. Primary screening of raw data & information

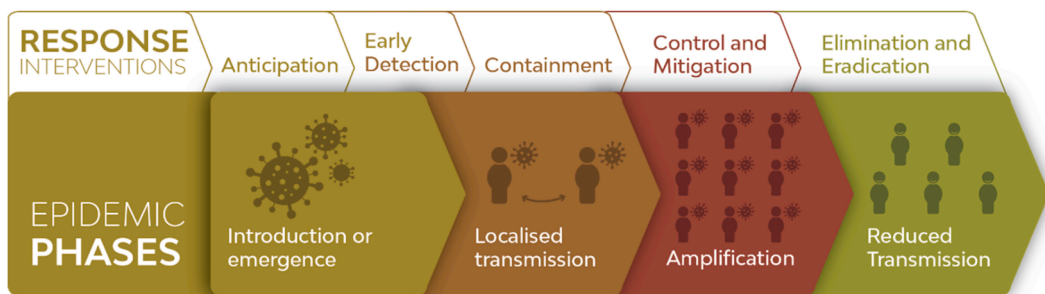


Fig. 2. Phases of Epidemic and response interventions.

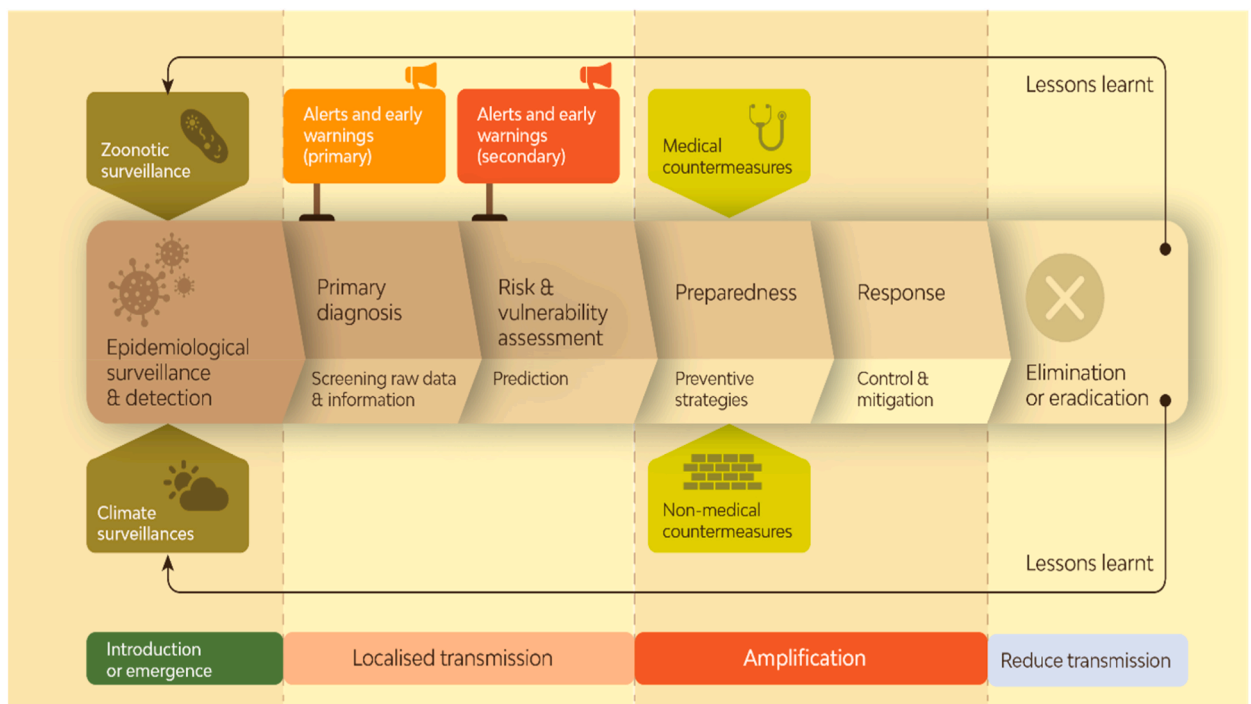


Fig. 3. An extensive framework proposed for the pandemic and epidemic EW and response based on the elements identified through the literature review. Source-Authors' Composition

