IoT and RFID Applications in Pandemic Management

Mohammad Elvan Nazayer

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ABSTRACT

A pandemic springing from an epidemic is a unique type of disaster that repeatedly haunts humanity by causing large losses of life and economic devastation. The coverage, duration and dynamic nature of these disasters make managing them an extreme challenge, which highlights the need for technological solutions to aid management processes. The COVID-19 pandemic has, consequently, seen a rise in epidemic and pandemic management research. Many recent studies have attempted to identify management challenges, and some have suggested technological applications to overcome some of these challenges. However, to date, no study has attempted to address research gaps. Therefore, in the current work, the first step in finding suitable solutions to as-yet unaddressed pandemic management challenges was to collate and closely examine academic literature describing the nature of these challenges. Our examination showed that most management challenges are, in fact, knowledge- and data-related, which means they can be addressed by modern technologies, such as the Internet of Things (IoT) and radio frequency identification (RFID). We then surveyed the literature for IoT/RFID-based solutions to the challenges of managing epidemics and pandemics. The results of two literature reviews were subsequently combined with expert opinions to clearly identify recurrent management issues. Finally, IoT/RFID-based solutions were suggested as solutions, and the solutions were evaluated by experts in fields related to disaster management. This thesis contributes to the body of knowledge in this area by classifying and defining pandemic management challenges. Furthermore, this study presents solutions to the challenges using a novel framework — the pandemic management cycle (PMC) — that we developed specifically to help practitioners successfully manage this type of disaster.

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List of Abbreviations and Acronyms

CDI	Case detection and identification
DMC	Disaster management cycle
EWS	Early warning systems
HCF	Healthcare facility
HCS	Healthcare system
HCW	Healthcare worker
IDO	Infectious disease outbreak
NPI	Non-pharmaceutical intervention
PI	Pharmaceutical intervention
PMC	Pandemic management cycle
PoC	Point-of-care

ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

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My thanks go to my dear family members who helped me become what I am today. I dedicate this work to the memory of my little sister Malak, an angle that left us too early. I also would like to dedicate it to the two short friends I lost on the way to today.

INTRODUCTION AND BACKGROUND

Chapter 1 provides an introduction to the research conducted and starts with a description of the research background and the motivation behind the study. The significance of the research is discussed in section 1.2. The research problem is then introduced, along with the goals of this project, in section 1.3. This section is followed by another exploring the project's scientific contributions. Finally, the structure of this thesis is outlined.

1.1 BACKGROUND AND MOTIVATION

Despite our frequent encounters with disasters, we still do not have a universal definition for these events [1]. However, one of the most widely accepted definitions is presented by the United Nations. According to it, a disaster is "a serious disruption of the functioning of society, causing widespread human, material or environmental losses which exceed the ability of affected society to cope using only its own resources" [2].

This broad definition covers a wide collection of unfortunate events, and many different classifications for these events exist. A widely used disaster classification taxonomy was reported by [3], which grouped disasters as natural, human-made or hybrid. As the name suggests, natural disasters result from adverse natural events out of humans' control. Natural disasters are further classified into four distinct subclasses. These are natural phenomena under the earth's surface, such as earthquakes; natural phenomena at the earth's surface, such as landslides; metrological, such as hurricanes; and biological phenomena, including epidemics, pandemics and infestations. Human-made disasters are defined as those resulting from direct human decisions.

The struggle to pinpoint a concrete definition of disasters can also be seen in the case of epidemics and pandemics. A study by [4] reported many definitions of epidemic. However, most of those reported by that study and others, such as [5-8], view epidemics as abnormal, adverse health-related events befalling a group of individuals in a specific geographical area. Pandemic refers to epidemics affecting several countries on more than one continent [7, 9, 10]. In addition to the two terms, this study also uses the term infectious disease outbreaks (IDOs), which refers to epidemics and pandemics. The term IDOs is used when the size or the geographical coverage of an outbreak is of little importance to the point being discussed.

Attempts to address the outcomes of disasters and reduce their impacts have resulted in a science called disaster management. Disaster management is defined as the coordination and integration of different activities to prepare, respond and recover from disasters [11]. This process also involves minimising the potential damage from disasters before they occur, whether the damage is to lives or environment [2].

Disaster management is a science that has evolved over the years, resulting in different disaster management frameworks. These frameworks provide a basic conceptual structure to examine and manage disasters, including IDOs [11]. One commonly used framework is the disaster management cycle (DMC). This framework breaks the disaster management process into four phases: preparedness, mitigation, response and recovery.

Preparedness can be broadly defined as any action conducted before a disaster to increase the quantity or quality of a resource or process required when addressing interruptions to humans' way of life [11]. On the other hand, mitigation refers to actions taken before detecting a disaster to prevent it and to reduce its likelihood, or the losses that could result from it [11]. Disaster response refers to all actions taken after or during a disaster to prevent or reduce damage [11]. Finally, recovery refers to actions taken after the disaster to return society and services to their pre-disaster states [12].

One of the fundamental ideas the DMC is built on is the generic view of disasters [13]. This view groups common challenges faced during different disasters under common themes. The DMC aims to provide a simple representation of the disaster management process to try to overcome the complex and multifaceted nature of different disasters [14]. Numerous studies are built on this assumption. These studies discuss challenges and solutions, and evaluate the suitability of technologies in terms of disasters in general [11, 15, 16].

The DMC and the generic view of disasters have recently been criticised by many scholars due to the outcomes of the COVID-19 pandemic. A study by [17] argued that even though the framework is still widely used, it is outdated and needs to be updated by including contemporary management insights. Another study by [18] echoed the same concerns and called for abandoning the generic view of disasters. The study cited and supported a top hazards approach put forth by [19]. This approach treats each type of disaster differently. Another study by [20] stated that even though it is not recommended to create separate plans for each different hazard, a single model cannot resolve issues arising from different disasters as they differ significantly.

Many similarities between certain types of disasters exist. However, this does not necessarily mean the same challenges and tools can be applied to all of them. Many aspects of IDOs distinguish them from other disasters and result in specific management challenges [10, 21]. The COVID-19 pandemic made it abundantly clear that pandemics can result in unique disturbances to life that span the globe and persist over time [22]. In addition, different IDOs vary greatly, which renders preparedness and response measures for some IDOs unsuitable for others [23-25].

One of the differences between IDOs and most other disasters is their geographical coverage, or the dynamic pace of IDOs expansion [22, 26-29]. In most instances, other disasters have fixed locations and geographical coverage areas. For example, we do not know the location of an earthquake in advance, and it could strike anywhere, but once an earthquake hits a specific area, the geographical area requiring a response does not shift unless another earthquake strikes it. The same applies to most other disasters such as floods, landslides and cyclones. The dynamic geographical coverage of IDOs introduces unique challenges during all phases of the IDO's management [20, 28, 30].

Another difference between IDOs and other disasters is the unknown duration of an IDO. IDOs can last from months to years [31]. This unknown introduces numerous management challenges, such as estimating the resources needed for the response. This challenge was faced during the COVID-19 pandemic, when shortages of personal protective equipment (PPE) were reported by many countries [32-36]. IDOs' unknown duration also increases the difficulty of managing supply chains [37]. The inability to estimate the duration of outbreaks can also influence public support for interventions, which is likely to affect their chances of success [38].

Other challenges faced during the management of IDOs include determining economic losses and financial requirements to manage these events. These difficulties arise because most of the losses resulting from IDOs are indirect [7, 29]. This unknown makes determining the costs versus the effects of control measures more challenging [10]. This issue, combined with difficulties in determining the resources required, makes justifications of expenditure, especially preparedness spending, harder for policymakers [38].

This unique nature of IDOs highlights the need to re-examine the challenges faced during IDOs separately from other disasters. This task should also be followed by a re-investigation of suitable solutions to these challenges.

1.2 TECHNOLOGICAL BACKGROUND

All the differences between other disasters and IDOs mentioned in Section 1.1 share one common factor — they are all knowledge-related. Outbreak management and epidemiology, in general, are highly dependent on data quantity and quality [6, 39-42]. Many studies have highlighted the need for more data, and data quality improvement [23, 43, 44]. These calls were made during past epidemics and pandemics [45, 46] and were echoed during the COVID-19 pandemic [47-49].

These data-related challenges were summed up by [50], who indicated that the difficulty in accruing the needed data to manage a pandemic permits labelling these IDOs as "wicked problems". Pandemics are complex, evolving, novel and unique problems with significant gaps in the knowledge required to solve them. This view was supported by [25, 51], who argued that uncertainty is one of the main challenges to IDO response planning.

Identifying suitable solutions for those knowledge-related challenges requires a closer examination of the quality attributes of the data needed. Section 3.2.2.3.1 Data quality and sharing of this study examines the data quality attributes most frequently mentioned in the literature. The examination reveals that management processes and related tools require timely, accurate, complete, standardised, unbiased and granular data.

While obtaining data with certain qualities can depend on the specific implementation of a system, the choice of technology also determines the system's potential to deliver data with the desired attributes. Two technologies that have the potential to provide data with desired quality attributes are the Internet of Things (IoT) and radio frequency identification (RFID) [52-58].

The IoT is a web of interconnected mechanical or digital devices. These devices can collect, transmit, and in some instances, process the data without the need for human intervention [59]. The applications of IoT devices have exploded in the last few years and have touched many disciplines. This growth has led to different subsets of IoT devices associated with different areas or applications. The Internet of Medical Things (IoMT) is an example of this. The IoMT is an interconnected network of medical equipment and smart sensors capable of collecting, aggregating and transmitting health-related data to information technology (IT) systems.

RFID technology is used extensively when physical objects need to be identified and tracked [60]. An object or a class of objects is/are assigned unique identifiers stored on a tag capable of transmitting those identifiers as radio signals. Those signals can be deciphered by special RFID readers. Some of these tags are readable, while others are readable and writable [61]. RFID tags can hold data associated with an object other than the identifiers, and this data could describe the state of an object and changes to that state [62].

1.3 SIGNIFICANCE OF THIS STUDY

Humanity has witnessed a few major pandemics during the last century, with a death toll of around 65–96 million lives. These included the Spanish flu, which occurred from 1919–1920, with a death toll estimated to be between 20 and 50 million [63]; the Asian flu in 1957–1958, which claimed 2–3 million lives [29]; the Hong Kong flu in 1968–1969, with a total death toll of 1 million [29]; the human immunodeficiency virus (HIV) pandemic, which has been ongoing since 1981, with a total death toll of around 36 million [64]; and finally, the COVID-19 pandemic, which started in 2019 and has claimed almost 6 million lives as of March 2022 [65].

According to a study by [66], the economic losses from an average large-scale pandemic are expected to be 60 billion USD. Another study by [7] argued that a flu pandemic could cost the world up to three trillion USD. Unfortunately, the COVID-19 pandemic showed that these impact estimates were very optimistic. According to [67], the current pandemic is expected to reduce the global economic output by $8.5 trillion from 2021 to 2022.

The possibility of facing new pandemics will remain as long as we are alive. Epidemics and pandemics have been a constant threat to humans since the beginning of time [29]. It is estimated that there are currently around 1.7 million unknown pathogens. Up to half of these could cause the next emergent infectious disease (EID) outbreak [68, 69]. The risk of epidemics and pandemics has increased significantly in recent years [10, 29, 70, 71]. This argument was echoed by [72], who indicated that at least one emerging pathogen has been identified each year in the last 20 years.

These risk factors highlight the need for an organised research effort in the IDO management field. Doing so requires identifying the research gaps and evaluating the possible solutions that could be used to improve IDO management.

1.4 RESEARCH GAPS

The COVID-19 pandemic resulted in an outburst of studies and literature reviews discussing technological solutions to support IDO management. As discussed in section 1.2

Technological background, many of the challenges introduced by IDOs are related to information availability and sharing. This implies the improving the data collection and sharing capabilities will result in IDO management improvement. IoT/RFID technologies are suitable to overcome such challenges as highlighted in section 1.2 Technological background. The suitability of those technologies for the task at hand highlights the need for an in depth investigate of those technologies in IDO management. A large number of studies examined applications of IoT in IDO management. The main limitation of most literature reviews and studies is that they simply describe existing or proposed IoT/RFID systems to manage IDOs [73-83]; however, none of the reviews have attempted to collate IDO management challenges and examine which of those are still unaddressed. In other words, most of these studies started with the solutions available rather than the problems, which has limited their ability to identify areas where research is needed.

1.5 RESEARCH OBJECTIVE AND QUESTIONS

The main objective of this study is to answer the question: "What is the role of the IoT and RFID in IDO management?". This question is broken down further into the following, specific sub-questions.

- What are the challenges faced in the IDO management process?
- How can IoT/RFID facilitate and improve preparedness for IDOs?
- How can IoT/RFID facilitate healthcare responses during IDOs?
- How can IoT/RFID aid decision-makers in devising effective IDO management policies?

These four sub-questions were selected to be the centre of focus as they are likely to cover most of the challenges faced in IDO management. For example, preparedness touches on the deficiencies faced during all other phase of the management process. Policymaking covers most of the interventions and responses employed during all phases, including preparedness. Finally, healthcare systems (HCSs) are probably the most crucial resource for the response phase.

Calls to improve preparedness levels to manage IDOs have been repeated numerous times. Many of those calls were a response to the inadequate global preparedness identified after pre-COVID-19 pandemics [7, 10, 45, 84-86]. A glance at the global impacts of COVID-19 is enough to recognise that these warnings were not heeded [37]. This shows the need to investigate and address IDO preparedness challenges. Preparedness for IDOs involves readying resources, process, and systems needed during all subsequent DMC phases. This highlights the need to also examine challenges faced during other phases DMC such as mitigation, response and recovery to improve the preparedness to face IDOs.

One of the most feared scenarios during the COVID-19 pandemic was an overwhelmed HCS. An overloaded HCS could increase the overall number of mortalities by 2.3 times during a pandemic [10]. Sadly, the overwhelmed HCS scenario had already became a reality on numerous occasions, for example, during the 2014–2016 Ebola outbreak in Guinea, Liberia and Sierra Leone [87]. This also happened during the COVID-19 pandemic in countries such as Italy [88], Spain [36] and India [89], to name a few. This sector also faces the highest risks during such events [90]. [91] argued that the COVID-19 pandemic exposed the fragility of HCSs around the world. This necessitates the search for new ways to employ technology to protect and improve HCSs.

Other crucial IDO management tools are public healthcare policies. Health policies are the main courses of action available before finding a vaccine or treatment for the disease. Optimal policies on their own can halt a virus' spread [41]. It has even been shown that suitable policies can be far more effective than vaccines in some cases [92].

Policymakers should be given every advantage possible to perform their duties effectively. Determining suitable policies is a complex endeavour on the best of days, but an IDO can make it an insurmountable task. Many variables need to be considered in the case of IDOs: pathogen attributes, resources available, the public's acceptance and adherence, the different needs of different groups, the changing epidemiological landscape and much more.

All of these issues show the need to investigate the suitability of IoT/RFID to support efforts to manage IDOs in general. The cruciality of preparedness, HCSs and policymaking tasks to the effective management of IDOs shows the need to support these tasks.

1.6 RESEARCH CONTRIBUTION

This project's contribution extends from entire societies to individuals working in and researching IDO management and related fields. Some of the project's outcomes are to:

- identify and highlight unaddressed IDO management challenges.
- suggest solutions based on IoT/RFID to overcome unaddressed IDO management challenges.
- evaluate the proposed solutions.
- present an IDO management framework more suitable than the DMC for the IDO management process.

1.7 THESIS STRUCTURE

Figure 1-1 provides an illustration of the thesis structure. Chapter 2 presents an overview of the different methodologies followed in this thesis. Chapter 3 presents the findings and the protocols followed to conduct comprehensive systematic literature review (SLR) conducted to identify the challenges faced during the management of IDOs. Chapter 4 presents the findings and protocols followed to conduct an SLR to identify current and suggested applications of IoT/RFID in the field of IDOs' management. Chapters 5 presents the protocols followed to conduct a Delphi study conducted to evaluate the applications of IoT/RFID suggested in this thesis to support IDOs' management. The findings of the Delphi study are also presented in chapter 5. Chapter 6 discusses the findings of this thesis. This chapter also discusses the limitations of this project and provides recommendations for future research.

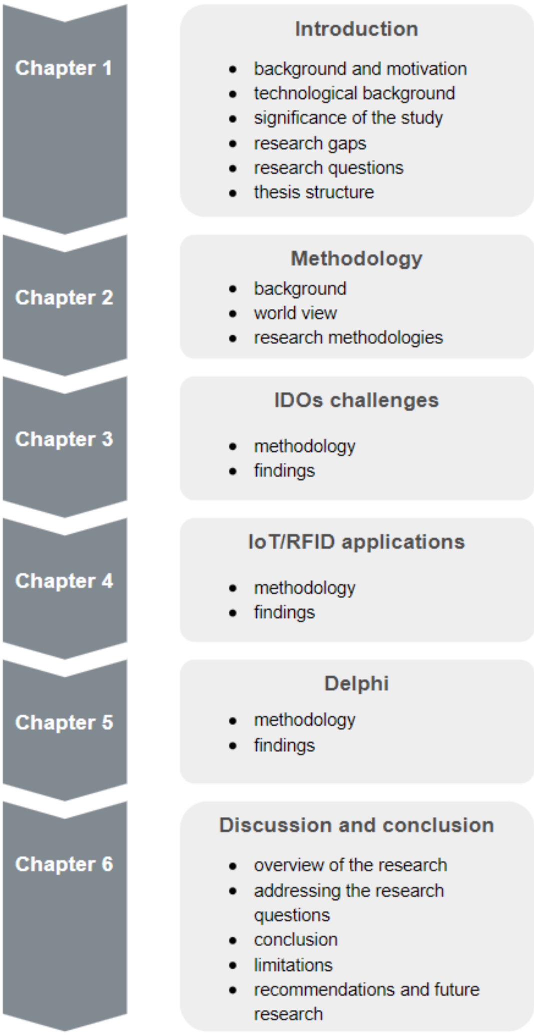

Figure 0-1 Overview of the thesis structure.

METHODOLOGY

Chapter 2 justifies and explains the research methods used in this thesis. It starts by reviewing the problem at hand and examining its qualities. The overall research approach is then explained and justified. This chapter also explains the distinct research methodologies applied in this project. The exact protocols followed in executing those methodologies are presented in the methodology sections presented in each of the chapters discussing the findings of the SLRs and the Delphi component of this research project.

2.1 BACKGROUND

The outcomes of the COVID-19 pandemic showed the world that managing IDOs is an arduous process that demands all available support. Two of the most promising technologies that can address unresolved challenges faced when managing IDOs are the IoT and RFID. This study aims to evaluate the suitability of these technologies for the tasks of preparedness, policymaking and healthcare provision during IDOs.

2.2 THE PRAGMATIST WORLDVIEW AND MIXED-METHODS APPROACH

Several factors influenced the identification and adoption of the theoretical framework used in this research. This research aims to identify suitable solutions to the problem of IDO management. However, IDOs are complex problems, evolving, novel and unique, with significant gaps in the knowledge required to derive solutions [48-50, 69, 93-97]. These characteristics of IDOs make it hard to determine fixed notions of truth and correctness, and they also prevent adequate testing of potential solutions.

The practicality and the urgency of the IDO problem permitted a shortcut to arrive at solutions without delving into questions about the philosophy of science, the laws of nature, epistemologies and ontologies. This shortcut is known as the pragmatist worldview [98]. Pragmatism is a methodological approach based on the work of William James. The epistemological view of pragmatism states that knowledge can be generated using quantitative or qualitative data. This view also implies that knowledge can be subjective or objective depending on the field of inquiry [99]. For example, objective truths are attainable in field such as mathematics, however, they can be hard to attain other fields.

The field of inquiry of this thesis is one which is hard to solve objectively. This can be justified by examining the problem at hand. As stated earlier, IDOs present significant knowledge related challenges. Some of those challenges mean that it is hard to find an objective starting point for this inquiry. For example, IDO effects that can be used to deduce management challenges are based on subjective observations and reports due to the inaccuracy and insufficiency of quantitative data describing IDOs.

Pragmatism focus is mainly on the problem to be addressed, rather than the methods behind solutions [100-102] and finding what works without being distracted by epistemological matters [103]. Pragmatism is often applied when dealing with ill-defined problems plagued by uncertainties that limit the ability to use empirical, scientific problem-solving methods [102, 104]. This worldview is considered suitable when a controlled evaluation of solutions is unavailable [105].

Pragmatism is a flexible methodology consistent with the mixed-methods research approach [102, 106]. The mixed-methods approach involves working with qualitative and quantitative data [107], and alternating between deductive and inductive reasoning based on the progression of the problem [108]. This approach is applied in disciplines involved in IDO management, including public health policy [105], healthcare and epidemiology [102]. The mixed-methods approach allows for a detailed analysis of complex and multidisciplinary phenomena, such as IDO management [109].

Different mixed-methods research topologies exist [105]. These topologies illustrate the possible weaving patterns of qualitative and quantitative research methods to form different schemas in mixed-methods research. These include parallel and sequential designs. The pattern used in this study is known as a sequential pattern. This pattern refers to research schemes when different stages of the research are built and informed by the results of previous stages. This topology was also called a multi-phase design by [105]. The particular topology selected for this research project is sequential where it starts with the qualitative component which is then followed by quantitative component. This design choice is suitable for exploratory studies aiming to identify solutions rather than confirm findings [110]. Furthermore, this topology is selected as it allows the findings from the qualitative systematic literature reviews to inform the quantitative Delphi study component.

The mixed-methods approach offers a flexible framework that can compensate for the limitations of using only one research method [109]. For example, statistical evaluation tools are undoubtedly one of the foundations of scientific enquiry; however, failure to identify the variables to be measured can lead to misleading insights, no matter how powerful the analysis tools applied are [105].

2.3 RESEARCH FRAMEWORKS

Section 2.3 presents and defines the research methodologies used in this project. This section also presents and discusses the rationale behind choosing these methodologies. The research flow and the structure are presented in Figure 0-1. The mixed-methods approach was used in this study because it allows carrying out the two main actions involved: (1) identifying relevant ideas and variables, and then, (2) evaluating solutions generated based on analysis of the variables. The variables, in this case, refer to unaddressed IDO management challenges. Identifying the variables was achieved by conducting a qualitative systematic literature review (SLR), followed by a second SLR to identify IoT/RFID applications in IDO management. The findings of the two SLRs were combined to identify unaddressed challenges faced while managing IDOs. Possible applications of IoT/RFID were then suggested. These applications were then evaluated by field experts participating in a Delphi study.