3. Risk and vulnerability assessments
4. Prediction and decision making
5. Alerts & early warnings
6. Preparedness - preventive strategies (medical and non-medical)
7. Response-control & mitigation
8. Reduce Transmission & Eradication

The first five elements are explicitly interlinked with the early warnings and dissemination process, which is the most significant in the pandemic preparedness and response ecosystem. Effective early detection and warning and dissemination process, therefore, provides significant guidance and direction to epidemic or pandemic preparedness, which strengthens the response activities that have been highlighted as a core principle in pandemic risk reduction [1–3]. Further, risk governance during a pandemic also relies on timely-driven and effective early warnings and dissemination processes, which have been heavily stressed during the current COVID-19 pandemic [21,23]. Even though surveillance of pathogens, data screening, risk assessment, and early warnings are advocated by top-level authorities, response and preparedness highly rely on downstream as a range of key stakeholders is involved in the response and preparedness planning [15,21,53].

Detection of pathogens and dissemination of timely early warnings play a crucial role in epidemic or pandemic preparedness and response. However, sporadic detection measures and inadequate attention to timely warnings make preparedness and response interventions ineffective and complicated. Therefore, the functionality and regularity of all elements of the pandemic response system, from surveillance to elimination, are highly significant. Further, identifying critical phases and interventions established to be measured under the respective phases, with interconnectedness between elements in the response environment, is essential in understanding the regulatory dimension of a pandemic and epidemic response system. Fig. 3 shows the framework designed to propose a functional pandemic and epidemic response system model with more focus on early warning and dissemination perspective. The bottom tier indicates the epidemic phases identified by the WHO, which explains the evolution of infectious disease outbreaks through four stages, as depicted in Fig. 2.

According to the features presented in this framework, epidemiological surveillance and detection are the first components interlinked with zoonotic and climate surveillance. This integrated surveillance system facilitates the detection of pathogens of zoonotic origin and other infections, such as vector-borne and helminths, that often emerge with climatic factors like changes in drought and rain. Coherent integration of climatic and public health early warnings is stressed mainly due to the complexity and combination of origins or sources of diseases [23,46].

Some mandatory national and international agencies regulate the detection of emerging and re-emerging infections with specific global initiatives, such as the Global Initiative on Sharing Avian Influenza Data (GISAID), to detect human, animal, and aquatic ecosystems [54]. Further, surveillance and detection of re-emerging or new pathogens must be rigorous and accurate to trigger their sources of origin, which enables identifying what prevention strategies need to be set up. Surveillance relies more on anticipating the emergence of pathogens, constant vigilance and anticipation of threats, and forecasting infections and drivers most likely to emerge. However, EWSs differ depending on the method used and the input data. Also, surveillance may vary according to purpose, such as for known pathogens and syndromic surveillance. Syndromic surveillance has already been utilized in the health sector as part of their early warning mechanisms. For example, they already use a surveillance case definition for a vector-borne disease such as dengue. A specific set of symptoms have been identified and included in the definition so that first-contact doctors can detect patients and potential outbreaks early. The same syndromic approach has been adopted in Influenza early detection platforms such as influenza-like illness (ILI) and severe acute respiratory infections (SARI) [55].

The primary diagnosis process needs to harmonize with the onset date of the sudden emergence of infections or re-emerging pathogens. When emergence is confirmed, this process must be well-equipped with a scientific screening of raw data and information. Therefore, the first warning and alert should be issued based on the primary diagnosis when the first case or cases are identified and confirmed through a scientific screening. This warning point has been embossed in the framework as a primary warning stage, facilitating the regulatory bodies for a steady response and keeping the public aware of the scenario.

The secondary warning point is set in the framework to issue warnings and alerts after rigorous predictions and risk and vulnerability assessment, assuring all regulatory bodies and the public are prepared for the immediate response. However, the primary alert is issued when a pathogen is first detected, assuming that amplification would primarily happen. This EW point guides all parties to take immediate decisions and be steady with effective response interventions. The second alert would be the precise warning alert issued with the possible magnitude of the outbreak in line with the scientific assessment and prediction. Thus, the secondary warning must be disseminated after a rigorous screening and detection process adopted by competent authorities.

Preparedness is the readiness point that generally executes medical countermeasures, such as vaccine/prophylaxis, or non-medical countermeasures, like social and physical distancing, self-isolation, travel bans and restrictions, disinfection measures and quarantine. Many of them seem to be preventive strategies imposed by authorities or regulatory bodies.

Furthermore, the response to pandemics and epidemics is identified mainly with a range of control and mitigation strategies determined by the scale of the disease outbreak. Further, the decisions about response interventions in an infectious disease outbreak largely depend on the implicit threat, including morbidity and mortality.

Elimination or eradication is the final component in the linear process proposed in the framework. According to the WHO, elimination means the disease is no longer considered a significant public health issue [56]. However, some interventions, such as continuous surveillance and control, should be executed to prevent from re-emerging of pathogens. Eradication of an infectious disease is much more complicated and rarely achieved, as eradication refers to permanently eliminating infectious diseases worldwide [25].

Finally, lessons learnt from the epidemic or pandemic need to be adequately integrated with capacity building for pandemic and epidemic preparedness planning by incorporating lessons learnt from the disease outbreak for building resilience in the post-pandemic stage. This framework suggests that the pandemic and epidemic response system should be cyclical, enabling the incorporation of best practices and lessons to the beginning of the process of the next circle.

4. Discussion

An effective detection process and early warning dissemination is key to the epidemic and pandemic preparedness and response. Early detection and warning appeared to be the most critical point of any epidemic and pandemic event. The Covid-19 pandemic provides critical testimony to analyses of the functionality of scientifically designed detection and EW processes that are critical in strengthening preparedness and response capabilities. Also, the complexity of pandemic outbreaks demonstrates that detection and EW are the most crucial and challenging. For example, during the pandemic, Slovakia was the first country to test its entire population for Covid-19 [57]. However, after one month, Slovakia had the highest seven-day rolling average of daily COVID-19 deaths per 1 million people in its population by the first week of March 2021, which was critically high compared to that rate with any other country. Similarly, Bahrain and Israel maintained the highest vaccination progress per 100 population in the initial stage of vaccine roll-out. Ironically, both countries faced several massive outbreaks afterwards [8]. The UK is the best showcase to understand how the pandemic has evolved even within an extensive vaccination programme. UK faced several devastating outbreaks due to Delta and Omicron variants despite the UK being the most vaccinated country among its European neighbours. These facts emphasize the significance of early detection and effective early warnings, even if other medical countermeasures, including large-scale vaccination programmes, have been massively administrated [6,10]. Also, these are a few pieces of real-life evidence to understand the evolving nature of infectious diseases and the unpredictability of disease outbreaks. Therefore, data suggests that almost all preventive measures and mitigation strategies primarily rely on timely detection, robust surveillance and adequate and effective early warnings.

Undoubtedly, many countries have almost satisfactorily mitigated the COVID-19 pandemic and 'pandemic-induced risks and vulnerabilities' by rolling out vaccination programmes, maintaining technical infrastructure for detection and surveillance and applying non-medical countermeasures [58]. However, a complete cessation of the transmission cycle is a distant dream due to several factors [59].

- a) The emergence and prevalence of COVID-19 variants, especially Variants of Concern (VOC), can potentially revert successes achieved through vaccination. Given the right circumstances, these variants have the potential to make the virus more transmissible and cause severe disease [60].
- b) Vaccine inequity and less purchasing power to reserve large consignments of vaccine stocks have led developing nations to think twice about their mass vaccination campaigns. Hence, achieving herd immunity is difficult, which creates a potential environment for the disease to make a comeback.
- c) The complacency of both the public and the governments in maintaining public health security measures has created a conducive environment for further transmission of the disease [61].
- d) Vaccine hesitancy and the anti-vaccine lobby have rolled back some of the achievements of initial vaccination campaigns; hence public acceptance for subsequent and booster vaccine doses is comparatively less. This has led to a situation where most of the population cohorts which were vaccinated earlier have a low and waning immunity profile, exposing them to a potential future outbreak [62,63].