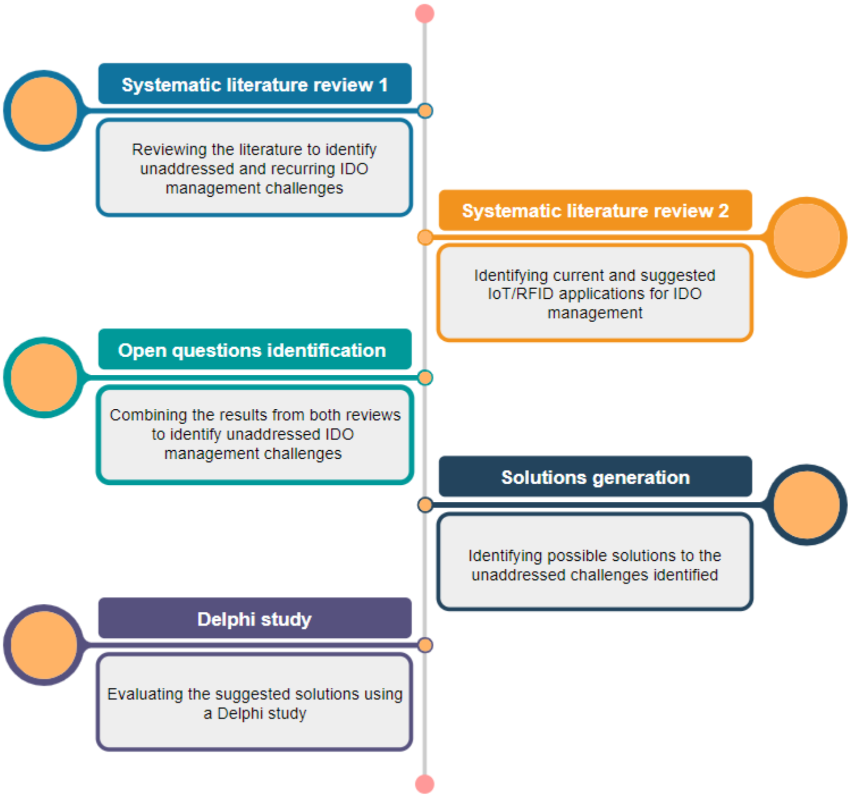

Figure 0-1 Overview of methodologies used in this project.

Note. Figure 1 is the author's original work.

Abbreviations. IDO, infectious disease outbreak; IoT, Internet of Things; RFID, radio frequency identification

2.3.1 Systematic Literature Reviews 1 and 2

Knowledge synthesis is a condition for scientific growth and development [111] as science is a cumulative process [112], and a literature review is a common tool designed for this purpose [113]. Literature reviews can be generally defined as surveys of scholarly work published on a particular topic [114]. A study by [115] identified and discussed 14 types of literature reviews. These reviews were classified based on the type of data collected, whether qualitative or quantitative, and the depth of the data analyses, among other aspects.

This study uses a type of literature review known as the SLR to integrate past knowledge in the field concerning challenges faced during IDO management. SLRs are research tools applied to identify and synthesise all available, quality research related to a specific subject in a systematic manner [116].

Different types of SLRs exist. One of these is known as the qualitative SLR [115]. As the name suggests, this type of SLR aims to synthesise the findings of qualitative studies. The synthesis may result in a new theory or an overarching field view. This process involves searching themes and concepts common across studies to facilitate the understanding of a complex phenomenon. This type of SLR can provide more generalisable findings than individual qualitative studies. One of the functions of this type of SLR, among many others, is to explore barriers encountered in specific fields and inform the prioritisation of services [115].

The strengths of the qualitative SLR mentioned above show that it is appropriate for this project. The first reason behind this conclusion is that most studies addressing challenges faced during IDOs are qualitative studies. This type of SLR therefore allows the identification of challenges and barriers faced when managing IDOs. The findings based on this type of SLR can provide a framework that is better suited to illustrate the challenges faced and guide the IDO management process.

According to [111, 117], literature reviews involve four main stages: (1) planning the review,(2) selection of the studies, (3) extraction of data, and finally, (4) the execution of the review. The planning stage involves identifying the review aims and creating a search protocol. Search protocols include creating a search string, identifying the inclusion and exclusion criteria and setting search stopping conditions to abort the search when no relevant results are returned. It should be noted that there is no common agreement on a search strategy for qualitative SLRs [115].

Once the plan is in place, the data collection phase starts and continues until the search stopping criteria are met. This step is followed by the filtration of the data retrieved, which is achieved by following the exclusion criteria defined during the planning phase. The data extraction task then commences, and once it is completed, the data synthesis stage begins [111, 117]. There are no set rules to conduct this task in the case of qualitative SLRs [115]. Search protocols and analysis methods that are not specific to qualitative SLRs were used in this thesis to overcome this challenge. These methods will be discussed in the section 3.1 Methodology 4.1 Methodology of Chapters 3 and 4.

2.3.2 The DELPHI method

The Delphi method has been used in this project to evaluate the insights and solutions generated from the SLRs. The Delphi research method is compatible with the pragmatic worldview this project is built on [118], and it can also be used for both qualitative and quantitative research [119]. The Delphi method can be defined as a process used to systematically collect expert opinions through iterations of questionnaires and controlled feedback [120, 121]. This method aims to produce a reliable consensus from a group of selected experts. The aim is to reach a statistically meaningful group response while preserving the anonymity of the participants [120, 122].

This research method has been used continuously in fields related to this project. These include information technology, and, in particular, improving the efficiency and effectiveness of the information technology infrastructure [123]. The Delphi method has also been used in public policy [124], studies aimed at improving systems for healthcare delivery [125] and IDO preparedness evaluations [124].

The Delphi method is suitable for complex areas of inquiry that suffer from high uncertainty levels [124, 126]. Furthermore, Delphi is suitable for investigating multidisciplinary issues requiring cooperation and communication between experts in different fields [124].
The Delphi component of this project was used to evaluate, and confirm or deny, the findings of the previous qualitative components and suggestions based on those. The aim was to enhance this study with multiple perspectives and add rigour to this project [127].

The Delphi process starts with selecting the experts to include on the panel, devising a questionnaire to collect the required data, and finally, determining consensuses measurement procedures and tools [126]. There are no set methods for the recruitment of panellists, but two main aspects are essential during this phase. These are the quantity and the quality of the expertise. The quantity here refers to the number of experts to recruit, and quality refers to their level of knowledge. There are no set rules or consensus on any of these aspects. One of the reasons behind the lack of rules is the different requirements of different problems and inquiry domains [128]. Despite this, some studies suggested that 5–10 experts are a suitable sample size for a panel [126]. There are no guidelines to determine suitable knowledge levels, either. However, two of the ways to determine a research participant's level of expertise are their academic contribution and the duration of their involvement in the field of interest [128].

A questionnaire is usually sent out once the panel selection and recruitment are complete. Different methods are used to compose the first questionnaire, and one of these is a literature review, which is the method used in this project [128]. Once the responses are collected, they are analysed, and the level of consensuses is measured. The results of the first round are used to compose a second questionnaire. Questions that did not generate the required level of consensus, or those that attracted comments and controversy, are re-evaluated, rephrased or the changes suggested by panel members are incorporated. The first-round results are sent back to the experts along with the second questionnaire. This process is repeated until a consensus is reached or a certain number of rounds has been executed [128].

The exact protocol followed when conducting the Delphi component of this study is presented in section 5.1 Delphi method used in this research along with its findings.

MANAGEMENT BARRIERS AND CHALLENGES

Chapter 3 presents the findings of a qualitative SLR conducted to identify and collate barriers and challenges faced when managing IDOs. The chapter starts with a methodology section explaining the protocol followed when conducting the review. This section is followed by the findings section, which presents the results from the SLR.

3.1 METHODOLOGY

This SLR aims to identify challenges in managing IDOs. Many obstacles were faced while conducting this SLR. These obstacles included: formulating the search string, defining key terms, identifying and addressing some of the databases' idiosyncrasies, formulating inclusion and exclusion criteria and devising a classification schema to use when extracting and presenting the data.

3.1.1 Search string

Creating the search string was an iterative process. This process started with an initial string based on SLR objectives. The search string was updated to address specific issues encountered during the data collection phase. These issues included biases in the literature, where certain subjects were more frequently addressed than others. Furthermore, database-specific idiosyncrasies necessitated adjusting the search string to suit the requirements of each database.

The initial search string was determined and refined based on consultations with peers and researchers active in fields related to this project. This process also involved consulting librarians at the Auckland University of Technology (AUT). After testing the search string, specific terms were omitted, and others were added. For example, the term "infectious diseases" returned many studies addressing diseases such as seasonal flu, so it was omitted. Terms such as "emergency" and "incident" were also removed because they returned studies addressing events not relevant to the SLR’s aims.

Furthermore, terms referring to DMC phases were omitted as searching these resulted in the propagation of pre-existing biases. For example, the response phase is discussed more frequently than mitigation in the literature; thus, the term response would have reduced the probability of retrieving studies discussing mitigation or other management phases.

Another reason for excluding such terms was the existence of numerous disaster management frameworks. These frameworks use different terms to refer to phases involved in disaster management, and some include up to eight phases [11]. Failure to include all terms could have omitted some challenges that may have been discussed under uncommon phases in uncommon frameworks. The inclusion of all the terms used to refer to phases in all frameworks was not considered due to this project's time limitations. In addition, the omission of DMC phases from the search string was unlikely to have impacted the relevancy of the results as it was likely that publications addressing DMC phases included terms such as "disaster management".

After considering the options, the following search string was composed:

("disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR “epidemic” OR “pandemic” OR “outbreak” OR "communicable disease" OR "communicable diseases")

AND

(“management” OR “control” OR “challenge”)

However, this string was further tailored based on databases searched. The changes to the search string are discussed in section 3.1.2 below.

3.1.2 Data collection and filtration

Databases primarily focusing on health, computer science, disaster and emergency management, health and health informatics were searched. These included PubMed, IEEE Explorer, PLOS, and Science Direct. These databases were determined based on AUT’s database list [129] for computer science and healthcare, and after consultations with AUT librarians. Google Scholar was also searched as it is a multidisciplinary database.

The databases selected influenced the search process in many ways. For example, index terms were not used in the search process because not all the selected databases supported these. The different syntaxes used in the databases necessitated tailoring the search string to address idiosyncrasies. For example, the maximum length of a search string that could be processed by Google Scholar was 256 characters [130]. This limitation was addressed by breaking the default search string into three substrings used to perform the search. Appendix “A” shows the databases, the search strings used and the reasons for string changes.

Search stopping criteria were determined before data collection. Stopping criteria were devised based on guidelines provided by [117, 131]. Stopping criteria were 10 consecutive articles, with two or fewer articles relevant to SLR aims. Once this condition was met, the search of a database that generated these results was discontinued.

Data collection was conducted in two stages. The first of these stages covered articles published in English from January 2010 until the end of March 2021. This round was followed by another that targeted studies published between the end of March 2021 and mid December 2021. The reason behind this choice was a desire to include as many of the studies that discussed challenges faced during the COVID-19 pandemic as possible. Figure 0-1 Number of studies retrieved and the number of those excluded at each stage of the filtration process. shows the number of records collected at each stage, and the updated article count after each screening step.

The screening protocol illustrated in Figure 0-2 was employed at both stages. The screening process started by excluding duplicates, non-English articles, and articles that did not allow access to the full text. This step was followed by screening the titles and abstracts of articles. Articles focusing on disasters other than IDOs were excluded. Perspectives and opinion pieces were also excluded at this step due to the project's time limitations.

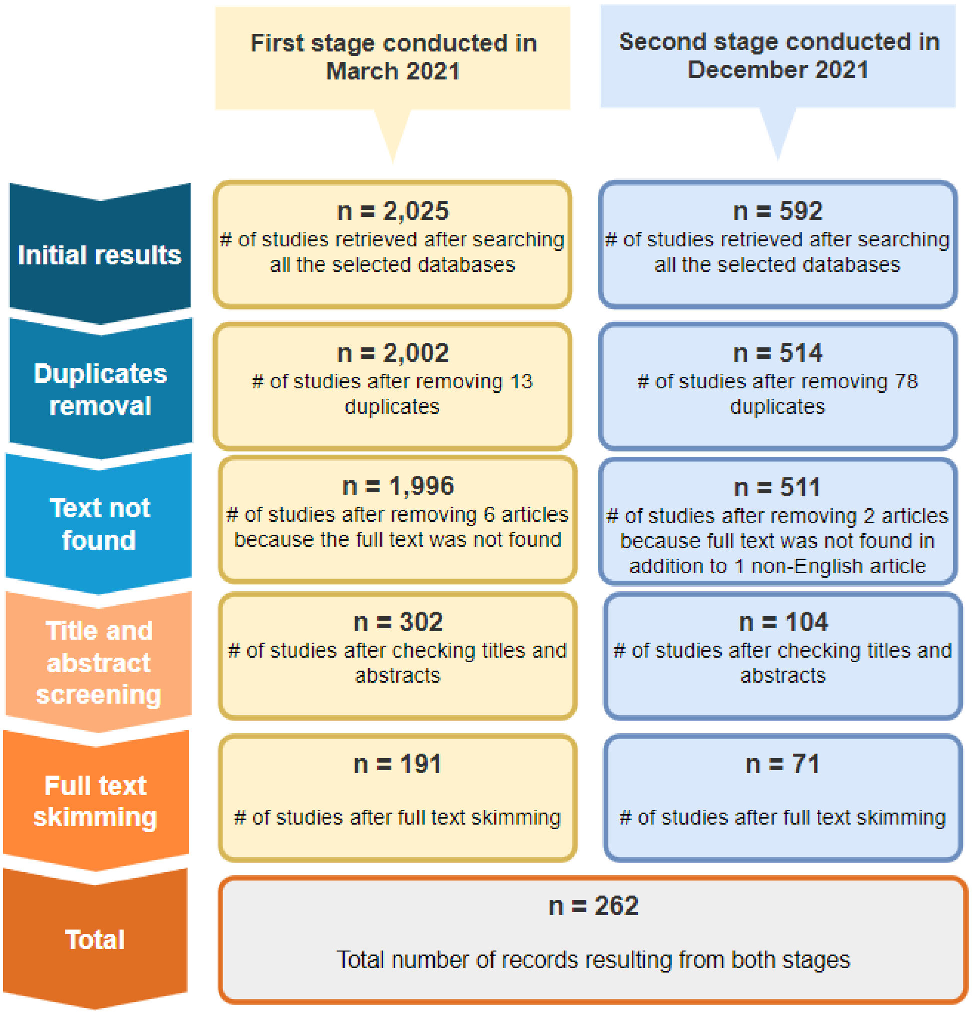

Figure 0-1 Number of studies retrieved and the number of those excluded at each stage of the filtration process.

Note. Figure 0-1 is the author's original work.

In the final exclusion step, the full texts of selected articles were skimmed. Articles that discussed IDOs' effects on domains such as education, power, supply chains and the environment were excluded unless it was stated that these challenges affected the ability to manage IDOs. For example, many articles discussed the problem of increased plastic waste generation during the COVID-19 pandemic. These articles were excluded unless they discussed infectious waste management related to infection spread during IDOs.

In addition, articles reporting on social issues and factors that did not clearly state any IDOs challenges were excluded. Reports on measures taken during an IDO without explicitly mentioning challenges were also removed. Articles discussing IDOs from a medical point of view were excluded. Articles presenting solutions, epidemiological models, general advice for the public, management frameworks or technical solutions without explicitly mentioning any IDO management challenges were also excluded. Articles with an architectural focus were excluded, as were articles discussing the legal aspects of IDO management.

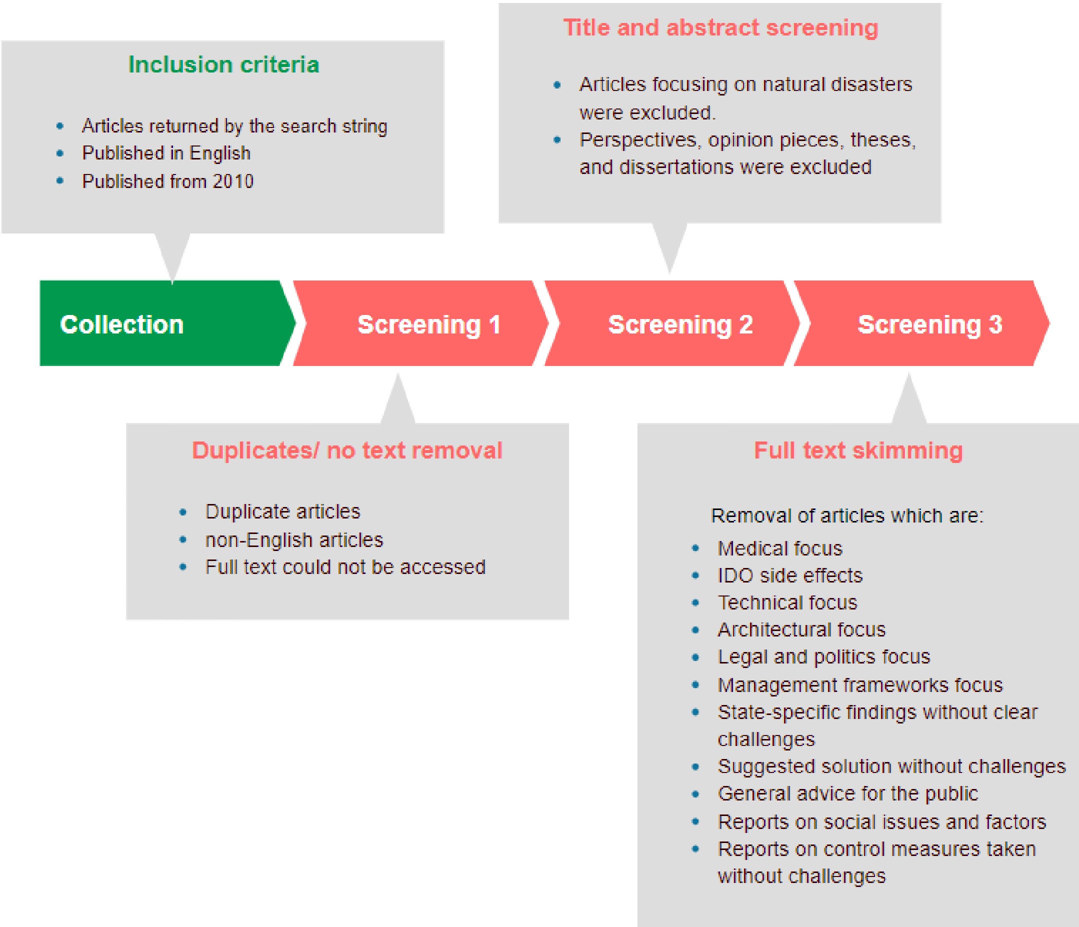

Figure 0-2 Overview of the inclusion and exclusion criteria employed in this SLR

Note. Figure 0-2 is the author's original work.

Abbreviations. IDO, infectious disease outbreak.

Many studies discussed procedures followed by specific departments in a healthcare facility to reduce transmission probability. Some of these articles were included to illustrate the challenges faced by these departments. Many of these studies reported similar information, but the focus was on the specific needs of these departments. Due to this project's time limitations, many of these studies were excluded.

Studies discussing disasters usually use quantifiers, such as the number of victims, to determine event inclusion or exclusion in literature reviews and the study scope. Different thresholds of disasters were reported by [11]. This project, however, did not follow suit. This decision was made because excluding outbreaks with sizes below a fixed threshold meant that some prevention challenges would have been excluded. In other words, including only outbreaks of specific sizes would have resulted in omitting discussion about challenges that arise when dealing with small-scale outbreaks, which can evolve to become IDOs.

3.1.3 Data analysis

This project used a qualitative data analysis method known as thematic analysis [132]. This approach aimed to identify and classify key themes mentioned explicitly or implicitly in the text to find solutions to real-world problems [132]. Thematic analysis is suitable for qualitative data, which most of the studies retrieved in this SLR presented.

The first stage of the data analysis phase was to identify themes to use when classifying challenges identified in the literature. For this purpose, a pilot test was carried out. The test involved sorting the studies retrieved according to publication date, and then, selecting 16 articles published over the 11 years from 2010 until 2021. This method was based on the conjecture that different epidemiological or health-related events are likely to influence the overall theme of publications during specific time periods, leading to a diverse set of categories. The challenges identified during the pilot test were grouped under common themes, which constituted an initial list of categories used to classify challenges extracted from the literature. The identified themes were further refined by consulting with the advisors involved in this project.

Once the initial themes' list was determined, the data extraction step started. This step involved using a qualitative data analysis software called NVivo to classify challenges according to the themes. These themes were revisited and updated three times while conducting the SLR after identifying new common themes among IDO management challenges collected from the literature. This process also included adding new themes to group challenges that did not fit any existing themes. Once the data analysis phase was finished, the themes were further updated based on the knowledge gained from the data extraction phase. The final update involved the creation of new categories and merging of others to produce a framework capable of addressing the special needs and challenges faced by the IDO management process.

3.2 FINDINGS

This section presents the results of the SLR conducted to identify challenges faced during IDO management. The section describes the framework and the categories used to present the findings. This section then presents common challenges faced in most phases of the IDO management process. Finally, each phase of the IDO management process is presented along with specific challenges specific to it. Figure 0-3 illustrates the layout of this section.

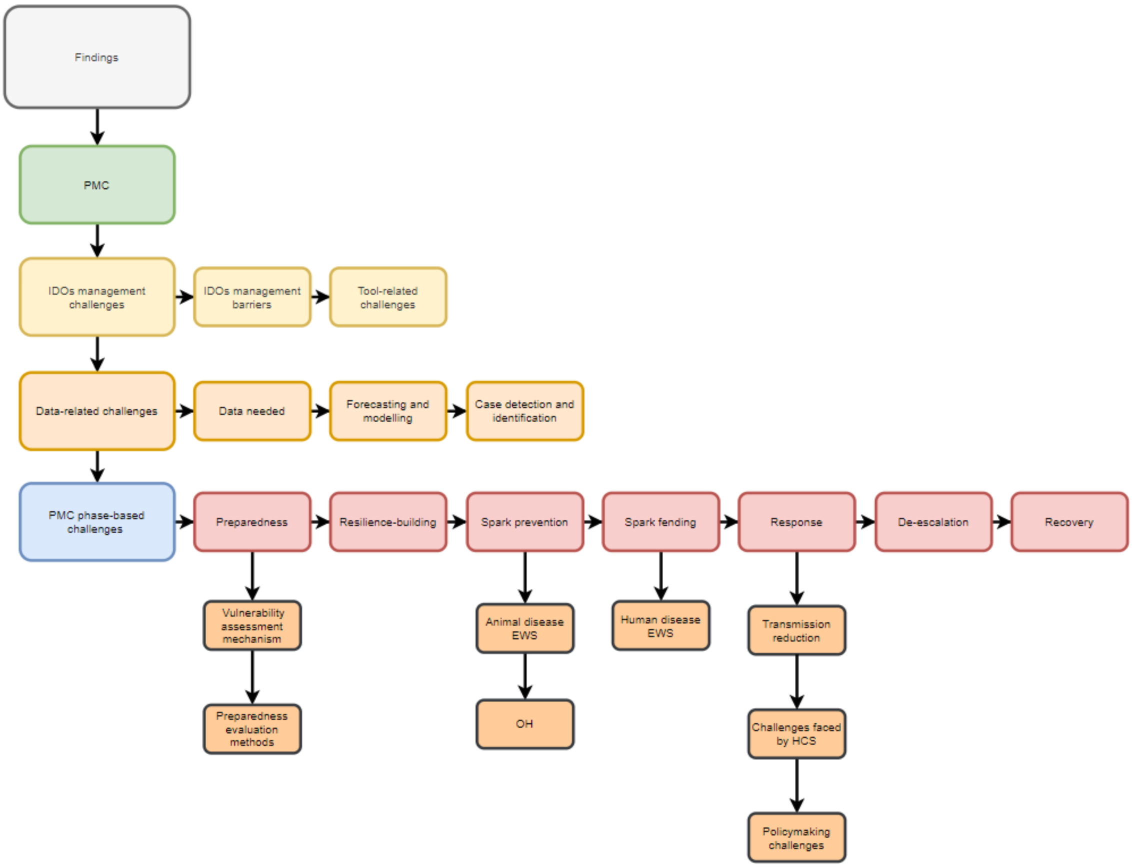

Figure 0-3 the layout of the findings section

Note. Figure 0-3 is the author's original work.

Abbreviations. PMC, pandemic management cycle; HCS, healthcare system; IDO, infectious disease outbreak; EWS, early warning systems; OH, one health.

3.2.1 The pandemic management cycle

One of the common methods used to organise and present findings addressing disaster management is disaster management frameworks. The DMC presented in the Chapter 1 is one such framework. However, the DMC is more suitable for studies addressing disaster management in general, rather than IDO management. This is because studies addressing disaster management are concerned with common factors between different disasters, resulting in reduced complexity. However, addressing IDO management on its own magnifies the limitations of the DMC framework.

Examining the literature addressing IDOs pre-COVID-19 showed that many studies opted for other methods to present, discuss and organise findings. Numerous studies discussing IDOs at the macro level opted for a new or a modified framework [24, 37, 53, 93, 133, 134]. Other studies, especially those addressing issues on a micro level, grouped findings according to common themes [7, 10, 135-137].

This work aims to address challenges at both the macro and micro levels of IDO management. Due to the scope of this study, the best method to present the findings and challenges is a hybrid approach. Challenges deemed common to all phases of the IDO management process are presented separately at the start of this section. Other challenges faced in specific phases are presented using a modified framework more suited to IDOs.

This study uses a framework that borrows ideas from the DMC and combines them with other concepts identified in the literature. A novel framework is presented in Figure 0-4; it is referred to as the pandemic management cycle (PMC). The DMC phases appear in the inner circle and the corresponding PMC phases are in the outer circle. The PMC comprises seven phases: (1) preparedness, (2) resilience building, (3) spark prevention, (4) spark fending, (5) response, (6) de-escalation and (7) recovery (Figure 0-4).

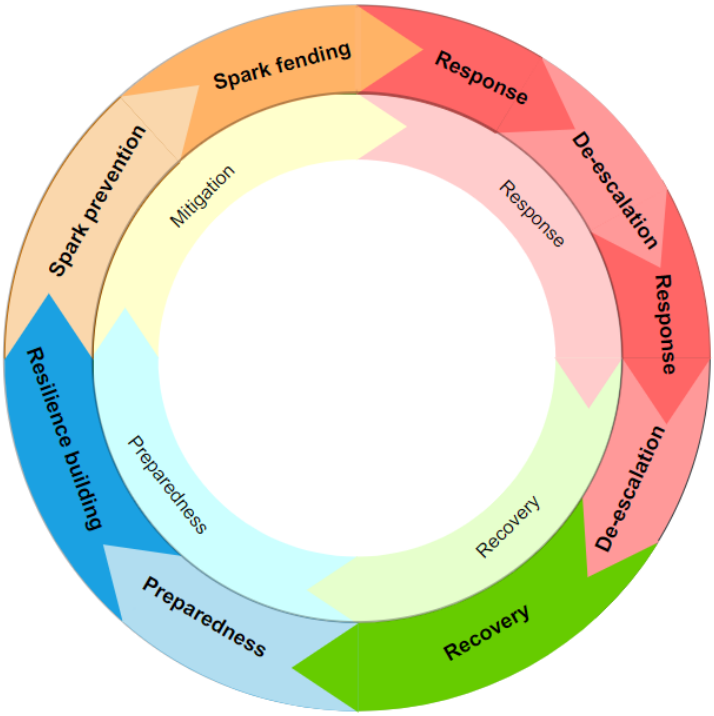

Figure 0-4 The pandemic management cycle.

Note. Figure 0-4 is the author's original work.

The first phase of the PMC is preparedness. The term *preparedness* in this study refers to any action conducted before detecting an outbreak designed to increase the quantity or quality of a resource or process required when addressing an outbreak or resolving outbreak-caused interruptions to the way of life [138]. For further clarification, preparedness does not involve using resources; instead, it encompasses planning and readying resources for later use. One exception is surveillance systems, as they are used in this phase to collect data to guide preparedness efforts.

Preparedness for IDOs is hampered by the uncertainties shrouding these disasters and should incorporate resilience in resources and processes [24, 31, 139-141]. Issues that add extra difficulty to IDO management are the unknown pathogen attributes and the unknown duration of the IDO. These issues complicate preparedness efforts and make rigid, tightly coupled plans risky [91, 141]. The solution is to include resilience elements such as robustness, flexibility and redundancy in preparedness plans [142, 143]. The need for resiliency is frequently mentioned in the literature addressing COVID-19 response limitations [31]; however, there is no clear point in time or component in IDO management explicitly mentioning resilience. In response, we added a phase called *resilience-building* to the PMC. This phase was added after the preparedness phase.

One of the most misunderstood disaster management phases in the DMC is mitigation. The original meaning of the word "mitigate" is to alleviate a burden [144]. This definition implies the existence of a burden to be alleviated, which contradicts mitigation's definition in the DMC. The DMC defines mitigation as actions taken before detecting an outbreak to prevent it, to reduce its likelihood or to reduce the losses that could result from an outbreak [138]. The confusion caused by this term is rampant: many studies have associated mitigation with response-related actions [18, 24].

In the current work, the mitigation phase was replaced by "spark prevention" and "spark fending" to clarify this confusion and to create a framework more suitable for IDOs. The introduced terms are built on the label "spark", which was used in a study by [10]. The term refers to events where a pathogen jumps from a nonhuman host to a human, leading to an emergent infectious disease outbreak (EIDO). The *spark prevention* phase involves actions to prevent the initial pathogen jump from nonhuman to human hosts. The actions and systems used in this phase could include biosafety measures, or early warning and detection, among many others. *Spark fending* is a term used originally to refer to installing barriers to reduce the probability of a spark landing on flammable objects and creating a fire [145]. In the context of this study and IDO management, spark fending stands for interventions and biosafety measures employed before detecting an IDO to reduce the transmission probability of the initial pathogenic spark from initial human cases to other humans, which may result in an epidemic.

The *response* phase in this study refers to all actions taken after detecting an outbreak to prevent or reduce its spread. This term also refers to actions taken during an outbreak to reduce losses, whether in lives or resources, to shorten the duration of an outbreak or to provide resources needed to perform any of the actions included in this phase [138]. The key point is that these actions are taken during an outbreak. Examples include contact tracing, donation collection and allocation, research and vaccination against the pathogen causing the outbreak.

The transition between the response and the recovery phases is different in IDOs than in other disasters. This transition is gradual and happens over time. This was highlighted by [30], who argued that one of the challenges faced when managing IDOs is determining the end of the response phase, as this can be unclear and fuzzy. This fuzzy end results in overlapping response and recovery phases, where tasks that fall under both of these phases need to be conducted simultaneously [30]. These tasks include restoring the healthcare services to pre-IDO states while being able to provide care to those infected with the pathogen. Furthermore, the uncertainties posed by IDOs can make identifying the nature of the drop in infectious case numbers hard. This drop could be the end of the IDO, or simply a gap between two infectious waves [146]. This means that response measures may need to be reinstated very quickly. To highlight those challenges faced during this period of the IDO management process, we added a phase called de-escalation and restoration to the PMC.

Finally, the DMC's *recovery* phase was added to the PMC framework. However, this study refers to recovery as actions taken after suppressing or eliminating an outbreak to return society and services to pre-outbreak conditions [147]. The key point here is the post-outbreak timing. These actions include long-term recovery efforts that span different domains such as the political, economic, social, health and infrastructure domains [30].

3.2.2 IDO management challenges and barriers

Examining the literature addressing IDOs management revealed different types of challenges and barriers faced at different levels of the management process. These challenges were divided into two major categories, which are defined and presented in sections 3.2.2.1

IDO management barriers and 3.2.2.2 Tool-related challenges. The first of these categories introduces IDO management barriers. These are barriers that arise due to the nature of the IDO, or how stakeholders perceive it. Barriers are faced throughout the PMC, and they limit IDO management. The second category includes tool-related challenges and limitations. These are tool-specific. Examples include data-related case detection and identification (CDI) challenges.

3.2.2.1 IDO management barriers

The literature addressing IDO management reveals common barriers encountered at all phases. These barriers arise mainly due to the nature of the IDO problem and its effects on the management process. Barriers can be grouped under four distinct categories: (1) knowledge, (2) organisational, (3) political and (3) ethical barriers.

3.2.2.1.1 Knowledge barriers

The uncertainties shrouding IDOs impede managing this type of disaster. Uncertainties stem from the nature of the problem, and they are magnified by the limitations to data collection tools [148]. The knowledge barriers discussed in this section refer to attributes of the problem itself, which makes obtaining the knowledge needed for IDO management hard.

The starting point for these uncertainties is the pathogen itself [149]. The high number and diversity of pathogens that could cause the next epidemic is a massive challenge. It is estimated that around 1.7 million unknown pathogens exist. Up to 850,000 of these could cause the next EIDO [68, 69]. The differences between those pathogens further complicate things. Pathogens vary widely in severity, transmission routes, symptoms, infectivity levels, host susceptibility and survivability, among many other factors [23, 24, 150].

Management challenges caused by the high number and diversity of pathogens can be magnified by pathogens' evolutionary responses. Different pathogens respond to evolutionary pressures in varying ways, resulting in constant mutations and a fluid epidemiological landscape. This problem is further complicated because this pressure can result from diverse factors, some of which are not fully understood [97]. Examples include the host's immune system [68], host behavioural changes [49] and other environmental factors [97, 151, 152].

Pathogens' evolutionary responses and host mobility can result in significant management challenges, which make determining IDO duration challenging. The duration of most other disasters can be estimated in advance, and plausible estimates of durations are finite [20]. However, IDOs can last from months to years [31], which introduces significant challenges to the management process. Pathogen mutation and host mobility can also make determining the geographical coverage of IDOs challenging [69]. Dynamic geographical coverage can result in significant complications [20, 28, 30, 69].

These variables limit human ability to derive the knowledge needed for preparedness. The high diversity of pathogens limits managers' ability to determine the types and qualities of resources needed to manage an IDO [10, 37]. Pathogen diversity also makes devising adequate and comprehensive plans difficult [153]. During the COVID-19 pandemic, different countries tried to deploy preparedness plans crafted for a flu pandemic, such as the 2009 H1N1. However, the plans' effectiveness was undermined by the differences between flu viruses and severe acute respiratory syndrome coronavirus-2 (SARS-COV-2) [23, 24].

Furthermore, unknown coverage and duration can make identifying response stakeholders difficult. Constantly expanding and shrinking outbreak areas mean the stakeholder networks continuously change. Networks can evolve quickly from a national to an international network [141], complicating coordination plans.

These issues can also reduce the ability to obtain the knowledge needed for spark prevention and fending. The high number of pathogens, and their diversity and mutability, can mean symptoms overlap with those arising from other diseases, thus affecting early detection efforts. This issue is especially challenging when symptoms are shared between endemic and emergent diseases [10, 154]. This argument is supported by [155], who indicated that COVID-19 emergence in the winter made it hard to detect as it was harder to detect due to other winter-season, endemic pathogens. Detection was also hindered by the overlapping of COVID-19 symptoms with other non-seasonal diseases, such as dengue fever [156] and malaria [157].

These knowledge-based limitations can also hinder response efforts [158]. Constant pathogen mutations and reactions to changes in host immunity and behaviour make determining optimal public health response challenging, if not impossible [149]. Evaluating interventions' suitability and effectiveness is challenging because identifying IDO spread and severity indicators is very difficult. There is also a feedback loop between pathogen and response interventions: response interventions influence the pathogen's mutations and change its evolutionary course [30, 38, 72, 141]. Response interventions also result in population behavioural changes [149, 159, 160], introducing further evolutionary pressure and a cycle of actions and reactions [72].

These barriers make de-escalation and restoration of healthcare services after each infectious wave in an IDO hard. Evolutionary pressures on pathogens increase the closer IDO managers get to eradicating the pathogen, leading to increased volatility, mutation probability and uncertainty [39]. Furthermore, knowledge limitations make it harder to determine if a drop in infection rates signals the end of an infectious wave or the end of the IDO itself [161]. This argument has been supported by [161], who argued that it is practically impossible to predict the exact turning points of an IDO.

Knowledge limitations can also affect determination and quantification of an IDOs' aftermath, thus complicating recovery efforts. The aftermath of an IDO is complex, and some factors remain hidden [30]. Impacts and aftermaths of IDOs differ between countries, which means the transfer of recovery experiences between countries may be ineffective [20, 141].

Clearly, each IDO is a unique event, and uniqueness reduces the effectiveness of historical data and models based on previous epidemics [49]. Each new epidemic introduces a new "cold-start" problem [162]. At the start of an epidemic, the data available are not sufficient to produce accurate models to guide the response [42, 43, 47, 50, 88]. Models only become accurate as the IDO progresses and more data are collected. The cold-start problem is also revived, to a certain extent, every time the pathogen causing the epidemic mutates and changes its behaviour.

The elusive nature of the problem at hand and the management difficulties that arise due to uncertainties surrounding IDO create the most significant management barrier. In addition, knowledge barriers are a main cause of other barriers and/or magnify other barriers, thus reducing IDO managers’ ability to navigate them.

3.2.2.1.2 Organisational barriers

Knowledge is necessary for disaster management processes; however, knowledge alone is insufficient for optimal management [163]. The scope and reach of IDOs expose other organisational barriers that impact management. This vast scope, combined with inadequate organisational coordination and structures, results in the diffusion of management responsibilities [164]. For example, organisational challenges were identified before the COVID-19 pandemic [10], and inadequate management of this IDO, plus its severity, brought these to the forefront [84, 164, 165].

Effective preparedness requires close cooperation and coordination between different systems and organisations [93] including healthcare, social care, housing, employment and defence [40, 166]. The absence of a central department responsible for IDO preparedness, the high number of stakeholders and the difficulty in coordinating between them are all factors that can exacerbate the diffusion of preparedness responsibilities [10, 84, 167]. A study by [7] indicated that some governments and institutions view IDOs as human health issues, which the healthcare sector should address alone. However, healthcare sectors are more concerned with immediate health issues, resulting in preparedness being ignored by all actors.

This organisational fragmentation can also be seen within the health domain. EIDOs start as animal health issues in the veterinary domain, and then, once transmitted to humans, pathogens migrate to human health domains. The migration of the problem's responsibility and the pathogen itself highlights the need for an overarching organisation or an organisational structure to bridge the gap between sectors [69, 168].

Management barriers also arise when the flexibility and scalability of a management structure cannot keep up with the growth of an IDO. IDOs start as "regular" health issues, but once they cross a certain threshold and become epidemics, they migrate to the disaster management domain. IDOs also start at a regional level, but once they become epidemics and then, pandemics, their management is usually transferred to higher-level organisations. This can result in clashing response policies within the same country, as was the case in the USA when preparedness plans at state and federal levels were inconsistent, resulting in an unsatisfactory COVID-19 response [166, 169].

These organisational barriers can be seen even within a single system. Studies have highlighted the confusion caused by unclear organisational structures within a single HCS or organisation; for example, [170, 171] reported that this resulted in mixed messages to HCWs, which in some cases limited the ability of the HCS to provide healthcare [165]. Furthermore, [172] stated that unclear organisational structures resulted in multiple case definitions for COVID-19 applied by different healthcare facilities in one country.

It should be noted that there is a two-way relationship between knowledge and organisational barriers. Organisational barriers can magnify knowledge-related barriers and reduce the effectiveness of possible solutions, such as surveillance systems. An example of this is the diffusion of surveillance systems control where different organisations control and collect epidemiological data without clear coordination and data sharing plans [85, 173]. The alleviation of knowledge barriers can also reduce the impact of those organisational barriers. For example, accurate forecasts of an outbreak's spread can help determine a suitable organisational structure or identify stakeholders needed to manage the situation.

3.2.2.1.3 Political barriers

The scale of IDOs makes them a public health issue requiring public policy interventions. This need introduces political barriers, factors and considerations that can hinder or slow the management process [141, 174]. For example, the delayed returns of investments in preparedness can weaken the political will to carry out preparedness actions [7]. This problem does not only originate at the political level; in the eyes of the general population, preparedness' delayed returns make dedicated resources seem as waste compared to more immediate needs. This makes addressing preparedness deficiencies difficult, even if policymakers are motivated [141].

Political consideration can result in different preparedness and response policies within the same country, too. This was the case in countries such as Australia and the USA, where different states responded differently to the COVID-19 pandemic [149]. These same factors can also result in preparedness and response capabilities focused on certain areas to achieve short-term political gains, which was reported during the Ebola epidemic in Liberia [175]. The potentials of wide geographical coverage and the long durations of IDOs can make the political orientation of the population an important factor in IDO management as well. The general public's political orientation has been reported to affect compliance with response measures in some countries [49, 176].

IDOs can turn into global pandemics very quickly. National-level institutions usually manage these pandemics. This mismatch between the scope of the threat and the tool can result in inconsistent and conflicting global responses, leading to a prolonged pandemic [177]. Furthermore, creating international cooperation can be hindered by political considerations. [178] highlighted the difficulties in creating international cooperation, e.g., during the COVID-19 pandemic. According to the study, creating a cooperative network involves participating countries in pooling sovereignty or giving away certain aspects of political independence, which reduces their willingness to carry out preparedness tasks. Economics and trade considerations also influence attitudes towards international cooperation [169].

Political factors can also limit global research cooperation [178], as witnessed during the COVID-19 pandemic. At the initial stages, researchers worldwide cooperated despite political strains between their countries. Later on, however, cooperation levels were affected by unfounded accusations about the origin of the virus [178].

3.2.2.1.4 Ethical barriers

The nature of IDOs also presents perplexing ethical dilemmas that act as barriers hindering IDO management [179, 180]. According to [179], these barriers have been faced during past IDOs, and their intensity corresponds with the severity of an IDO. Recent studies published during the COVID-19 pandemic have highlighted the need to find ways to navigate those barriers [180-182], but such challenges are become harder to navigate as an IDO progresses and escalates.

IDO management involves balancing the interests and ethical views of members of society and other stakeholders [181]. This process involves finding trade-offs based on adequate justifications to balance delicate and complex subjects such as human rights, privacy, liberties, equality and the public good [181-183]. Failures to find suitable trade-offs may result in civil unrest, further worsening the situation [10].

The difficulties in adequately addressing ethical burdens are magnified by IDO management practices based on the generic view of disasters, as these are too broad to address IDO-specific ethical challenges [179]. Furthermore, current IDOs management plans lack systematic ethical reasoning methods that allow their transferability to fit different IDOs [179], highlighting the need for an adaptable, yet clear, ethical framework for IDO management [179, 181]. Management can be hindered because some of the main intervention tools available face ethical controversies and require special ethical consideration when employed. These include surveillance [153], contact tracing [179, 184], resource allocation [88], quarantine [88] and prioritisation of treatment, or rationing of resources [48, 181].

Unfortunately, such dilemmas are not only faced at the management level. Rather, they are faced at the individual level, affecting humans' performance during IDOs. HCWs, for example, must choose between going to work to serve the community while facing infection risks that could also affect their loved ones, or they must abstain from work [88, 164]. Members of the public have to weigh up whether to adhere to certain interventions at the cost of certain liberties. For example, participation in contact tracing can conflict with their rights to privacy [49].

Failure of the scientific community to navigate ethical dilemmas can affect research quality, e.g., researchers may find themselves forced to choose between speed and quality due to time pressures produced by IDOs [185]. Or, they may need to choose between sharing data to aid response efforts vs. guarding data to accomplish academic goals [46].

Knowledge barriers play a major role in those ethical dilemmas, and the uncertainties an IDO poses increase the frequency and intensity of ethical challenges [179]. Furthermore, different infectious diseases raise different ethical dilemmas and require different ethics guidelines [179]. Thus, the dynamic nature of IDOs can result in fluid and complex ethical challenges [182], which affect the transferability of response plans between countries [179].