Therefore, strengthening EW could be considered one of the most feasible and cost-effective ways to address these uncertainties surrounding COVID-19 and other future occurrences. An effective EW would enable public health planners and communicators to inform the masses about a potential outbreak of COVID-19, thus reiterating the importance of adhering to public health security measures and vaccination. It would also facilitate governments' preparedness planning for a future outbreak by appreciating the gaps in their systems and the vulnerabilities of their population [64]. Furthermore, EW would enable scientists to anticipate potentially virulent forms of the virus, thus enabling them to advise the policymakers to augment the stringency level of their protection mechanisms.

However, practitioners are increasingly concerned about the risk of data privacy and ethics of shared data when information systems function as integrative mechanisms. Therefore, ethical awareness, accountability and transparency have been identified as key concerns in assessing shared risks in healthcare infrastructure [65]. For example, this aspect was identified as a concern during the contact tracing and quarantine process of COVID-19. Details of possible contacts generated through multiple agencies were collected at the epidemiology units or competent authorities. All identification and personal details were removed and stored under lock and key, only accessible to a few ears marked officials. In the data dissemination process, all precautions were taken not to expose individuals.

Moreover, the benefit of a properly functioning EW would be immense at the grass root level. For example, public health and disaster management practitioners often work in a resource-constraint setting in downstream. Such a setting would not facilitate a robust response to a sudden, unexpected surge of the infection. Instead, this would further constrain their capacity to work, thereby exposing the most vulnerable to the brunt of the disease. However, an early warning that readily communicates the dangers of an impending outbreak would enable them to fill the gaps in the system, request assistance in advance or a worst-case scenario, and scale down the routine public health interventions to facilitate the emergency response [23].

Additionally, the benefits are of mutual interest as well. While the downstream would benefit from the early warnings to scale up their interventions, the upstream would be able to collect and analyse data or evidence generated through the interventions at the downstream for future policy and strategic level changes to the system. Identified best practices from the grass root level would en-

able critical gap analysis of preparedness planning, thus creating a space for future improvements. In an instance where total eradication of the disease is nearly impossible, this would be the best option to strengthen grass root communities towards future shocks.

Further, the rapid spread of different variants across the countries and the failures of some mitigation strategies emphasize that early warning and dissemination capacity must be further strengthened. This may be due to the asymmetry of regulatory bodies, policies and practices adopted by various countries [67]. For instance, despite the provisions of the Sendai framework adopted by many countries, only 81 countries reported maintaining a national policy for DRR. Also, only a few countries have embodied pandemics and epidemics into mainstream DRR policies [21,66]. This implication further stresses the need for regulatory guidelines between domestic and global levels. Therefore, what is required is to develop sectorial and interconnected cross-border systems for detection and EW in response to epidemics and pandemics.

Also, the importance of integrated hazard-specific early warning systems to address cascading risks of multiple hazards is emphasized more than ever during the COVID-19 pandemic. As a result, UNDRR has recognized the priorities of facilitating the development of a multi-hazard information system. Key concerns of linked hazard and risk identification and early warning systems are engaging users and sectors for more significant alignment, consistency of hazard definitions, and addressing cascading and complex hazards and risks [48].

MHEWS to operate effectively, all key actors and stakeholders need to be integrated at all levels, and the roles and responsibilities of actors involved in the MHEWS should be well defined. Therefore, the World Meteorological Organization has identified the following key actors and responsibilities (Table 2) in assessing the roles and involvement of MHEWS at different levels [51].