Clearly, four major barriers — knowledge, organisational, political and ethical — affect the entire disaster management process. IDO management and certain actions it involves can be viewed as a four-task cycle. This cycle consists of identifying, quantifying, implementing and evaluating actions and resources. Knowledge barriers hinder the identification and quantification of actions or resources needed. Ethical concerns hinder the identification and quantification of actions and resources because of the need to balance different groups' interests. Political and organisational barriers hinder the implementation of the actions identified. Finally, knowledge and organisational barriers can make evaluating actions and resources difficult. The effect of these barriers is summarised in Figure 0-5 The effects of the IDO management barriers on the management tasks.

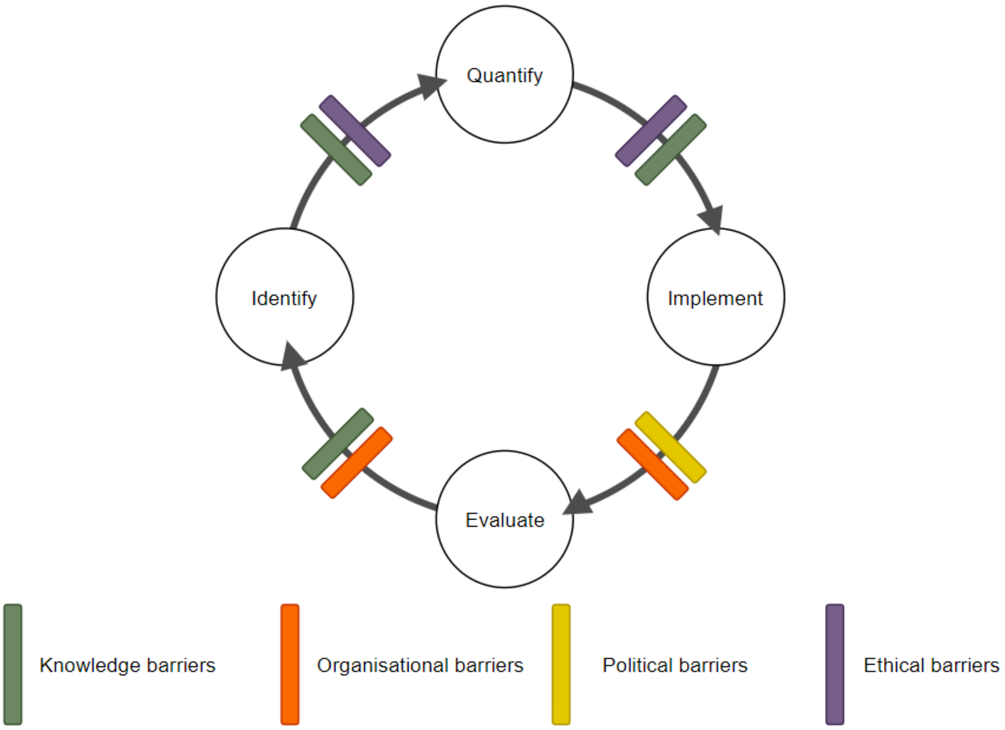

Figure 0-5 The effects of the IDO management barriers on the management tasks.

Note. Figure 0-5 is the author's original work.

3.2.2.2 Tool-related challenges

A significant obstacle faced at the early stages of this study was finding a suitable definition for the term "challenge". According to the Cambridge Dictionary, a challenge is "something needing great mental or physical effort to be done successfully" [186]. Such a definition is too broad and vague, and a more specific definition of a "challenge" based on IDO management was needed. The ideal definition would provide a general idea of tools and methods used in IDO management. Unfortunately, no suitable definitions were found, and attention was directed to disaster management definitions instead. However, none of these captured the management process in a manner suitable for our purposes. Some sources defined disaster management in terms of its aims, but without mentioning the tools used [2, 187, 188], while others mentioned only some of the tools [189, 190].

To resolve these limitations, the main ideas included in the available definitions were combined to produce a single definition of "challenge" fit for this study. This study views *disaster management* as a process that involves utilising systems and processes supported by specific resources to reduce the potential harm and damage from current or future disasters. Based on this interpretation of disaster management, the term challenge can be defined as an obstacle that may undermine the effectiveness of the resources, processes and systems involved in disaster management. This definition highlights three sets of possible challenges: (1) those affecting resources, (2) those affecting processes, and (2) challenges impacting systems (Figure 0-6).

Resource-related challenges can be defined as events or factors that reduce a resource's quality or availability. An example of a challenge that reduces resource quality is cold supply-chain limitations affecting vaccine quality due to refrigeration failures. An example of a challenge that reduces the availability of resources is the high quarantine rate, which could reduce the number of HCWs available.

Process-related challenges can be defined as events and factors that worsen the outcomes of a process, prevent employing it or hinder it. Such challenges include low-accuracy pathogen testing, which reduces the effectiveness of quarantines. A challenge that prevents carrying out digital contact tracing is the population's low technology adoption rate. Furthermore, process-related failures like a lack of trained personnel and supply-chain glitches slow or complicate vaccination campaigns.

Systems can be defined as elements connected via relationships to form a whole functioning entity; the elements can affect parts of the system and are affected by it [191]. Systems used in IDO management can be viewed as a composition of elements, e.g., resources and processes. Therefore, this study defines systems-related challenges as the disturbance of relationships between a system's elements. Inadequate coordination and governance of system components could result in severance or disruption of system relationships, which could deprive components of the services provided by other components.

Disruptions to one part of a system result in ripple effects impacting the entire IDO management process [40]. A concrete example of systems challenges at this level is the early warning system (EWS). The EWS consists of surveillance sub-systems working together to produce an up-to-date epidemiological view that includes pathogens, animals and humans [192]. The isolation of one of those sub-systems can result in a blind spot, hindering the early detection of IDOs.

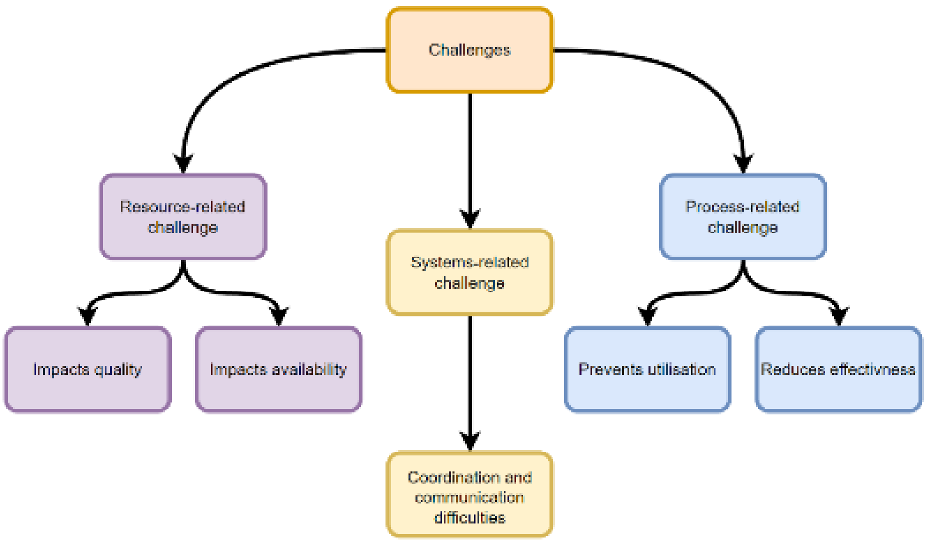

Figure 0-6 Types of tool related challenges.

Note. Figure 0-6 is the author's original work.

3.2.2.3 Data-related challenges

Data is one of the most important resources for IDO management. Data applications mentioned in related studies were numerous, including forecasting [43, 193], modelling [42, 50], risk assessment [194, 195], identification of vulnerable populations [24, 193], public communications [20, 23, 196], policy-making [20, 23, 37, 197], case management [23, 24, 37, 196], resource allocation, treatment prioritisation [182], research [20] and infectious waste management [137, 198-202]. The cruciality of data to IDO management means that no effort should be spared to bridge the knowledge gap and collect as much data as possible [203]. However, many studies cited data-related challenges in past pandemics [43, 45, 46, 204], and in the current COVID-19 pandemic [23, 49, 156, 165, 166].

This section presents crucial data-related challenges identified in the literature and the associated challenges of collecting and utilising data. This section starts by discussing the data needed and their attributes. This is followed by a discussion of modelling and forecasting challenges. Finally, the challenges faced when collecting and processing data for infectious CDI are discussed.

3.2.2.3.1 Data quality and sharing

This section is dedicated to discussing challenges related to data quality and sharing needs. The section lists key data items needed for IDO management as identified in the literature, and then the desired quality attributes of the data are presented. A discussion of data-sharing challenges follows.

Many studies have mentioned the need for specific data. These data items can be classified into primary and derived data. Primary data are collected directly by observation. In contrast, derived data refers to data resulting from the combination of different primary data items. Primary data can be collected by directly observing the pathogen, host or the environment they exist in [197]. Table 0-1 illustrates some of the pathogen-related primary data mentioned in the literature, such as genomic sequencing data, which theoretically reveal the identity, drug resistance and relatedness of a specific pathogen to other pathogens [205].

Table 0-1 Literature describing pathogen profiles.

Topic	**Citations**
Genomic sequencing	[47, 205-207]
Transmission dynamics and risk factors	[43, 47, 134, 168, 197]
Severity	[46, 153]

Table 0-2 displays host-related primary data mentioned in the literature, which can be divided into health, behavioural, mobility, host characteristics, and potential transmission methods data.

Table 0-2. Host-related primary data and supporting citations.

Topic	Citations
Morbidity (case count, symptoms)	[42, 43, 47, 192, 203, 208-210]
Mortality	[42, 68, 166, 192, 203, 208]
Details of diagnoses (date, time, symptoms)	[211]
Health records	[37]
Immunisation coverage (including livestock)	[38, 43]
Population behavioural changes	[49, 72]
Population mobility (including international travel, contact tracing)	[37, 43, 146, 203, 211-213]
Vector movement	[43]
Animal movement	[72, 134, 214]
Demographic data	[42, 43, 72, 156, 192, 193, 208]
Nutritional data	[192]
Animal products tracking data	[134]

Table 0-3 shows examples of environment-related primary data mentioned in the literature. The word environment here refers to climate and circumstances affecting the IDO management. An example of such data is IDO management resources, e.g., healthcare metrics describing the state of an HCS.

Table 0-3. Primary environmental data and supporting citations.

Topic	Citations
Climate	[43, 45, 72, 97, 156, 197]
Resources available/healthcare capacity	[23, 42, 43, 196, 213]
Food availability	[208]

Combining primary data allows for deriving data crucial to IDO management. Pathogen-related primary data can be used to derive data such as pathogen risk levels and geographical distribution [197], among other items. These data, in combination with host-related data, can help identify vulnerable hosts, whether animal or human [24, 193].

Data required for IDO management must have certain quality attributes to maximise effectiveness. The literature is full of calls to improve various aspects of the data collected. The most frequently mentioned desired attributes are listed in Table 0-4. It should be noted that different terms describing the same thing were used in the literature. For example, the term “timeliness” as used in Table 0-4 covers references in the literature that used the terms “timely”, “rapid”, “real-time”, and “continually updated data”.

Table 0-4. Frequently mentioned, most-desired IDO data attributes.

Attribute	No. mentions	Citations
Timeliness (timely, rapid, real-time, continually updated)	26	[7, 10, 33, 34, 39, 42, 43, 46, 47, 49, 50, 72, 146, 156, 163, 172, 183, 197, 205, 213, 215-220]

Attribute	No. mentions	Citations
Accuracy (accurate, reliability of data, consistency)	19	[7, 10, 24, 33, 39, 42, 43, 45, 48, 72, 87, 88, 153, 166, 172, 193, 196, 202, 221]
Completeness	9	[7, 24, 33, 39, 43, 197, 216, 219, 221]
Standardisation (integrability, aggregability)	9	[33, 43, 49, 165, 166, 193, 205, 214, 220]
Unbiased (balanced)	5	[10, 49, 72, 163, 221]
Granular (detailed)	5	[43-45, 148, 222]

Abbreviation. No., number of.

Timeliness, which refers to data collection and processing speed, was the most mentioned attribute. This quality attribute is essential in overcoming knowledge barriers because IDOs are unpredictable and evolve quickly [49, 163]. A study by [205] argued that the more timely the data, the higher the chance of outbreak containment. Data timeliness is a crucial factor for risk reduction, too [156]. Timely data are needed to devise models crucial to policymaking [42, 49]. Supply-chain disruptions can be managed and alleviated if timely supply-and-demand data are available [217]. Timely data can also increase HCSs' abilities to respond to IDOs [45] and to support updated treatment protocols [196].

The main reasons behind failures to collect and process data in a timely manner are collection systems [216], ageing infrastructure [85], the time lag introduced by some processes [216] and the costs of carrying out data collection processes [72, 85]. Many studies have called for the incorporation of technology to overcome these challenges [43, 46, 156, 183, 213, 215]

Low data accuracy is a key reason that IDO management delivers poor outcomes. Accuracy in this context means describing the phenomena observed and being free from errors if the phenomena are describable; otherwise, the issue is a knowledge barrier. Data accuracy was cited as a reason behind the poor planning and response to COVID-19 across different countries [39]. This included developed countries, e.g., the USA, where the low accuracy of data forced policymakers to rely on healthcare billing data for guidance [166].

In theory, epidemiological data should become more accurate as an IDO progresses because the number of cases increases, and the higher volume of data results in a reduced number of errors [24, 42, 88, 162]. However, a study by [216] argued that this is not always the case and that COVID-19 was an example. After a certain point, the high workload of HCWs results in more errors and reduces attention to reporting duties as the focus is on managing cases [24].

A high workload can also result in data incompleteness [24], which was is one of the issues affecting IDO management [216]. "Completeness" refers to collecting all data items specified in the data collection guidelines. Calls to address data incompleteness have been repeated during past pandemics such as Ebola [197], and again recently during the COVID-19 pandemic [33, 39, 221].

Data standardisation is another attribute highlighted in the literature. "Standardisation" in this context means collecting the same data items and the uniform representation of collected data. Many studies have highlighted the importance of data standardisation and the potential impact of this quality attribute on data processing and sharing [33, 214]. Other studies have highlighted the advantages of data integration and aggregation at the national and international levels, which is facilitated by standardisation [43, 205]. Failure to ensure data standardisation often limits the potential to guide and unify response policies across regions or countries [33, 166, 220]. This failure also prevents comparing outcomes of interventions implemented in different regions and countries, which curtails the ability to improve response measures [43]. In addition, data without standardisation magnifies organisational barriers by creating knowledge silos [214].

The need for balanced data is another important attribute; "balance" in this context refers to the equal representation of various input samples. Examples specific to IDOs include datasets with equal numbers of positive and negative test cases, or even equal representation of different countries or regions [49, 72, 223]. Unbalanced data results in poor training datasets that undermine machine learning (ML) algorithms [221]. Unbalanced data also result in misleading and biased epidemiological models [49].

Data granularity is also an important quality attribute. "Granularity" refers to the level of detail, which can also be seen as the number of entity attributes included in the dataset, for example, the address of a positive case of COVID-19. If the address of a positive case is not collected, the resulting dataset can only describe the situation for the whole country, without regard to specific regions [43, 44]. If the city name, or even a suburb, of the positive case is collected, this information provides a more detailed view of the epidemiological situation in those areas. Granular data can be used to devise accurate vector maps to identify high-risk areas precisely [45], accurate epidemiological models [43] and consequently, targeted policy and intervention implementations [148, 224].

The quantity of the data itself must be adequate. "Quantity" refers to coverage, e.g., covering enough cases [72]. This is important because, without data representing enough cases, there is a higher chance that the conclusions formed about the epidemiological situation at a certain point in time will be invalid. "Coverage" refers to a sufficient period of time to enable the identification of epidemiological trends that underpin forecasting of disease spread.

Sharing is another data-related challenge frequently highlighted in the literature [23, 43, 47, 49, 69, 195, 205, 215, 218, 223]. Adequate data sharing saves lives by facilitating coordination and reducing the impacts of organisational barriers [93, 205]. Data sharing is also a crucial component of surveillance systems — one of the main support tools for IDO management [69]. Furthermore, research supporting response efforts is highly dependent on prompt data sharing [205], and many studies have highlighted the need for sharing processes to be timely and reliable [23, 43, 47, 49, 69, 195, 205, 215, 218, 223]. Fast data sharing is crucial is IDOs as detection and response speed are among the main determinants of successful IDO management [225].

Data sharing challenges can be divided into the technical and non-technical. Technical challenges relate to infrastructure [7, 205]. Specific data collection methods such as manual and paper-based data collection systems are also some of the technical challenges that render data sharing difficult [10]. Non-technical issues relate to laws, privacy and data security [33, 205]. Some of the issues discussed in sections 3.2.2.1.3 Political barriersand 3.2.2.1.4

Ethical barriers can lead to reluctance to share data. The existence of data sharing challenges at a national level can result in these difficulties being reflected and magnified at an international level [205]. Other non-technical challenges spring from the desire to conserve a competitive advantage, whether in research or economic goals. The desire to preserve competitive advantage can lead countries and companies hoarding disease-related data, such as genomic sequencing data [7].

3.2.2.3.2 Forecasting and modelling

COVID-19 has brought forecasting models to the forefront of IDO management [226]. Models assist in producing crucial forecasts underpinning preparedness and resilience-building [141]. Accurate modelling of pathogen evolution in wildlife provides a way to prevent the emergence and re-emergence of diseases [141, 227]. In addition, models support and guide response interventions and policies [161], e.g., forecasting virus spread [31] or the allocation of healthcare resources, such as PPE [31, 166, 228], and treatment prioritisation [193]. Furthermore, models allow humans to evaluate the results of interventions such as vaccination campaigns, lockdowns, physical distancing and facemask mandates [31, 37, 227]. Models can also be used to determine thresholds for actions such as the number of cases when a lockdown is requires [31].

Some studies have discussed specific fields involved in IDO management that require improved models. For example, [229] argued that water-based epidemiological modelling must be improved, and [91] argued that governments' and societies' actions and reactions must be modelled. The same study called for creating and improving models of HCSs that can anticipate and evaluate demand for services. The same study advocated for modelling of risk perception and public compliance with interventions. Another study by [38] argued that different spark prevention methods should be modelled.

Unfortunately, knowledge barriers reduce modelling accuracy. Epidemiological models are a simplification of a complex phenomenon that results in unavoidable divergences between both [146]. The complexity of IDOs also makes it hard to model all of their crucial aspects. For example, [38] argued that the cost-effectiveness of disease eradication campaigns is hard to model fully because campaigns have secondary and intangible benefits. Another study by [226] stated that forecasting healthcare capacity and peak demand is challenging as it is difficult to quantify the effects of response policies, such as physical distancing, on overall IDO spread.

In addition, constant changes in the epidemiological situation also introduce modelling challenges [42, 47]; for example, [230] highlighted the need to tune models as new data are collected. The challenges posed by unknown pathogens, which make models unsuitable to guide response efforts at the beginning of an EIDO, also act as barriers [230]. Furthermore, models needed for EID responses often take up to several weeks to be ML trained [227], which can negatively affect the IDO management efforts. Organisational barriers can also affect model creation and validation because the data and knowledge needed for forecasting models come from varied sources, e.g., biology, epidemiology, HCSs and demographics [193].

Different models can result in different insights with varying degrees of accuracy. According to [50], certain studies have attempted to test the accuracy of forecasting tools; results showed that some of the most cited tools were highly inaccurate. In fact, [226] highlighted gross variations in modelling results used to allocate resources during the COVID-19 pandemic [226], such as estimates produced by three different models, one of which was used by the World Health Organization (WHO). Certainly, models rely heavily on data, and failure to attain quality leads to inaccurate models [43, 48, 146, 166, 221, 227]. Data limitations causing inaccurate models that are most frequently mentioned in the literature include inadequate reporting [88, 227], inaccurate case definitions [43] and data timeliness [43, 88, 227].

The need for balanced and suitable data to create valid models was also highlighted in the literature. According to [141] and [49], most models are based on data collected from developing countries which makes these models unsuitable for guiding the response in developing countries [49, 141]. This highlights the need for country-based models capable of generating tailored and valid IDO management insights. This, however, does not mean that each country needs to work on its models in isolation from other countries, which would waste research effort. Instead, the solution is to find a balanced approach and identify generalisable findings and models [141]. There is also a need to determine conditions that can affect the validity of model transfer and applications between different countries [141].

Multiple studies have cited data granularity and standardisation as affecting models' accuracy [45]. National-level models aggregate data from different regions with different transmission dynamics, leading to inaccurate modelling results at the regional level [88, 222]. In fact, [96] argued that many models are suitable only for state-level responses and do not account for urban–rural disparities because the data used to generate them is not granular enough.

Furthermore, different modelling techniques require varying amounts of data to produce adequate results [146]. "Amount" here refers to both coverage of a suitable timeframe and sample scale. A study by [38] argued that the data must be collected for a sufficient time to identify trends. Also, [43] stated that data should cover a sufficient number of cases for insights to be valid.

The models' inaccuracies discussed above show that relying on a single model may be risky [166]. One of the solutions suggested to deal with this is using more than one model [226], but this introduces a new challenge related to averaging and comparing models results. A study by [226] highlighted the need for improvements and standardisation in this field.

Improving and expanding the modelling tools available is crucial for IDO management [38]. However, many challenges make this a difficult task. The first is the lack of standard models evaluation methods [49]. A study by [231] also argued that animal epidemiological models, in particular, suffer from the issue. In addition, validation and evaluation processes require suitable data. A study by [50] argued that model validation using data collected under circumstances different from those the training data was collected under could result in misleading results. Furthermore, model validation requires historical data, which means surveillance activities must be ongoing, and not just once outbreaks are detected [43].

3.2.2.3.3 Case detection and identification

Data collected as a part of the CDI process can support numerous IDO phases. Such data enhance preparedness and resilience-building efforts [9, 72, 195, 230], and are the primary resource supporting spark prevention and fending [10, 44, 50, 72, 156, 197]. The success of the response phase and restoration of the post-response capabilities also depend on the data [23, 193]. Finally, accurate and timely data significantly aid the de-escalation and recovery phases [84].

The two terms “case detection” and “identification” were used synonymously in most of the literature reviewed to refer to activities conducted to discover infectious cases. This study, however, distinguishes between those terms to minimise confusion when discussing surveillance activities before and after outbreak detection. Herein, "case detection" refers to discovering suspected infectious cases that could signal an IDO before an outbreak is spotted. Detection occurs during the spark prevention or fending phases, which is the main aim of any EWS. In contrast, “case identification” refers to spotting and confirming infectious cases during a known epidemic or pandemic, which means case identification also occurs during the response, de-escalation and recovery phases.

Various methods and tools are used to collect the data needed for CDI. The classification of these tools is a challenging process, with no standard method. Studies have presented and organised these tools differently [39, 43, 72, 207], but this study classifies CDI tools into three main categories: (1) surveillance systems, (2) testing methods and (3) contact tracing (Figure 0-7), This classification schema was selected to allow grouping all CDI methods in one section in a clear manner that minimises confusion.

Each of these CDI methods can be deployed as a human resource or a digitised system. Testing can be done in laboratories or using point-of-care (PoC) testing tools, which are intelligent devices that return a quick reading based on a sample, without needing a laboratory or a technician. Surveillance systems and contact tracing can also be performed using digital systems and sensors, or by using humans, also known as (aka) traditional methods.

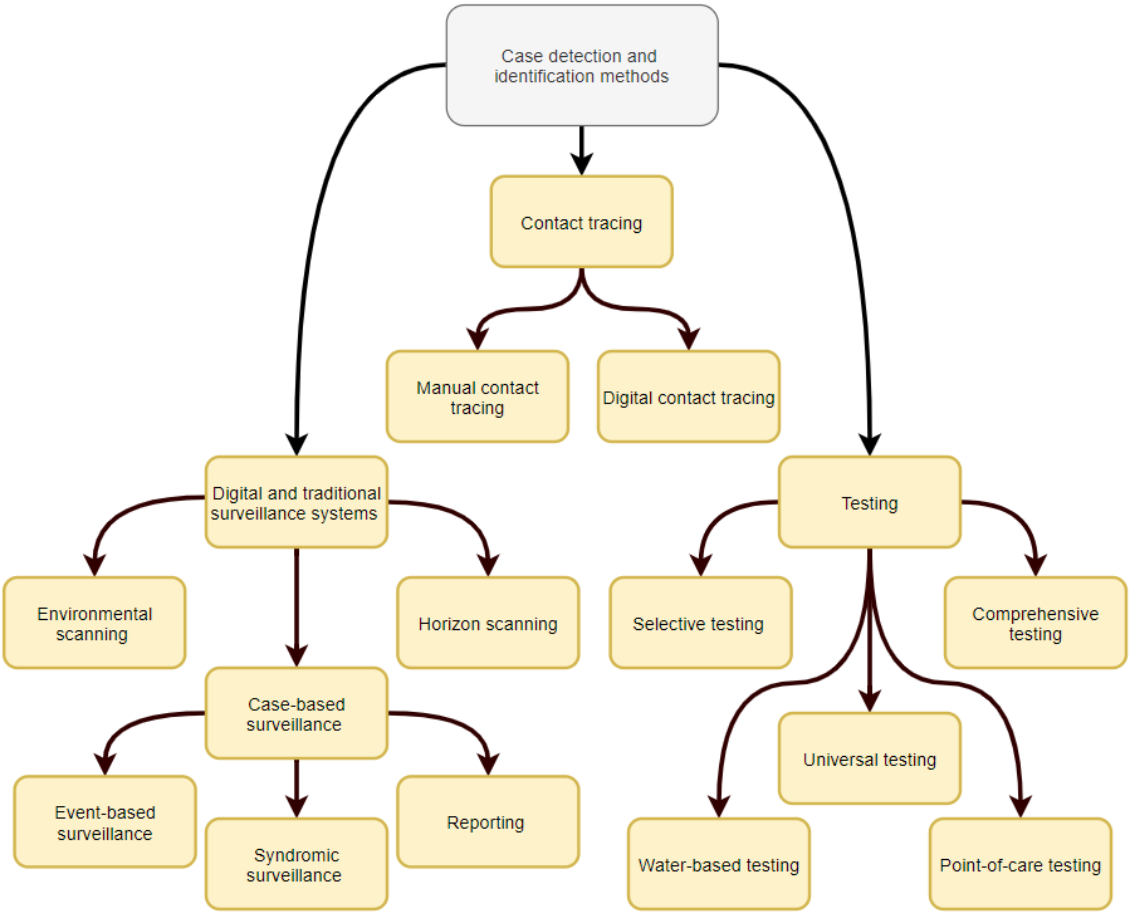

Figure 0-7 Case detection and identification methods.

Note. Figure 0-7 is the author's original work.

3.2.2.3.4 *Surveillance systems*

The importance of surveillance systems in IDO management cannot be overstated as the data collected can provide support throughout the IDO. A recent study by [41] argued that accurate and timely surveillance activities were enough to stop the spread of COVID-19 in densely populated Asian countries. Surveillance data supports processes including risk assessment and prioritisation [72] to predict outbreaks [87], create and improve models [50, 72, 141, 193], identify vulnerable populations [31, 193], prioritise access to treatment and vaccines [182, 193] and allocate resources on national and international levels [31, 43, 72]. Surveillance systems are the heart of EWSs [87, 165, 193, 232] (see Section 3.3.3.1.3, "Spark fending", for more details). In addition, these systems help practitioners identify suitable non-pharmaceutical interventions (NPIs) and evaluate their outcome [23, 49, 212, 216]. Pharmaceutical interventions (PIs), such as vaccines and optimal treatment methods, can also be enhanced by data generated from surveillance systems [193].

More than one definition of epidemiological surveillance can be found in the literature; however, these definitions share a few concepts [10, 78, 153, 233]. By combining the concepts, we can define surveillance as the continuous collection, sharing and analysis of data to identify major health-related events affecting humans, livestock or wildlife in a specific geographical area. Surveillance systems target host, pathogen and/or environmental data [9, 234], and they consist of collection nodes, communication methods and analysis systems. Data collection nodes range from simple, paper-based recording systems to advanced sensors that directly target data sources [10, 45, 214]. Communication systems also range widely, from roads or telephone lines to 5G wireless communications [10].

Data collection nodes are considered the most important component as they influence the accuracy, completeness and granularity of data [216]. Collection nodes are either humans, or digital sensors. The involvement of the human factor introduces various limitations and can compromise data quality [72], but digital systems are less dependent on human resources and more reliant on sensors, which cater for the automation of surveillance [78]. Automated systems collect data from digital media [71] or directly, by monitoring hosts and environments with different sensors [39]. Both manual and digital systems can perform all types of surveillance activities, so they can be classified based on method, type of data collected, communication method, or data usage. This study divides systems according to the data they collect. Using this method, systems can be classified as (1) environmental scanning, (2) horizon scanning, (3) case-based as discussed in Sections 3.2.2.3.4.1–3.2.2.3.4.4.

3.2.2.3.4.1 Environmental scanning. Environmental scanning involves collecting data from sources that yield social, demographic, behavioural, technological and economic data not directly related to health or epidemiology, in order to predict or identify long-term epidemiological risks [72]. After being polled and analysed, data are combined with expert opinions to gain insights on plausible future scenarios. Data are also used to produce causal analyses to facilitate long-term strategic plans to guide preparedness, resilience, spark prevention and fending [72]. The identification of factors that facilitate the emergence and spread of infectious diseases and potential hosts' vulnerabilities can also be facilitated by environmental scanning, which increases the accuracy of predictive models [43]. Long-term research needs are formulated using environmental scanning, too [72].

Environmental scanning, however, suffers from multiple challenges. These limitations include the inability to anticipate the emergence of specific EIDs when emergence factors are not fully understood. The information generated by environmental scanning is nonspecific, which introduces problems identifying relevant vs. non-relevant data from the large amounts collected [72]. The data's predictive value is therefore limited as it is problematic to determine accurate causality chains in advance. This means that identifying the effects of social events on pathogen spread is challenging, to say the least [50]. Another limitation is the lack of systematic methods that can be used to translate findings from environmental scanning into IDO management actions [43, 72].

3.2.2.3.4.2 Horizon scanning. Horizon scanning is more specific than environmental scanning as it targets data sources directly connected to adverse health events.

These data are not necessarily disease-specific and originate from/address the needs of large geographical areas. Data collected using horizon scanning increases the probability of early IDO detection and assists with identifying stakeholders needing support [72]. Horizon scanning data can be gleaned from IDO reports by related organisations, scientific studies and grey literature. According to [235] and [45], another source of data that can also be included under the category of horizon scanning is climate data, which can be used to predict the probability of infectious disease incursions. This data can be used to predict the spread and the breading habits of vectors carrying diseases such as mosquitos.

3.2.2.3.4.3 Case-based surveillance. Case-based surveillance includes different types such as syndromic, event-based surveillance and reporting systems. Case-based surveillance systems use different methods to collect data representing circumstances and conditions related to a host, whether human or animal. Data are analysed using different methods to produce epidemiological snapshots and trend graphs. The analysis process involves detecting an unusual data pattern or a high number of cases that meet predefined criteria.

Case-based surveillance can detect IDOs; however, detection speed is likely to be too slow to allow for epidemic prevention. A study by [236] cited an article by [237] in which the author argued that once the number of COVID-19 cases surpassed 40, the probability of failure to contain the COVID-19 pandemic was around 80%, even if 80% of the cases were traced. Although the 40-case limit is not applicable to all diseases, it shows how low the epidemic threshold can be for some pathogens. This low threshold is likely to be statistically insignificant compared to the collected dataset [211].

The accuracy of case-based surveillance depends on finding a balance between the analysis method’s sensitivity and specificity [192]. Sensitivity, or more precisely, "high sensitivity", means the ability to detect all, or most, probable cases. High sensitivity leads to increased false-positive cases, or repeated false alarms [192, 207]. "High specificity" on the other hand, means the ability to detect only true cases, and it can result in a high number of false negatives, or failure to detect an outbreak [38, 71, 192, 220]. Also, the optimal balance between sensitivity and specificity can change depending on the outbreak’s stage [38].

Case-based surveillance faces inherent delays that mean data do not reflect the current state of an IDO [211]. For example, the asymptomatic period of a COVID-19 infection means that the number of identified symptomatic cases only signals infection rates that occurred several days earlier. The same applies to the number of cases admitted to intensive care units (ICUs) as it may reflect infection rates before five days. In contrast, death counts can reflect infection rates occurring before 14 days [210, 238].

3.2.2.3.4.3.1 Syndromic surveillance. Syndromic surveillance is a subtype of case-based surveillance. This method aims to identify infectious cases by observing host symptoms without a definitive laboratory test [71], and data are collected by tracking subjects’ vital signs, or by analysing healthcare records [39]. Syndromic surveillance is a versatile method that can overcome other methods' limitations; it can be used to detect EIDs [71, 239] and to monitor humans, wildlife and livestock. Syndromic surveillance is especially useful in countries with limited laboratory infrastructure as it does not involve testing [235].

Despite its strengths, syndromic surveillance has limitations, which include its high cost [235]. Implementation costs depend on the ability to use existing hardware to collect data. For example, [39] cited [240], who experimented with using smartphones to collect voluntary data. The author stated that the cost of identifying one case of COVID-19 using this method was only 6 USD. Syndromic surveillance also suffers from inherent delays as it is dependent on the appearance of symptoms and the adequacy of data sharing methods [72]. These delays can be up to two weeks [235]. In addition to the delays, syndromic surveillance suffers from inaccuracies; systems that rely on manual data entry suffer from errors and inconsistencies in the data entered, impacting the analysis process [235]. In cases where one disease's symptoms overlap with another, this type of surveillance also produces inaccurate insights [10, 156]. Even digital syndromic surveillance systems often suffer from inaccuracies because some sensor results are unreliable, for example, thermal scanners [46, 153].

3.2.2.3.4.3.2 Event-based surveillance. Event-based surveillance, a subset of case-based surveillance, is a method used to collect unstructured data from social media, news reports, internet search histories and medication sales statistics, among others [146, 235]. Such unstructured data are analysed using different methods, including natural language processing, to look for signals of IDOs, or other health-related events [146]. As a low-cost surveillance method, event-based surveillance has the potential to detect changes in overall IDO trends. It provides real-time surveillance data, even in countries with weak HCSs, and is usable in countries with few laboratories [235].

Event-based surveillance shares similarities with syndromic surveillance, including its potential to detect EIDOs; however, it also suffers from the statistical significance problem, which means outbreak detection might come too late to prevent a full-scale epidemic. Inaccurate results are also possible depending on communication infrastructure and the rate of technology adoption by the general population. In countries with a high number of internet users, data signals may be missed due to the high data volumes. In other countries with few internet users, data analysis may lead to false positives where data volumes are low, leading to the magnification of weak data signals [235].

3.2.2.3.4.4 Reporting (Indicator-based surveillance). Many studies have referred to reporting as indicator-based surveillance [39, 43, 71, 72, 173, 192, 216, 235]. This surveillance typology involves the collection and dissemination of data gleaned from varying sources, such as healthcare records, vaccination sites, death records, helplines and surveys [39, 68, 153, 192]. Some of the indicators used can be hard to collect or verify due to the nature of IDOs. An example of these indicators is the death count: mortality data are easy to collect; however, ensuring that the data are a true reflection of deaths caused by the IDO is a challenge

[39]. Even for novel diseases, such as COVID-19, there are multiple sources of mortality data, but the actual number is hard to determine [68].

Reporting is considered the primary surveillance method in HCSs, and the data reports are used intensively in health policymaking [173]. A study by [216] argued that optimal policymaking and control of IDOs require accurate reporting at all levels. Even though, these systems come in both manual [173] or digital [39], reporting is largely depends on human resources. This dependence introduces numerous challenges, including the need to train new or existing people to perform these duties [39, 173, 216], which is difficult when shortages of human resources in this field are well-known [72, 216].

The infrastructure, or the medium used to transmit data, is another area that impacts system effectiveness [10, 72]. Different systems transmit data using different methods, ranging from roads and physical transportation to advanced computer hardware and software [216, 220]. A study by [216] highlighted the need for intensive investments in infrastructure, particularly if it is not already available country-wide. The study also indicated that existing reporting systems in most countries suffer from inadequate infrastructure and support, making improvements very difficult. The dependency of reporting on resources can be demonstrated by the fact that reporting delays are shorter in countries with higher gross domestic products (GDPs) [241], and the rarity of such systems in developing countries [223].

Reporting system efficiency is impacted by organisational barriers, too; coordination deficiencies result in delayed or incomplete reports [85]. Furthermore, the same study indicated that this is a common problem with existing systems as the planning and execution of reporting networks can be challenging when many stakeholders are involved, an argument supported by [173]. Such complicated challenges arise due to the multidisciplinary nature of the data collected by these systems, and the involvement of different sectors, e.g., animal and human health, private or public, and other stakeholders [173]. Organisational barriers can also result in reporting challenges within a single discipline; for example, fragmentation of reporting systems beleaguers animal disease reporting systems [214], a situation exacerbated by resource limitations faced by veterinary practices [242]

Timeliness and completeness of datasets are highly desirable attributes in reporting systems, and this is also, paradoxically, their main challenge [10, 24, 39, 88, 216, 219]. A study by [85] citing [243] argued that the slow speed of reporting and analysis prevents timely IDO interventions.

The current HCS workload also affects both the accuracy and completeness of the reporting process. The prevalent perception is that data are more accurate as the IDO progresses; however, during the COVID-19 pandemic, reporting accuracy and completeness dropped in several countries as the pandemic progressed due to acutes pressure on the HCS [24]. The lack of incentives to report, or underestimating the importance of accurate reporting (by reporters or patients), also affects data accuracy and completeness [85]. High workloads also result in underreporting, where some cases are not reported. Underreporting significantly impacts the analysis [216, 223]. In some cases, underreporting can be accounted for; however, if reporting variabilities are temporary and not quantified, reconciliation becomes challenging [43].

Underreporting, data inaccuracy and incompleteness arise from inadequate, unclear and outdated case definitions. Case definitions are a set of symptoms and diagnostic criteria that form the basic conditions to consider a case positive for a specific disease or pathogen [192]. HCSs and other reporting sectors use such case definitions to identify reportable cases and to ensure reporting uniformity [42, 97, 192, 214, 244]. Case definitions are based on clinical or laboratory criteria [192], and they cover different categories, such as confirmed and suspected [192]. Inadequate case definitions cause inconsistent diagnoses that affect the accuracy of reporting systems [173], in both animal [214, 245] and human HCSs [219]. In Mexico during the COVID-19 pandemic, HCWs were confronted with frequent changes to case definitions, which varied between institutions and undermined reporting [172]. A lack of updates to case definitions and lists of reportable diseases occurs, for example, when some physicians' knowledge about reportable diseases was gained during their education and has not been updated since [85]. The need to find a balance between sensitivity and specificity is also an issue beleaguering case definitions [192].

Reporting involves assigning reporting thresholds for different diseases. Once those thresholds are reached, the alarm is raised. Different diseases have different thresholds that depend on the pathogen's characteristics. The threshold can be as low as one case for diseases such as diphtheria or viral haemorrhagic fever [192].

Data delays and inaccuracies arise due to challenges in data collection, sharing and analysis [10, 72, 216], and low analysis capabilities cause reporting delays [10]. A study by [23] highlighted the importance of sufficient analysis capabilities in reporting systems as the insights generated depend on these capabilities. Reporting delays also hinge on the frequency of reporting; for example, some departments produce only weekly or monthly reports, and poor system design also contributes to delays [10, 85]. In addition, factors outside the system, such as the wait time for laboratory test results [216], laboratory capacity or equipment limitations [241], also exacerbate reporting delays. Familiarity with a disease and a different risk perceptions affect reporting speed [173, 241]. There are variations of the reporting time based on the diseases as well [219].

Another external issue that impacts reporting accuracy is that IDO dynamics can result in new patterns of host behaviour, which distort data signals. A study by [246] found that only 31% of those who had COVID-19-like symptoms sought healthcare during the first COVID-19 outbreak in France, which may have been due to the fear of visiting healthcare facilities (HCFs) [209]. This shows that even robust healthcare reporting systems can suffer from low case identification rates [246]. Another study by [209] argued that the COVID-19 pandemic resulted in a considerable loss of jobs in the USA, leading to the loss of health insurance for many people. They then avoided seeking healthcare, which resulted in reporting data that did not reflect the actual pandemic situation [209].

Clearly, reporting challenges faced by individual countries likely result in inadequate international reporting systems. Some of the same challenges faced at a national level can be reflected internationally, and some countries even lack incentive to report [10]. Low standardisation and integration of national reporting systems reflect the global reporting system [220]. Countries with weak reporting systems are unable to effectively perform their international reporting duties, which increases global pandemic risks [7]. For example, the COVID-19 pandemic showed that national-level reporting should be evaluated regularly, enhanced and ramped up. This pandemic also showed that transparent and responsive alert systems should be implemented [155]. However, designing evaluation and improvement processes for these systems is not a simple task, especially in the case of manual reporting systems [216, 219]. In addition, system design can make it hard to provide feedback from higher levels to the reporter [216].

3.2.2.3.5 Testing

Surveillance systems on their own cannot provide all the data needed for IDO management. A study by [246] argued that surveillance systems did not identify nine out of 10 COVID-19 cases in the first seven weeks of lockdown in France, from 11 May to 28 June, 2020. As we have seen in the case of COVID-19, asymptomatic cases pose a great challenge to response efforts as clinically confirmed cases are nothing but the tip of the iceberg [39]. Pre-symptomatic and asymptomatic cases are significant challenges for both case detection and identification, and are the main drivers of epidemics and pandemics [148, 157, 247]. Identifying such cases early on during an outbreak is critical to preventing widescale epidemics and pandemics [248].

Testing is one of the most important CDI methods employed during an IDO [249]. It is one of the few methods that can be used to identify asymptomatic cases [146]. Rapid testing also provides a tool to overcome the challenges associated with identifying cross-border infections [39]. This method is also used to derive valuable data, such as maps of high-risk areas based on regional population immunisation levels [146]. Furthermore, rapid testing helps authorities to monitor pathogen mutations to aid vaccine research [39].

Despite all those advantages, testing faces accuracy, cost and speed challenges. Tests for EIDs are likely to suffer from accuracy issues when first deployed, as was evident during the COVID-19 pandemic [153]. Testing, in general, is a high-cost case identification tool [203], which makes it an unviable solution for many developing countries [39]. The speed with which test results can be made available is also an essential factor that affects outcomes of other forms of surveillance, such as contact tracing. This is because any delay in test results introduces a delay in contact tracing, and further delays in pinpointing outbreak spread [146, 250]. Such delays can result from poor infrastructure and a paucity of laboratories. Some developing countries have few laboratories capable of carrying out tests. This, combined with logistical challenges that hinder sample transportation, can result in delays and poor testing capabilities. For example, [242] cited a study by [251], which reported that some avian influenza samples took up to 24 hours to reach a laboratory in Vietnam. [242] cited another study by [252], which stated that the average transportation time for human tuberculosis samples was 12 days in Uganda.

Three testing strategies can be followed: universal, comprehensive and selective testing. Universal testing means testing the entire population [247], and this method produces adequate estimates of infection rates and their geographical distribution because the entire population is tested. The same study suggested that household-based testing should be applied during COVID-19. This strategy involves testing the combined samples from all household members, or a group of individuals, to reduce testing costs and time. Yet, testing accuracy and population compliance challenge such schemes. Different pathogens can also pose different challenges to this method as some of those who recover from certain diseases can still be infectious [247].

Comprehensive testing does not cover the whole population, but rather, it involves testing all suspected cases [39]. This method can still provide accurate estimates of infection numbers, geographic spread and infection trends [39]. The main challenges to both universal and comprehensive testing are the organisation and execution of widescale campaigns, which are highly complex and need to be fast, safe and cost-effective, with maximal coverage [39, 249]. However, [247] argued that although these strategies are logistically challenging, the process is clear and transparent once the logistics are organised.