Analysing the roles and responsibilities of all actors, including primary data providers, data repositories, and data collection methods for hazards and impacts, is also significant in understanding the overall spectrum of EWS [50]. Further, Assessing the functions of different EWS, such as public health surveillance systems and natural hazard EWS, to operate as MHEWS is also significant in enhancing the capacity of epidemic and pandemic EWS. For example, in Sri Lanka, other sectors' early warnings are considerably integrated into health surveillance under different pathways. For example, weather alerts issued by the Met Department are incorporated into climatic surveillance portals of the National Dengue Control Unit of the Ministry of Health. Then the epidemiologists will overlap epidemiological data with climatic data to create a comprehensive risk assessment for dengue high-risk districts. Another example would be the urgent public calls and queries received at the Disaster Management Centre, which will be filtered under different thematic areas, e.g. health and diverted to respective authorities. For example, in the case of health, such calls will be regarded as part of the community surveillance network and utilized to identify disease trends and the emergence of diseases.

Yet establishing effective MHEWS is a potential gap as many countries have developed EWS to single hazard. According to the analysis done by Šakić Trogrlić et al. [50], very few countries have MHEWS to cover all hazards and rarely integrated with sharing data, risk analysis, interactions, synthesise SoPs for the response, and shared communication methods/channels.

5. Conclusions

Significant factors need consideration in understanding disease dynamics and the importance of EW for infectious disease outbreaks. It is evident from experiences worldwide that successful vaccination campaigns have curtailed the spread of COVID-19 infections to a manageable level. However, effective early detection of pathogens and early warnings need to be efficiently integrated into the whole process of epidemic and pandemic preparedness and response planning. This is a drier need, especially among developing nations, where many marginalized and underprivileged groups live under the constant risks of infectious diseases and other potential hazards. Due to fragile economies and a lack of health infrastructure and supplies, many developing nations have been dragged into a critical socio-economic crisis where they can no longer sustain their medical and non-medical countermeasures in a pandemic outbreak. On the other hand, some rich countries stockpile essentials, including vaccines and medicines, which shows the bitter truth of

Table 2
Roles and responsibilities of actors involved in MHEWS.

Operational level	Actors	Responsibilities
Local level	Communities	Involve in all aspects of the establishment and operation of early warning systems, be aware of the hazards and potential impacts to which they are exposed, and be able to take actions to minimize the threat of loss or damage
	Local governments	Assess hazards to which their communities are exposed and be actively involved in the design and maintenance of early warning systems
National level	National governments	High-level policies and frameworks that facilitate early warning and for the technical systems that predict and issue national hazard warnings
Regional level	Regional institutions and organizations	Providing specialized knowledge and advice which support national efforts to develop and sustain early warning capabilities in countries that share a common geographical environment
International level	International level	Providing coordination, standardization and support for national early warning activities and fostering the exchange of data and knowledge between individual countries and regions
Other stakeholders	Non-government organizations	Help raise awareness among individuals, communities and organizations involved in early warning, particularly at the community level
	The media	Improving the disaster consciousness of the general population and disseminating early warnings
	The private sector	Development of early warning capabilities by private organizations
	The academic community	Providing specialized scientific and technical input to assist governments and communities in developing and improving early warning systems

Adopted from [51].

'pandemic capitalism' primarily seen during the mass-vaccination stage of the COVID-19 pandemic. Therefore, analyse and guide to strengthen detection and early warning systems to combat pandemic and epidemic-associated risks; thus, the effective response strategy is most cost-effective in terms of preparedness and response planning. Framework suggests that epidemiological surveillance & detection, primary screening of raw data & information, risk and vulnerability assessments, prediction and decision-making, alerts & early warnings are key components of a dedicated EWS for epidemics and pandemics. Further, response-control & mitigation, preparedness-preventive strategies, reduce transmission & eradication of the disease are integrated components of the early warning ecosystem associated with preparedness and response, dependent on effective EW. Also, integrating public health EWS with other EWS to function effectively as MHEWS to respond to compound and cascading challenges associated with epidemics and pandemics is timely and significant. However, the lacking of EWS to be integrated are proper coordination, sharing data between key stakeholders and well-defined roles and responsibilities among actors, which disable preparedness planning to be multi-hazards and multi-stakeholder. These grey areas can be investigated further by future research focusing on specific hazard contexts in different countries according to their prevailing hazards and risks.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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