The third testing strategy is selective testing, which reduces both the speed required and the cost of testing campaigns [48, 146]. Selective testing was applied by many countries, including Spain and Italy, during the COVID-19 pandemic [48]. However, with more than one prioritisation method available, data inaccuracies between countries arose [48]. For example, prioritisation may be based on the level of risk selected individuals are exposed to [146], e.g., essential workers or vulnerable populations [39]. In contrast, prioritisation may be based on contact tracing results [146] or symptomatic cases [193]. Often, prioritisation methods require updating as the outbreak progresses, which introduces challenges related to elucidating the best updates and their timing [193].

3.2.2.3.5.1 PoC testing. Testing tools were scarce during the COVID-19 pandemic, and in previous epidemics such as the 2012 Lassa fever epidemic in Nigeria [86, 169]. During the Lassa pandemic, samples had to travel, in some instances, up to 300km to be tested at the one national laboratory. The same lack of testing resources was faced in Iran during the COVID-19 pandemic [86]. This highlights the need for testing solutions that can be applied outside of laboratories, and PoC testing is a promising tool that could provide such a solution. This type of testing can be a game-changer for surveillance everywhere, especially developing countries [242]. PoC tests are portable, and sometimes disposable, testing devices that can be used outside of laboratories [253], and they offer many advantages over traditional laboratory-based testing. The samples needed for testing are usually small [242]. These tests can be conducted without highly trained laboratory personnel as they are either fully or partially automated, and they can deliver results on the same day [242, 253]. This means that PoC testing can be also be used in countries where invasive sampling is considered inappropriate [242].

PoC testing can further enhance EWSs in high-risk areas. This type of testing is used to test both humans and animals [242] and can be employed in animal markets, especially "wet markets" [242]. PoC testing may also be used to identify the origins of infections if transportation records of the animals and goods are kept, thus improving EWSs. PoC testing can further enhance EWSs due to the possibility of integrating data transmission devices into the PoC [242]. Some PoC testing tools can collect and transmit data efficiently, as some they can transmit results using Bluetooth devices or internet connections [235, 242]. Some PoC tests can even differentiate between vaccinated and infected animals [242]. This is an important issue as determining immunisation levels is an important process that aids disease eradication [38]. The lack of livestock immunisation records is one of the challenges faced when responding to livestock disease outbreaks, which could be solved by such PoC tests [43].

In addition, some PoC tests allow testing for more than one disease at once. The increase in the number of such tests will likely increase the acceptance of those tests in the agricultural and livestock breeding sectors [242]. Examples of multi-disease PoC tests include those that can identify all seven variations of foot-and-mouth disease (FMD) [242]. Veterinary PoC tests have been trialled in developing countries, and the results were encouraging [242]. The limitation, however, is that existing PoC tests cover only a small number of diseases. There are some PoC tests that can target high-risk animal diseases; however, these tests are rarely taken out of laboratories into the field for practical application where challenges and limitations of outdoors testing can be identified and addressed. Also, the validation process for veterinary PoC tests is inadequate, an issue that resulted in unreliable tests on the market, which reduced end users' trust in the tests [242].

Other challenges that limit the usability of PoC tests are the high costs associated with developing these tests, and the fact that there are many diseases for which there are no PoC tests. This is because it takes a lot of time and money to create such tests [242]. [242] cited a [254], who reported that developing new human diagnostic PoC tests can cost from 2–10 million USD, and that the process can also take between 5–10 years[242].

3.2.2.3.5.2 Wastewater testing. The news that SARS-CoV2 had been detected in wastewater brought water-based epidemiology to the global forefront [24, 229]. A study by [214] indicated that wastewater testing is a surveillance methods that proved effective during the COVID-19 pandemic. Wastewater testing is rapid, cost-effective and can be used as a universal testing tool to collect data about large geographical areas and to identify hotspots of disease spread [229, 255]. A study by [229] cited Germany as an example to illustrate the time-savings this type of surveillance can provide: it would have taken Germany 3 months to test its entire population using individualised tests; however, the task was accomplished in 24–48 hours using wastewater testing. Wastewater testing can be used to identify asymptomatic infections in non-invasive ways and as an early-detection tool for predicting risk [214, 255]. It can produce geographically specific data through the strategic selection of sampling points, which support targeted interventions [214]. The results of wastewater testing are also used for resource allocation to highly infected regions [41], and results guide traditional testing campaigns [214].

Despite the promise in this form of testing, it suffers from serious challenges, e.g., the inability to pinpoint positive cases exactly [255]. Another limitation is that wastewater testing does not allow testers to identify the host species that shed the virus into the water [255], and this form of testing is effective only when pathogens that can be detected in water [255]. In addition, wastewater testing is still in its early stages; uncertainties surround some aspects, e.g., the quantities of the viral material an infected person can shed during different stages of an infection [255]. This viral load can vary between patients and between testing times for the same patient, which means wastewater testing cannot provide insights into IDO progression [255].

Reports on the wastewater testing accuracy vary. For example, [229] reported that it is theoretically possible to identify one asymptomatic patient out of 100–2 million non-infected patients. However, challenges affect accuracy, sample dilution being one of the issues that results in false negatives [229, 255]. Sample dilution arises as the sample travels further from its source; however, one possible solution is frequent sampling from different points [255]. Differing characteristics of wastewater also increase difficulties in detecting pathogens. These include water PH levels, among others [255]. Some pathogens like SARS-CoV-2, which are not waterborne, can be found in water, but not in high quantities. This means that to get valid tests, a large volume of water needs to be analysed [255], which challenges global current capabilities in wastewater monitoring [229]. Furthermore, wastewater testing lacks standard sample collection protocols. A study by [255] indicated that data variability was observed when collecting wastewater samples manually vs. other sampling methods. The same study called for the application of smart technology to increase test effectiveness, which may address the sample variability issue.

3.2.2.3.6 Contact tracing

Contact tracing, along with case isolation and testing, is an effective method to reduce IDO spread and suppress outbreaks [146, 203, 256]. Contact tracing has three steps: (1) identifying the first case in a cluster, usually by testing [96], followed by (2) contact identification, which is done using human or digital-based systems, and finally, (3) informing contacts and isolating them for a specific period of time [96, 184]. Modelling suggests that contact tracing and other NPIs' effectiveness depends on pathogen severity, transmission rate, public compliance with the intervention, implementation timing, duration and the number of asymptomatic cases [256]. Such challenges to contact tracing can be divided into the technical and non-technical. Non-technical challenges include privacy and legal considerations [184], which affect the population's acceptance of the contact tracing process, another, major non-technical challenge to contact tracing [184]. A specific adoption threshold must be established; otherwise, contact tracing efforts will not achieve their desired outcomes [96]. This threshold differs based on the pathogen and its infectiousness [96].

Contact tracing faces technical challenges that can reduce its effectiveness, including the accuracy and the speed of testing methods applied to identify the first case in a cluster, and the accuracy of contact identification methods [184, 250]. A study by [247] argued that containing an IDO using contact tracing alone is challenging, and that the index case must be identified as fast as possible for contact tracing to work. Index cases also need to cooperate with the authorities and share close contact data. Other technical challenges related to contact tracing can result from the technology applied. For example, the lack of a global positioning (GPS) signal indoors, or barriers that obstruct Bluetooth signals, can reduce the accuracy of contact tracing [184]. High-density populations and their mobility magnify these challenges [96].

Contact tracing can be less effective for vector-borne, food-borne or water-borne diseases [86], and if the number of cases and the transmission rate are too high in a specific region, which increase the difficulties in tracking clusters [37, 69, 87]. Although contact tracing can be conducted using human resources or digitised systems, each of these methods faces challenges. Human-based contact tracing is a time- and labour-intensive process [250] that also faces language and cultural barriers because it involves direct communication between cases and contact tracing staff [250]. On the other hand, digital contact tracing comes with numerous privacy and security threats [24, 184, 213, 256]. Different data may be used, e.g., GPS, Bluetooth exchange data packets with user identifiers, quick response (QR) codes, and wireless fidelity (Wi-Fi)-based location data [256]. Each of those methods faces challenges related to accuracy and social acceptance. Different protocols involving database management and encryption were introduced to overcome those challenges. However, none of these protocols can be viewed as a universal solution as contact tracing protocols are devised based on local customs and contexts to increase their social acceptability [256].

3.2.3 PMC Phase Challenges

This section presents the IDO management challenges specific to the seven phases of the PMC framework.

3.3.3.1 Phase 1: Preparedness

Adequate preparedness is crucial for the success of IDOs management. Numerous studies have highlighted previous IDOs' preparedness deficiencies and have called for the improvement of preparedness measures [9, 10, 45, 141, 174, 257, 258]. For example, [45] argued that preparedness improvements were needed to respond to the Zika and the dengue fever pandemics, a sentiment echoed by [10] in a study addressing pandemics in general. Despite these calls and numerous others, preparedness limitations have not been addressed, as the COVID-19 pandemic made clear. The preparedness of countries and organisations such as the WHO was inadequate and contributed to the pandemic's outcomes [178, 259], specifically, delayed IDO response, which significantly impacted management efforts [174, 185, 260]. Furthermore, certain changes to human lives further increased the need for adequate preparedness. For example, intensifying global connectedness increased the risk of faster and wider infection spread, highlighting the need for improved preparedness [261, 262].

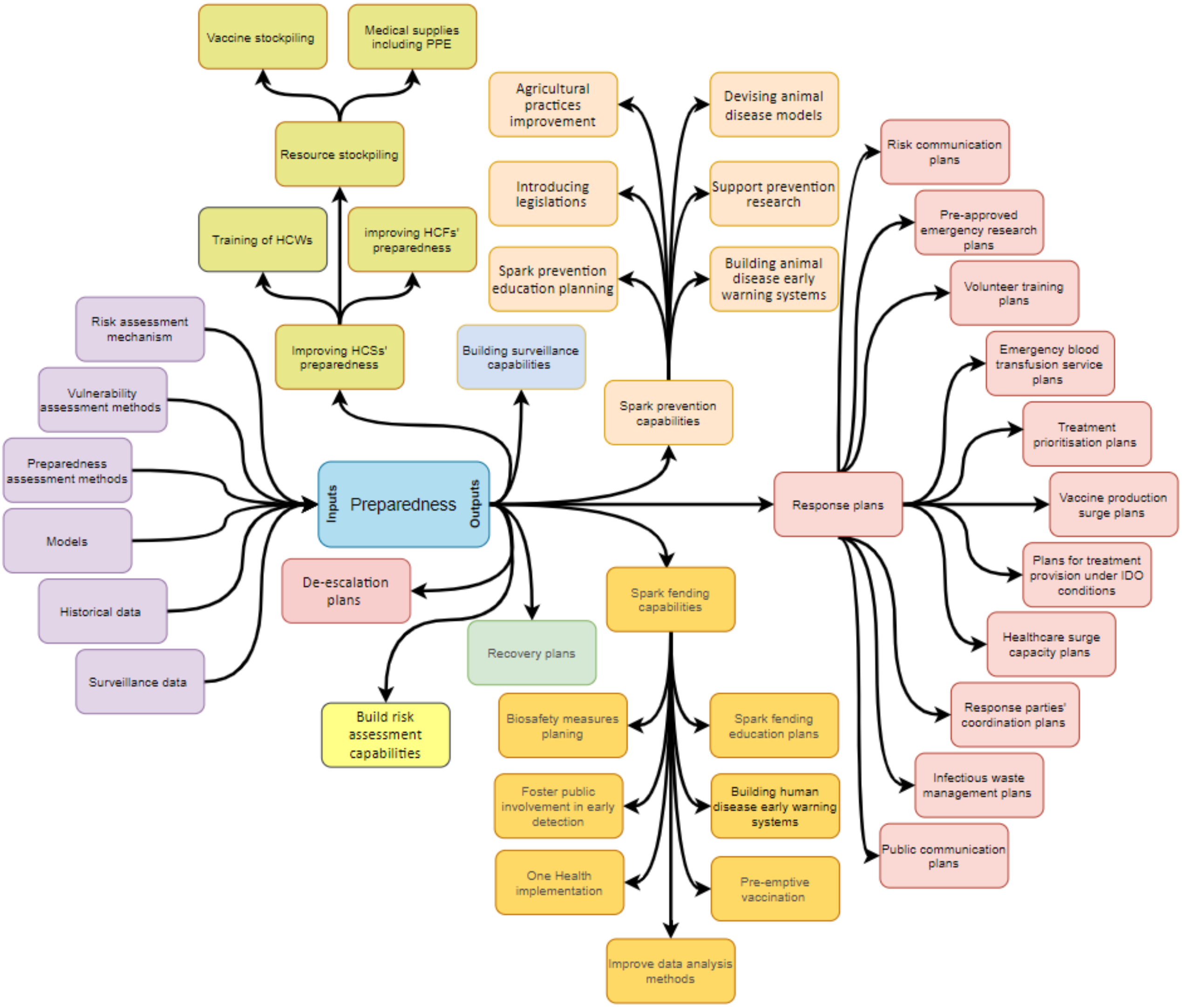

Figure 0-8 preparedness inputs and outputs.

Note. Figure 0-8 is the author's original work.

Abbreviations. HCF, healthcare facility; HCS, healthcare system; HCW, healthcare worker; IDO, infectious disease outbreak; PPE, personal protective equipment.

There is no internationally agreed definition for preparedness. In this work, we define *preparedness* as any actions conducted before detecting an outbreak that aim to increase the quantity or quality of a resource needed during all other subsequent management phases. These actions also improve the processes and systems required to manage an IDO [11, 46, 263]. According to our definition, the preparedness phase does not involve using any of the resources or interventions intended for an outbreak, but rather, preparedness involves only planning, assessing and readying resources. The only exception is knowledge and data collection, which provide information needed to evaluate and improve preparedness. Figure 0-8 shows the inputs and the outputs of the preparedness phase in IDO management. Most of these in Section 3.2.2.3, “Data-related challenges”. Preparedness tools include current or historical data [43, 264], predictive models [43, 72, 141, 193] and risk assessment methods [7, 72, 173, 239].

1.3.3.1.1. Vulnerability assessment mechanism:

In addition to those tools, mechanisms to assess a population's vulnerability are needed [93, 155, 193]. Vulnerable populations include individuals that could be disproportionately affected by an IDO [45, 172, 265]; their protection reduces overall infection spread in the community [146]. However, identifying vulnerable populations is challenging as the notion of vulnerability in IDO management is dynamic, and differs for different IDOs and pathogens. Furthermore, vulnerable populations can also change within the same IDO as the pathogen mutates [44]. Confoundingly, different factors can render a population vulnerable. These include personal traits of the individual, such as age or underlying health conditions and other chronic diseases [172, 266]. Vulnerability may be based on ethnicity; for example, indigenous people may be more vulnerable to certain diseases than other groups [172]. The cognitive capabilities of an individual also contribute to vulnerability [24, 267]. For example, people with intellectual disabilities may not be able to follow hand hygiene practices or social distancing protocols, which increases their risk of contracting the disease [267].

Vulnerability also results from the environment a population is situated in. For example, those in correctional institutions or refugee camps do not have much choice when it comes to physical distancing. Infections in such crowded environments spread very quickly [268]. The displacement or constant movement of these populations makes them vulnerable to diseases as it is difficult for them to adhere to physical distancing, isolation, surveillance and vaccination campaigns [192]. Homeless people constitute such a group [269, 270].

Vulnerability also results from gender disparities arising from cultural practices [271]. For example, a study by [167] argued that 68% of tuberculosis cases in Afghanistan were females due to cultural practices that limited women’s access to healthcare and vaccines. Another study by [271] argued that the risk of death faced by Pakistani girls was 11% higher than for boys. Side effects and impact of IDOs on services and stakeholders also exacerbate vulnerabilities. For example, supply-chain disruptions due to lockdowns result in medication shortages for people living with chronic diseases [272, 273]. Also, increased healthcare costs during the COVID-19 pandemic limited pregnant women's access to healthcare in some countries [35]. Vulnerabilities are compounded in cases where one person belongs to more than one of the groups described [270]. This introduces the need to find transparent, timely and repeatable methods to assess population vulnerabilities [193].

1.3.3.1.2. Preparedness evaluation methods

Another tool needed is preparedness evaluation methods, one of the most critical tasks in IDO management that deals with the effectiveness of almost all systems and resources used in its management. Preparedness evaluation helps authorities address systems gaps and overcome resource limitations. The international community can also use evaluation processes to allocate aid to regions and countries that urgently need it [263]. But the difficulties of evaluating preparedness have been highlighted in many studies, including [47, 166, 263]. Difficulties result from the high number of systems and resources involved in the IDO management process [7, 134]. This means that data representing each component need to be collected and evaluated. The evaluation process can result in recommendations for actions that, when carried out, affect other systems and resources involved, and thus, require repetition of the process. New data about epidemiological risks also introduce the need for repeated evaluations of preparedness levels. A study by [153] argued that changes to the epidemiological landscape occur quickly, meaning evaluations must be conducted often. This view was endorsed by [72], who argued that response plans devised as a part of preparedness efforts should be evaluated and updated as new data become available, a view supported by [263].

Traditionally, preparedness is evaluated using indicators and indices to convey the states of systems involved in IDO management. One of the most basic indicators is a country's national income, which is used to deduce the state of its HCS. This indicator is considered an inaccurate indicator by some [10]. Other, more sophisticated, examples of evaluation indices include the WHO’s State Parties Self-Assessment Annual Reporting (SPAR) [274] and the Global Health Security (GHS) index [275]. The SPAR is based on self-assessment, where countries report on their strengths and weaknesses. The accuracy of this index is questionable as countries with enough resources to investigate and evaluate systems are bound to find more gaps in preparedness levels [169]. In contrast, the GHS index uses specific indicators to measure different countries' preparedness levels. This index is calculated based on 140 questions under six different categories: (1) the prevention of emergent diseases, (2) the identification of deaths and confirmed cases, (3) response speed, (4) HCS indicators, (5) compliance with global guidelines and (6) risk environment indicators [9, 276]. Unfortunately, the COVID-19 pandemic showed that the GHS could not accurately measure a country's preparedness level [9, 150]. Some of the countries considered most prepared were among those that fared the worst [141]. The performance of the USA, which was ranked the highest on the GHS during the COVID-19 pandemic, was bad [139]. Despite this, some argue that the lessons learnt from COVID-19 can be incorporated into the GHS index, which can still be used to measure a country's preparedness [139].

Different ideas are presented for the GHS's failure to predict the performance of different countries during the COVID-19 pandemic. A study by [166] argued that the problem is due to data inaccuracies as the official numbers underpinning indicators are nothing more than rough estimates. Others have argued that the problem arises because some conditions for adequate IDO management were not included in the GHS index [20]; [155] argued that political leadership capabilities should be included as an element of IDO preparedness, and [140] suggested that vaccination acceptance and rates should be included when evaluating a country's preparedness. Others called for rapid vaccine production capabilities to be considered as a part of preparedness [139, 277]

The limitations of the existing preparedness evaluation methods have fuelled the search for new methods. Some new evaluation methods are starkly different from the old methods. The COVID-19 Safety, Risk and Treatment Efficiency framework and indices developed recently [278], leaves some of the best-ranked countries according to the 2019 GHS out of the top 40 positions [9]. Another recent attempt to find improved preparedness indices was carried out by [263], who cited preparedness evaluation methods used for other disasters and suggested a composite preparedness index for IDOs. The index used data about available resources, including human resources, communications and coordination, operational plans and procedures, budget indicators and community engagement.

Countries' preparedness levels can also be affected by a lack of resources. Many countries are struggling with immediate healthcare needs, and they require assistance to obtain the resources needed to improve their preparedness to face IDOs [10]. Resource limitations include a lack of funds, expertise and infrastructure [84]. A study by [7] indicated that preparedness involves building surge capacity, which implies building a degree of redundancy; however, most developing countries could use surge capacity to deal with the currently high demand on their HCSs. [10] highlighted the need to increase investment in preparedness, and argued that increased investment usually occurs after outbreaks but does not last over the long term. [7] supported this by arguing that IDO prevention and preparedness assistance to developing countries reached around 1 billion USD per year after the swine flu (H1N1) and the bird flu (H5N1) outbreaks; however, funding dropped to less than 450 million USD per year soon after.

IDO management barriers impact the ability to perform adequate preparedness. A close examination of the literature addressing preparedness reveals that it involves four main tasks: (1) the identification of resources, systems and actions needed; (2) the estimation of quantities and qualities of these items; (3) the implementation of the necessary measures identified; and finally, (4) constant evaluation and improvement of all items. Knowledge barriers hinder the data gathering needed to quantify resources, actions and systems needed. Ethical barriers make determining the best options difficult [25, 43, 134, 141, 179, 180, 225]. Political barriers result in weak incentives to carry out the actions identified and quantified [7, 141, 174], and organisational barriers can result in fragmentation and confusion of responsibilities and duties, foreclosing implementation [10] [84, 167]. Finally, knowledge barriers limit the ability to collect data needed to evaluate the results of actions taken. Furthermore, organisational barriers result in diffusion of responsibilities and fragmentation of systems, limiting capabilities to evaluate the results of preparedness efforts. Figure 9 illustrates the effects of barriers.

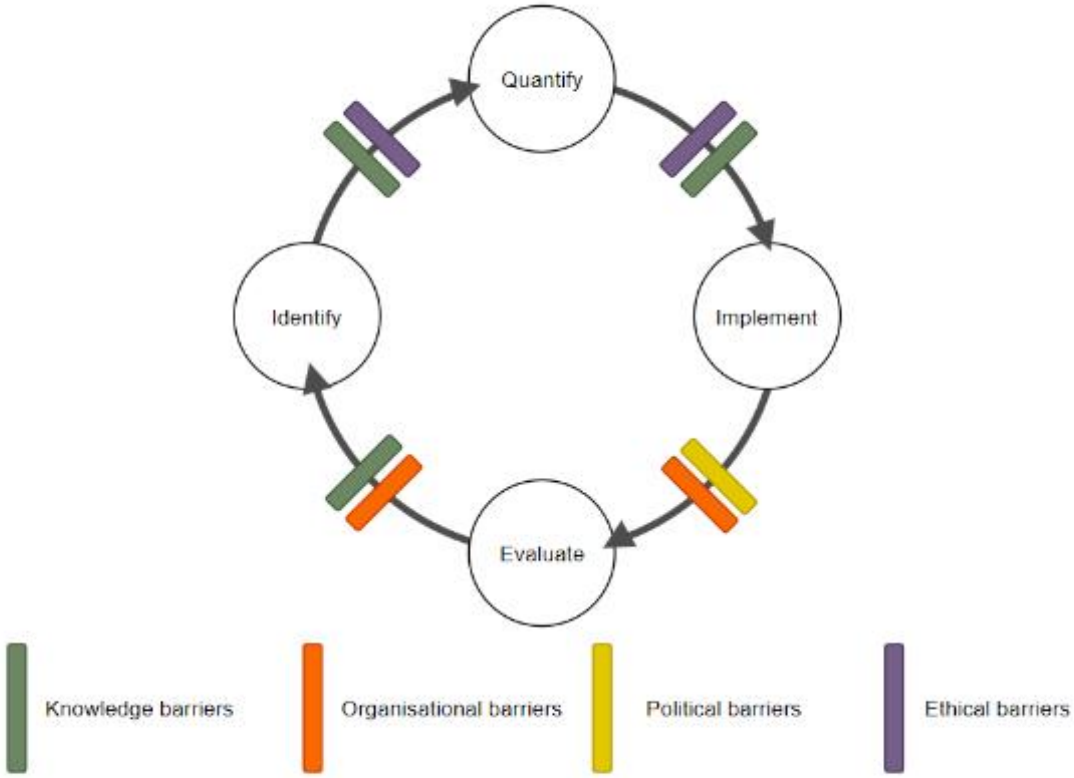

Figure 0-9 The effects of management barriers on preparedness efforts

Note. Figure 0-9 is the author's original work.

Outputs of the preparedness phase identified in the literature can be divided into eight different categories: (1) building surveillance capabilities, (2) ensuring HCSs' preparedness, (3) building risk assessment capabilities, (4) building spark prevention capabilities, (5) building spark fending capabilities, (6) devising response plans, (7) devising de-escalation plans, and (8) devising recovery plans. The measures which were not discussed before are detailed in Table 0-5, Table 0-6, Table 0-7, and Table 0-8.

Table 0-5. Ensuring HCSs' preparedness.

Measure	**Citations**
Surveillance capabilities	[9, 10, 24, 45]
Training of emergency service personnel	[279] [280] [225] [271] [10] [20]
Surveillance capabilities	[10] [9] [24, 45]
Communication and data sharing capabilities	[24, 45]

Measure	Citations
Early detection capabilities	[45] [45]
Ensuring the preparedness of HCFs	[84] [87] [225] [43]
Resource stockpiling	[10]
Vaccine stockpiling	[20, 68]
Prevention measures	[9]
Simulation exercises	[10]

Abbreviations. HCF, healthcare facility; HCS, healthcare system.

Table 0-6. Building spark prevention measures.

Measure	Citations
Capabilities to identify high-spark-risk situations and locations	[234, 281]
Building animal disease EWSs	[45, 281, 282]
Devising regulations to reduce the probability of transmission from wildlife or livestock to humans	[259]
Planning and introducing biosafety measures to prevent transmission from wildlife and livestock to humans	[9, 24, 97, 134]
Planning public education campaigns	[45, 168, 283]
Supporting research aimed at spark prevention	[97, 207]

Abbreviation. EWS, early warning system.

Table 0-7. Building spark fending measures.

Measure	Citations
Introduction of biosafety measures that could help reduce transmission between humans early during an outbreak	[134, 245]
Pre-emptive vaccination campaigns	[45]
Human diseases EWSs	[7, 10, 34, 45, 72, 211, 220, 258, 284]
Fostering community trust in the authorities	[45, 185, 283, 284]
Long-term plans to promote vaccine acceptance	[150]
Improvements to data analysis methods used for early detection	[285]

Abbreviation. EWS, early warning system.

Table 0-8. Devising response plans.

Measure	Citations
Response plans for different diseases	[9, 150]
Public communication plans	[20]
Planning for healthcare surge capacity	[24, 45] [20] [279]
Treatment prioritisation plans	[23, 31, 279]
Vaccine production surge plans	[24]
Coordination plans	[20, 279]
Waste management plans	[136]
Volunteer training plans	[20]
Communication plans between stakeholders	[20, 46]
Preapproved emergency research plans	[24]
Vulnerable population support plans	[148, 193]
Public communication plans	[146]
Emergency blood transfusion service plans	[286, 287]

3.3.3.2 Phase 2: Resilience building

The world's poor response to the COVID-19 pandemic highlighted the limitations of traditional approaches to IDO preparedness, which resulted in overwhelmed HCSs, resource shortages and supply-chain complications. Lack of data, poor risk assessment capabilities and knowledge barriers leave no choice but to build preparedness plans based on assumptions [72, 139, 179]. The tight coupling of preparedness plans and assumptions results in rigid subsystems. This rigidity, combined with the dynamic nature of IDOs and their potential long duration, results in catastrophic failures. The differences between the unfolding reality and the assumptions render plans and systems unusable, and cause ripple effects that are hard to anticipate or manage [91]. In response to this challenge, many scholars have recommended including the concept of resilience in future preparedness plans [24, 31, 139-141]. *Resilience* can be defined as the ability of a system to react to obstacles and recover from unexpected disturbances quickly, with minimal effects on dynamic stability [24, 288]. Creating a resilient IDO management system requires incorporating robustness, redundancy and flexibility into preparedness plans and systems [24, 142, 143].

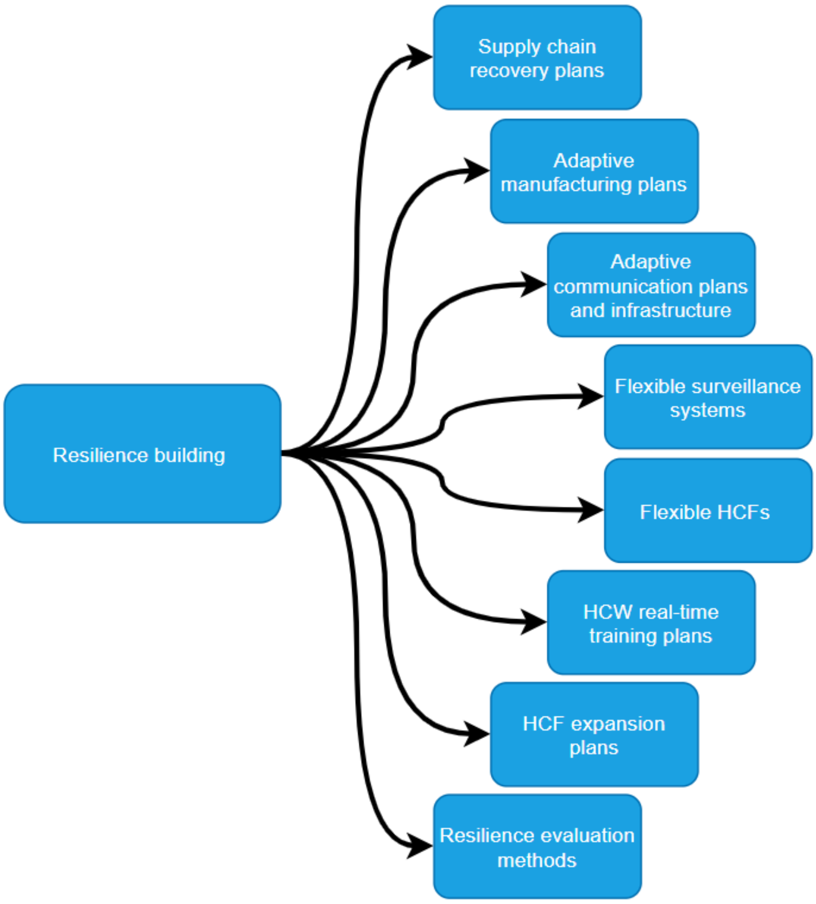

Figure 0-10 Resilience-building phase outputs.

Note. Figure 0-10 is the author's original work.

Abbreviations. HCF, healthcare facility; HCW, healthcare worker.

We added the resilience-building phase to our PMC framework to highlight the importance of the concept and to ensure any challenges arising from the lack of resilience-building were covered. The main aim was to highlight the need for flexibility in preparedness plans, which eases responses to increased infections beyond the assumed limits. Flexibility n plans also increases the chances of successfully responding to different pathogens and resource shortages. Yet, the number of studies that have discussed resilience are few and addressed the subject sporadically. Systems should have specific attributes that fall under resilience, and they should avoid specific planning defects that clash with resilience by proposing solutions to overcome rigid preparedness measures. For example, many of current systems target specific diseases, e.g., a global flu surveillance network consisting of 144 national centres exists, but there is nothing like this for other diseases [68]. Failure to ensure the fixability of surveillance systems means that preparedness and response plans are coupled with specific pathogens only, a challenge faced during the COVID-19 pandemic [23, 24, 141]. Surveillance systems' sensitivity also requires flexibility. Different stages of the IDO evolution require different surveillance strategies and system sensitivity levels [38].

Resource shortages experienced during past pandemics showcase the need to incorporate flexibility when planning responses [20, 141]. These shortages result from countries' financial constraints and low budgets. The COVID-19 pandemic showed that these resource shortages also result from supply-chain disruptions [172, 234]. A study by [289] called for supply-chain recovery planning to be included as a part of recovery phase, but challenges arising during COVID-19 show that such plans should be devised as a part of the resilience-building phase in order to recover and restore supply-chain functions during the later response phase, at least for crucial response resources.

Shortages of resources can be caused by limitations faced by the manufacturing sector, highlighting the need for plans to increase sector resilience, especially when it comes to supplies and equipment that may be needed for an IDO response. Resilience measures include enabling manufacturers operating suitable production lines to produce the needed items [91, 143]. This could be achieved by devising adaptive emergency manufacturing plans and training materials to support the plans. A basic example inspired by the COVID-19 pandemic occurred when breweries started producing sanitisers [234]. Other examples are the production of PPE by clothes manufacturers, or car manufacturers switching to ventilator production [77].

HCS preparedness and resilience are significant determinants of an IDO's impact on the population, especially since pandemics can last for years [31, 146]. A resilient HCS is one that can adapt response measures promptly. Such a system must identify threats early in order to evaluate performance [169]. Responsiveness also requires data sharing and strong coordination and communication with stakeholders. These communication and data sharing systems should be flexible enough to enable systems to respond to a pandemic spread's dynamic nature [169]. For example, IDOs can result in sudden increases in infectious cases requiring medical attention, highlighting the need to build HCSs' surge capacity. Surge capacity refers to the ability to care for a markedly increased volume of patients that challenges or exceeds normal operating capacity [279]. One of the crucial components of HCSs required to achieve surge capacity is HCWs, who face significant risks during IDOs, and their numbers can fluctuate due to infections and deaths [279]. Therefore, HCSs need solutions for staff shortages. Possible measures that can be implemented during the resilience-building phase to achieve this include devising real-time and remote training programmes that can be deployed as needed during the response phase to help address possible HCW shortages [279]. The influx of infectious cases can also lead to bed space shortages and a high demand for certain healthcare services. These influxes require plans for the physical expansion of HCFs and the creation of temporary HCFs [20]. During the COVID-19 pandemic, the first wave caused an increase in patients requiring ICU admission. This increase necessitated the expansion of ICUs, which required changes to infrastructure including the installation of piping for ventilator oxygen, among others [185]. Clearly, the concept of flexibility should be built into HCF designs and the creation of temporary facilities.

The resilience of systems must be measured and improved. However, this is challenging as "resilience" is not a fixed concept, and resilience attributes differ between systems [142]. This is further complicated in the case of disaster management as attributes differ depending on the disaster type [142]. For example, the term "robustness" can convey different meanings in different contexts: in the case of an earthquake, a robust HCS is one with strongly built infrastructure that can support service provision, even when infrastructure is damaged. However, in the case of IDOs, robustness means an HCS that continues to provide healthcare services even when faced with shortages in resources, such as bed space, equipment, or HCWs, or an HCS that can cope with high demand during an IDO [142].

A study by [142], which addressed HCF resilience, reviewed different assessment methods and indicators in depth, including the multitude of possible evaluation methods and their limitations. These included indicator-based approaches, which rank a system based on quantitative measures such as bed space or other available resources. This approach is similar to a resilience assessment method proposed by [140]. These indicators, however, were considered static and incapable of measuring the resilience of a system in a dynamic environment [142]. Another way to measure HCSs' resilience is the function-based approach, which ranks systems by assigning metrics to functions the system performs [142]. This approach can overcome the limitations of indicator-based approaches, but cannot deliver a complete, detailed picture of evaluated systems, often leading to difficulties in elucidating deficiencies and improvements [142]. Figure 0-10 shows the resilience-building phase and related measures as identified in the literature.

3.3.3.3 Phase 3: Spark prevention

EIDs are significant causes of epidemics and pandemics [7]. It is estimated that there are around 1.7 million unknown viruses, and of these, up to 850,000 can cause the next EIDO [68, 69]. EIDs can be defined as increased instances of distinct clinical conditions caused by a pathogen spreading between humans. This pathogen may be newly introduced to the population, or may have been circulating for some time but has recently been identified [290]. Most EIDs are zoonoses [7, 154, 235]. Zoonotic diseases are caused by pathogens switching hosts from other vertebrate animals to humans [291]. Examples include the H1N1 (bird) flu [292], Ebola [7], and finally, presumably COVID-19 [258]. Studies estimate that between 60% and 75% of diseases the infect humans are zoonotic in origin [69, 148, 151]. The risk of zoonotic diseases has increased in recent years, and pandemics and epidemics caused by these are more frequent [151, 292].

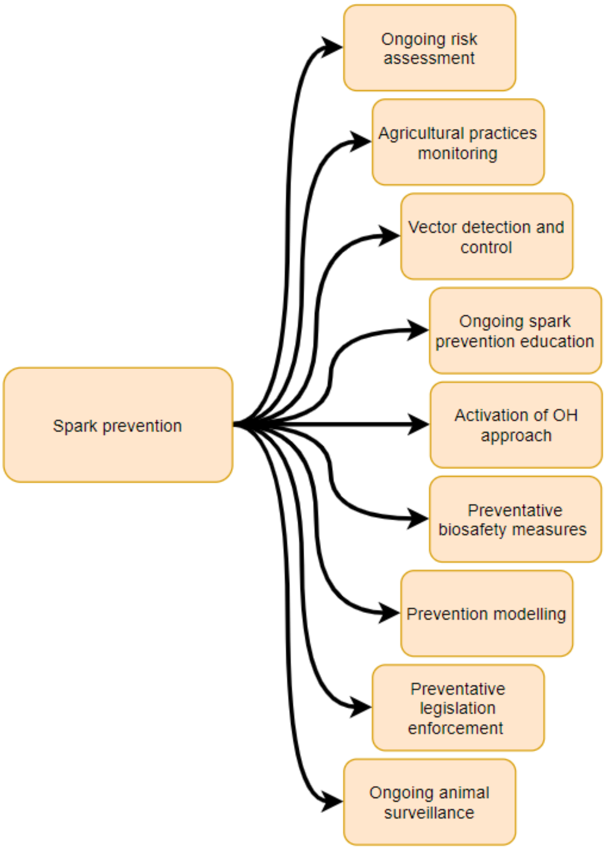

Figure 0-11 Sprak prevetion phase outputs.

Note. Figure 0-11 is the author's original work.

Abbreviations. OH, one health.

Zoonotic infectious diseases go through different evolutionary stages before they make the host change to humans [10]. The starting point is when a pathogen circulates in nonhuman reservoirs without infecting humans. The second stage is when the virus transfers from nonhuman to human hosts, but still cannot circulate within the human population. The third stage is referred to as a “limited outbreak”, which involves transmission between humans, but transmission chains are limited. This stage poses a high risk of an EIDO and requires immediate attention because it can further escalate to include sustained outbreaks, which involve numerous human-to-human transmissions. These outbreaks, however, are still not full-fledged as some of the pathogen's characteristics limit full-blown spread. The highest risk involves predominantly human transmission. During this stage, the pathogen circulates the human population freely without the pathogen attributes' limiting the transmission chains.

The term spark used to refer to animal-to-human transmission [10]. Therefore, this study defines *spark prevention* as actions that aim to prevent the pathogenic jump from nonhuman to human hosts. Spark prevention also aims to reduce the probability of pathogenic sparks by identifying and avoiding situations that could lead to such events, which result from increased interactions between humans and animals, whether domesticated or wild [7, 95, 207, 281]. Increased urbanisation and human encroachments on wildlife expand the interaction interface between humans, livestock and wildlife which can lead to such sparks [68, 151]. Urbanisation, along with other factors, leads to reduced wildlife diversity. Some pathogens then lose their natural hosts and are put under evolutionary pressure, increasing the possibility of mutations resulting in cross-species transmission [151].

According to some studies, certain wildlife species pose a higher spark risk, including bats and marine-life forms such as filter-feeders [68, 69, 214]. Bats harbour pathogens such as chikungunya, Zika malaria, Ebola and yellow fever. [69] cited a study by [293] that highlighted bats' ability to tolerate pathogens due to their limited immunological response, which allows them to asymptomatically carry and spread pathogens that can be harmful to other species. Transmission can also occur from wildlife to livestock, and then, to humans [281]. Such secondary transmission was considered by [7] to be more challenging to prevent than direct wildlife-to-human transmissions. The risk of “sparks” originating from livestock is enhanced by unsafe agricultural practices [7, 43, 242].

Pathogenic sparks can also be transmitted to humans indirectly via waterways that carry specific pathogens far from their origins, contaminating drinking water sources [69]. Other species can also carry pathogens that can survive in water to humans. Sea creatures such as filter feeders including mussels and oysters are known to capture viruses such as norovirus, hepatitis A and hepatitis B from coastal waters and concentrate them within their filter structures [69]. Consuming and handling these creatures may result in pathogen transmission.

Other high risks considered to be a public health concerns are vector-borne pathogens [151]. These diseases are transmitted indirectly from the host animal or human and other humans via vectors such as mosquitoes. The vectors then carry the pathogen from infected humans/animals to others by feeding on the blood of uninfected target [151]. Examples of vector-borne diseases include dengue fever and chikungunya fever, among many others [97]. [151] argued that climate factors and human activities, such as building dams and irrigation networks increase these diseases. The same study highlighted the role of global warming in exacerbating the situation by providing favourable conditions for vector breeding and survival, e.g., prolonged periods of optimal temperatures that increase pathogen survival outside a host, an argument supported by [97, 151, 152]. Other human activities also increase vectors' ability to move around the globe. For example, modern air transport also increases the probability of introducing vectors to new locations [97]. In addition, vectors face more pressure to move, thus increasing spread. These pressures can result from pollution, habitat, destruction and host density reduction due to urbanisation [223].

Authorities should increase spark prevention efforts as such activity is of the most cost-effective ways to stop IDOs. This cost of containing an IDO increases gradually, and it reaches a peak as clinical signs are identified among humans when they seek healthcare [7, 46]. Yet, most nations direct their spending to response efforts, rather than prevention [7, 24, 46]. For example, vaccine development gets substantial government funding, while spending on prevention methods in developing nations is much lower [7]. The focus on response also derives from the experience and background of public health policymakers. Physicians trained to save lives become leaders, and their policies are more biased towards response [7]. The whole HCS is therefore focused on responding to healthcare issues. Prevention is out of its scope, partly because prevention does not bring tangible rewards to the sector [7]. This means that authorities' involvement in the prevention phase is crucial because no commercial incentives underpinning the process [7].

Spark prevention requires continuous cooperation between multiple stakeholders; however, no central organisation is responsible for coordinating efforts [7]. Disciplines involved include the human biomedical field, animal health and environmental monitoring organisations [68]. The multidisciplinary nature of this task and the absence of precise coordination mechanisms result in responsibility and accountability challenges. Yet, reducing wildlife-related spark risks are under discussion, and these include legislation to curb direct interactions between humans and possible hosts in the wild. One of the methods suggested was to reduce the size of the interaction interface by stopping the urbanisation and destruction of wildlife habitats [234]. Another suggestion was to introduce legislation to ban the consumption of wild animals [259]. Carrying out ongoing educational initiatives to increase the public's awareness of epidemiological spark risk and prevention was also suggested by [283]. Finally, the introduction of biosecurity measures for the wildlife trade was suggested by [39].

Suggestions aimed at reducing transmissions from wildlife to livestock, including limitations to interactions between livestock and wildlife [168], have also been mooted. Furthermore, agricultural practice improvements to reduce the probability of transmission from livestock to humans [168] have been discussed. The introduction and enforcement of biosafety measures [24, 97, 134, 211] is also recommended, along with mandatory vet checks and reporting of cases by farmers and vets [134]. The main challenge when implementing such biosafety measures is the lack of adherence, which highlights the need for monitoring of workers in high-risk occupations, e.g., farmers [24], veterinarians [245] and HCWs [294]. A study of the management of an emerging zoonosis in Australia [245] highlighted some of the reasons behind the lack of veterinarians' biosafety adherence, which included training-related deficiencies. The effects of these measures on work schedules were deemed profound, and the changes they introduced to work cultures were another reason behind the resistance [245].

Specific research fields that support spark prevention, and the need for their continued involvement, was highlighted by [97, 207]. Areas of interest include studying the evolution of pathogenic agents and drivers for mutation, including host attributes that influence mutation. A deeper understanding of environmental emergence factors also requires focus.

One of the best possible ways to prevent vector-borne diseases is vector control. Chemical vector control is possible; however, it is not a desirable option as it results in further vector movement [223]. Furthermore, this method's effectiveness reduces as a vector's resistance to insecticides builds [223]. Chemical vector control methods also drive pathogen mutation because the chemicals used damage the pathogen's genes [151].

In some cases, vector control can be achieved using other methods. For example, environmental sanitisation works on specific vectors [208]. An example of this is the *Anopheles* mosquito that transmits malaria. These mosquitoes are known to breed in still, clean water, which means reducing puddles may prove to be an effective control method. Another way to control vector-borne diseases is by limiting human and domesticated animal movements in high-risk areas [234].

Spark prevention and fending depend on accurate risk assessment and prediction to avoid high-risk situations [10, 69, 72, 168]. Prediction and forecasting, in turn, require studying a virus' ecology [168]. Identifying the geographical distribution of pathogens, factors driving their mutation and emergence risks are prerequisites for predicting significant future epidemiological events [69]. Tracking pathogens' past evolutionary behaviour, especially those circulating in animal populations close to humans, can also be helpful [69, 207, 293]. Models devised to evaluate different prevention methods [38], alongside epidemiological models for livestock, should also be improved [43].

3.3.3.3.1 Animal disease EWSs

Animal disease EWSs also require improvement. In most cases, the detection of EIDOs occur after human cases are found [7]. This highlights the need for more focus on wildlife and livestock surveillance. Unfortunately, animal surveillance systems do not get much attention; [72] reported that around 50% of surveillance systems worldwide collect only human-related data. The same study also stated that around 70% of those EWS systems targeted known pathogens, with little attention paid to EIDs. Yet, surveillance systems should target high-risk species and susceptible animals and humans interacting with those [39, 214]. However, wildlife surveillance faces logistics, regulations and resource limitations [242]. Data collection and accuracy challenges in this domain are rife: [242] cited a study by [295], which revealed that even basics, such as record-keeping when collecting epidemiological samples from wildlife, were inadequate in some cases, which impacts lab test validity. Clearly, EWSs built to target the livestock trade can reduce the risk of epidemics, and even pandemics, due to the international livestock trade [214]. This includes installing surveillance systems on farms [134]. These surveillance activities should be increased after detecting a high-risk zoonosis in areas where livestock are in or pass through [214]. One of the challenges faced when attempting livestock monitoring is surveillance in non-commercial settings, such as nomadic communities and others dependent on substance farming [7].

Commercial considerations also thwart livestock surveillance, resulting in the failure of EWSs. Farmers' incentives to prevent and report infections are limited to their losses, and reporting diseases results in losses for them [7]. The same also applies to countries. Many countries that are getting involved in the global livestock trade do not have the capabilities to detect outbreaks promptly [7]. Other countries are reluctant to report such outbreaks due to possible economic losses [95].

Three knowledge-related challenges can reduce the effectiveness of EWSs: (1) the challenge of detecting EIDs, (2) overlapping symptoms and (3) asymptomatic infections. Surveillance systems on their own are not enough to address the problem of EIDs [97]. This task requires extensive time and resources to collect the data needed from diverse sources [211]. For example, continuous genome sequencing is required to collect data to help understand and track pathogens' evolution over long periods [211]. Social and environmental changes that affect pathogen mutation and evolution should also be tracked and analysed continuously [30].

Detection of EIDs requires improved wildlife surveillance methods; however, some knowledge limitations hamper this. Water-based surveillance has been proposed as a tool for wildlife epidemiological surveillance [69] as it effectively allows monitoring of many species over a large area. The challenge, however, is that water-based epidemiology requires pathogen samples to enable testing, just like most other testing types [155]. This means the method is unsuitable for detecting unknown pathogens or EIDs, which are the highest risk threats. Although syndromic surveillance can be used to overcome these challenges [43, 71], the method faces technical issues that limit its benefits. First, syndromic surveillance cannot help in the case of asymptomatic infections, which pose a significant challenge to spark prevention efforts [7, 156]. Syndromic surveillance also suffers from inherent delays that limit pathogen detection speed [72]. The accuracy of syndromic surveillance is also affected by the overlapping symptoms of disease [7], especially when there are shared symptoms between endemic and emergent diseases [10, 154]. [155] argued that COVID-19 emergence in the winter made it hard to detect as it was less likely to be noticed alongside other winter-endemic pathogens. This scenario was further complicated by other non-seasonal diseases with symptoms overlapping those of COVID-19, including dengue fever [156] and malaria [157].

EWSs are basically a collection of surveillance systems working together to detect outbreaks early [192]. The involvement of multiple systems produces coordination challenges and organisational barriers. The different systems involved in the early detection process operate under different sectors of healthcare and other organisations, and some of those sectors are not prepared to conduct adequate surveillance, which could significantly reduce the effectiveness of the EWSs.

One of the healthcare sectors critical to spark prevention, e.g., early detection, is the veterinary health system. Veterinarians have amassed practical IDO management skills through their numerous encounters with EIDOs [69], and they are highly attuned when it comes to EID detection. Furthermore, veterinarians likely have more knowledge about animal outbreaks in their local areas [154], which means they can provide valuable data before transmission to humans occurs. Veterinary systems, however, are under-resourced and have no adequate surveillance systems that can collect data useful for early detection efforts [69, 242]. This renders their input almost unreliable because very few infectious diseases have distinct clinical and syndromic signs [242]. A study by [242] cited [296], who argued that veterinarians' accuracy in diagnosing FMD in is around 54%, highlighting the need for adequate testing capabilities. However, animal testing in developing countries can take weeks [242]. Furthermore, inaccurate and out-of-date livestock disease case definitions plague veterinary systems [214, 245].

3.3.3.3.2 One Health

Another spark prevention challenge that hinders early detection efforts is the separation between human and animal HCSs [235], which means each of these systems has a narrow view of its responsibilities. Organisations only address issues within their domain, leading to failures to effectively detect or respond to an outbreak [7]. Coordination and data integration challenges are faced at both the national and international levels, preventing the detection of both epidemics and pandemics [87, 236, 280].

One Health (OH) is a promising framework proposed by numerous studies to overcome organisational limitations [68, 69, 72, 154, 214]. OH is a cross-disciplinary approach that attempts to generate new insights by combining expertise from human biomedical, animal health and the environmental monitoring systems [68]. The aim is to understand disease emergence factors in order to intercept and extinguish pathogenic sparks before they turn into epidemics and pandemics [69] [154]. This approach also aims to foster national and international collaboration to maximise the global ability to address future health challenges [7, 154]. OH implementation may help overcome other challenges faced during the other phases of the IDO. This initiative may also provide valuable data helpful in directing preparedness and response efforts [72]. An example of the great potential of OH is Italy’s preparedness and response plan for the West Nile virus, which incorporated data from veterinary virologists and combined these with data about human health [69]. Veterinarians detected viral load in vectors

9 days before the first confirmed human case, which enabled extinguishment of the pathogenic spark using vector control measures, among other interventions.

Unfortunately, calls to implement OH, oft repeated over the past 10 years, have not been heeded, even in high-risk areas [69, 168]. Medical schools have a role in incorporating OH into the medical field [154], but due to weak political commitment, the communication and training required to implement the OH approach remains underfunded [46, 69]. Fund distribution is usually sector-based, which means bridging initiatives such as OH are underfunded because OH spans sectors [297]. Finally, neither the World Organisation for Animal Health nor the WHO has the authority or experience to fund and oversee a massive, multi-sectoral initiative, such as OH, at the global level [7].

Figure 0-11 illustrates the spark prevention phase, its inputs and outputs.

3.3.3.4 Phase 4: Spark fending

The term "spark fending" is derived from a process that involves installing barriers to prevent a spark from reaching flammable objects [145]. In this study, we define this term as employing long-term biosafety measures, education, pre-emptive vaccination and early detection methods to reduce the spread risk of a “spark”, so it does not become an epidemic. To further clarify the differences between the spark prevention and fending phases, spark prevention aims to reduce the probability of the pathogen jumping from non-human hosts to humans, while spark fending aims to reduce the probability of transmission of this emergent pathogen from one human to another, before the occurrence of a full-scale epidemic or pandemic.

The speed of COVID-19 spread illustrates the speed of spark spread. Recent work by [237] examined the feasibility of controlling a COVID-19 outbreak. Outbreaks of varied sizes were evaluated using a model to determine the feasibility of controlling these. The study reported that containing outbreaks consisting of 40 or more cases using contact tracing and case is unlikely under plausible conditions. It should be noted that this threshold differs from one disease to another due to the differences in pathogens' transmission rates, and also, the models applied [96]. However, this threshold can be used to show that a spark can turn into an epidemic very quickly, which highlights the importance of robust biosafety measures and timely early detection capabilities. In addition to biosafety measures, public education aids spark fending efforts. Fending tools are different from those needed for spark prevention because they target transmission between humans, instead of non-human to humans. These measures should be implemented in laboratories, especially those dealing with zoonotic diseases [134, 245], at HCFs [9, 294] and on farms [24].

Pre-emptive vaccination can also slow the spread risk [45], very helpful for high-risk occupations such as HCW and veterinarian. The vaccination of HCWs reduces the risk of transmission [84, 208], but it should be noted that this method cannot address the problem of emergent diseases as these are unlikely have a vaccine available.

3.3.3.4.1 Human disease EWSs

Failure to detect an outbreak early can result in unsuccessful spark fending, increase the cost of containment measures [10, 45, 211, 232] and greatly complicate the response phase [154]. Numerous studies have highlighted the need for human disease EWSs to enable rapid detection, containment and response [7, 10, 34, 45, 72, 211, 220, 258, 284], but more than any other measure, rapid detection of outbreaks significantly reduces their damage by containing spread [10, 211, 258]. The most crucial factor determining the success or failure of later containment efforts is the detection of the first case [248]; however, first cases have always been found retrospectively in previous epidemics [10].

A study by [298] have showcased different data categories that can be used to detect outbreaks early. The first category is pathogen-related data, including pathogen mutation and evolution data. The second describes certain events that increase epidemic risk, but are not pathogen dependent. Examples include events involving biosafety breaches in laboratories housing high-risk pathogens, or specific climate/environmental factors that increase outbreak probability. The third category includes reporting data collected by HCSs, including the numbers of people seeking healthcare, and the number of confirmed or suspected cases. The fourth type of data is event-based data, which includes medication purchase patterns, or data collected from online sources such as social media. However, this list should include another category that allows EWSs to detect cross-border infections at entry points [39].

Human disease EWSs can be traditional, digital systems or a mix. The process of early detection starts with a data collection phase, followed by an investigation, a confirmation process and finally, the declaration of an outbreak [284]. Traditional EWSs can face delays at all systems layers, including data collection, investigation, confirmation and declaration of outbreaks [284]. The data collection layer in traditional systems generates long delays, jeopardising the entire system [72, 193, 284]. Data collected usually consist of host-related data, including case-based surveillance data reported by human resources. The reporting speed is a significant determinant of detection timeliness [10]. Thus, the involvement of the human factor in the collection process causes delayed reporting and yields inaccurate data [216]. These are significant limitations as EWSs should be timely, accurate and practical [298]. Unfortunately, many high-spark-risk, fragile countries employ traditional EWSs, which is concerning given the limitations of such systems. To wit, [284] argued that the average lag time from the start of an outbreak until its detection was 29 days in developing countries, with the delay period ranging from 7–80 days. The author added that the delays in detection, investigation and response in fragile states are significant, with up to 5 months delay until the start of meaningful control. After receiving data alerting authorities to the possibility of an IDO, the investigation phase took 7 days, on average. Some investigations took up to 30 days to be completed. Confirmation of outbreaks took 23 days on average, ranging from 5–42 days. The average time that elapsed before a declaration was 30 days, ranging from 15–50 days. Finally, it took 55 days on average to initiate control efforts, and the range was significant, between 26 and 154 days [284].

Possible causes for these delays include low community cooperation due to distrust of investigative teams and poor infrastructure, including road conditions. Security challenges in specific regions and countries were another reason for these delays. Misconceptions and misunderstandings on behalf of the authorities also caused delays [283].

Digital EWSs face their own challenges because they poll data collected by different surveillance systems and analyse it using different methods; [284] highlighted limitations related to EWSs' data analysis components. This study compared different methods employed to detect outbreaks, and the author stated that the analyses led to the detections of very few outbreaks, whereas formal and informal notifications based on human reporting led to more frequent outbreak detection. However, methods dependent on data analysis were faster, but the single most limiting factor in digital data analysis was the small amount of data collected [284]. Other possible limitations not included in the study were the suitability of the analysis methods applied and data quality issues [285].

Figure 0-12 illustrates the spark fending phase, its inputs and outputs.

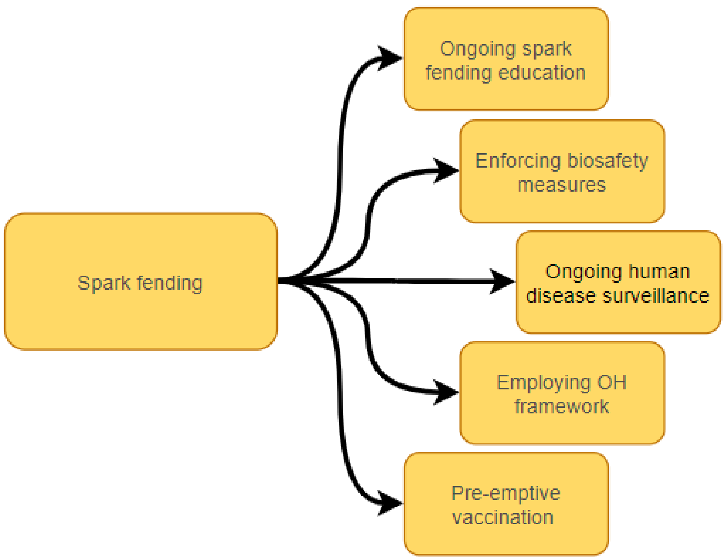

Figure 0-12 The spark fending phase outputs

Note. Figure 0-12 is the author's original work.

Abbreviations. OH, one health.

3.3.3.5 *Phase 5: Response*

The response phase of the PMC aims to reduce the IDO's effects on the population and put an end to the outbreak. This requires reducing pathogen transmission and containing spread as fast as possible using resources and processes targeting common transmission mechanisms. These resources and processes could be PIs, such as vaccines, or NPIs, such as lockdowns. Reducing the impact of the IDO also means providing adequate healthcare to the public. Furthermore, the response phase requires the execution of subtasks, such as coordination of efforts, resource allocation, support of the vulnerable population, communication with the public, research support and finally, elimination and eradication of the pathogen's threat [10, 11, 196]. Of course, the success of the response depends on its speed. Response delays can worsen the IDO's outcome and increase control costs [37, 141, 174]. At the start of the COVID-19 pandemic, European countries and the USA had the time to organise and initiate a rapid response. However, this opportunity was wasted [169], which resulted in failures to contain the pandemic [27].

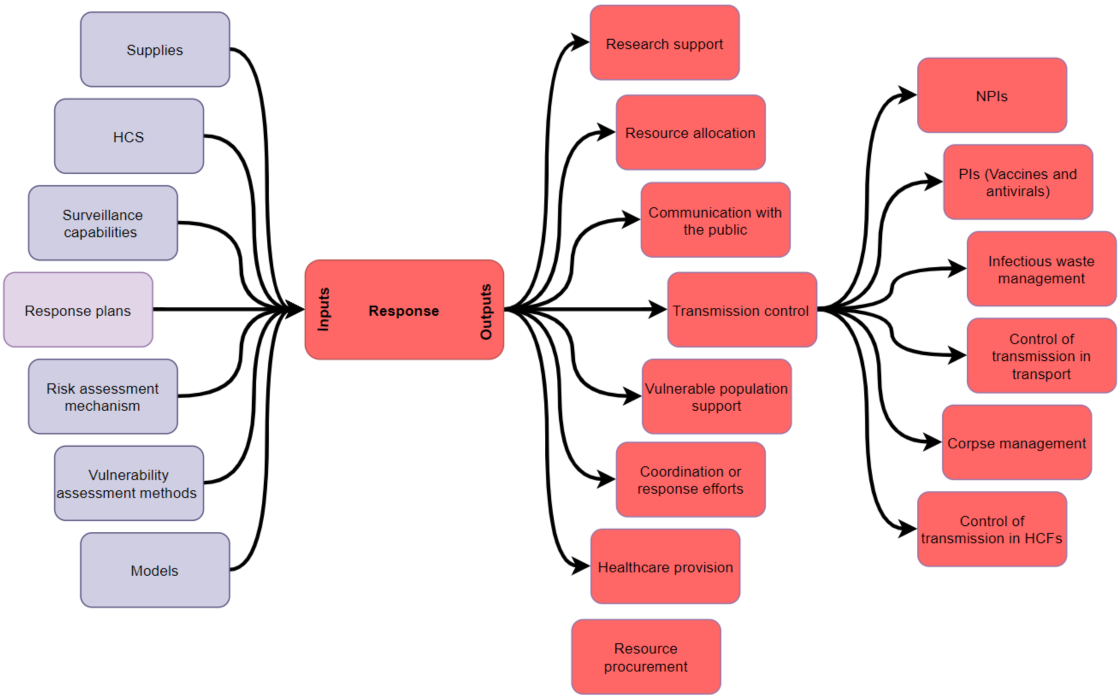

Figure 0-13 the response phase inputs and outputs

Note. Figure 0-13 is the author's original work.

Abbreviations. HCS, healthcare system; HCF, healthcare facility; NPI, non-pharmaceutical interventions; PI, pharmaceutical interventions

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The response phase requires resources and knowledge to be deployed effectively, and deployments include timely surveillance capabilities to detect cases and gain insights to guide the response [10, 37, 196, 205]. Surveillance timeliness is crucial as past IDO data are of limited use during the response phase [204]. However, fresh data are usually low in quantity and quality at the start of the IDO [88], leading to response delays, or the response being based on assumptions and uncertain insights during the early stages [48, 185]. Other requirements include response plans generated during the preparedness phase, risk and vulnerability assessments to aid in resource allocation and treatment prioritisation, and models to aid policymakers and guide NPI deployment. Response also requires supplies and fit-for-purpose HCSs. These requirements are discussed in detail in this section. Figure 3-13 illustrates the inputs and the outputs of the response phase.

3.3.3.5.1 Transmission reduction. Certain scenarios pose high transmission risks during IDOs. These include transmission in transport, be it land, air or sea. Transmission in HCFs, or while handling objects such as corpses, is also high-risk. Another scenario that results in heightened pathogen spread is the unsafe handling of solid and liquid infectious waste. Each of those is discussed in Sections 3.3.3.1.4.1.1–3.3.3.1.4.1.5 below.

3.3.3.5.1.1 Infections in HCFs. Infections occurring in HCFs are a major challenge that put the whole system at risk. [299] reported that as many as 50% of COVID-19 infections have been contracted in HCFs. Another study by [10] reported that during an Ebola outbreak in 1995, around 24% of infections were in HCWs. Infections in HCWs increase workload and extend overtime hours for other non-infected staff members, resulting in burnout [10, 279, 300]. Indeed, HCWs are at high risk of infection, but they also pose a high risk of infection to others. Increased close contact between HCWs and infectious patients abets infection transmission from HCWs to patients and visitors, and vice versa [88, 146]. [87] argued that infections in HCFs result in a cycle that magnifies the pathogen's spread within the community. [301] pointed out that, unlike infectious patients, HCWs travel from HCFs to homes often, which makes them unknowing super-vectors. High infection rates within hospitals mean patients avoid HCFs in some cases. This was experienced during an Ebola pandemic in 2014 which took place in Guinea, Liberia and Sierra Leone, where fear of transmission deterred patients from seeking help [87]. Patient hesitance was also observed during the COVID-19 pandemic in more than one county [157, 209], which saw some chronically ill patients avoiding HCFs [302].

An HCF’s layout can lead to increased transmission during IDOs. Tortuous layouts create difficulties in following measures such as physical distancing [88]. In addition, limited space between beds reduces the effectiveness of infection control measures [84]. The resemblance of long-term care facilities to the home environment makes the implementation of infectious control measures hard, too [88]. [165] argued that specific HCFs, such as hospices, require tailored infection control measures.

Furthermore, emergency care provision can result in infections. The need to provide urgent care sometimes could mean that performing patient triage and the implementation of infection control measures may lead to time waste which could affect a patients survival chance. The inability to perform triage or perform infection risk assessment means isolating infected patients from others at the initial stages of care could be difficult [302]. The fact that some HCWs perform both infectious case management and emergency care simultaneously further complicates this situation. [265] reported that this chaotic situation resulted in high risks and time-consuming processes during the COVID-19 pandemic.

Transporting infectious patients, whether indoors or outdoors, increases infection spread as well [264]. [23] highlighted the need for safe transportation pathways for patients, HCWs, clinical supplies and specimens within HCFs. The high workloads experienced during IDOs also require transporting patients to other HCFs, which is a complex process involving special measures in the case of highly infectious diseases [88]. This task's risk is increased by the lack of clear guidelines on preparing an ambulance for transporting highly infectious disease cases [264].

Failure to follow appropriate hand hygiene practices in HCFs also spreads infections [88, 303]. According to [303], during the COVID-19 pandemic, compliance with hand hygiene regulations in non-isolated areas in HCFs by patients and their families was around 40%. Furthermore, hand hygiene compliance of HCWs and patients fluctuates, even during a pandemic, as reported by [304]. In some cases, hand hygiene practices fail even if followed strictly. [305] reported on a case of an infectious bacterial outbreak in a hospital caused by contaminated faucet aerators used to wash hands.

Failure to follow infection control policies also spreads infection in HCFs. [23] stated that this issue arose from poor communication of infection control policy to HCWs and patients. [170] argued that the conflicting guidelines during the COVID-19 pandemic resulted in confusion among HCWs. The failure to follow infection control measures is also caused by unfamiliarity with regulations and inadequate training [33, 302, 306, 307]. Training on such measures should be incorporated into the preparedness phase and not performed during an outbreak. The lack of time required for training during an IDO was highlighted by [36, 300]. Training limitations faced by certain groups of HCWs were also mentioned: [35] reported how midwives lacked the proper training to perform their duties under IDO conditions. [264] argued that there is a need to train HCWs to perform ICU medical procedures while wearing cumbersome PPE.

Laboratories pose a high risk of infection spread [10]. Laboratory staff and technicians easily catch infections during their work [239]. Veterinary laboratories are especially dangerous as they handle many high-risk pathogens infectious to humans and animals [134]. This high risk requires strict adherence to safety protocols and infection control measures, such as the selection of appropriate PPE matching specific specimen requirements; following correct donning and duffing procedures; and following other laboratory safety measures, such as buddy systems [239, 264]. In addition, it is important to identify staff members working with specific high-risk specimens. and for them to pay special attention when transporting specimens [239, 264].

3.3.3.5.1.2 *Corpse transmission.* Another high-risk scenario is transmission via corpses of IDO victims. Corpses can have a high viral load, especially in the cases of specific diseases, such as Ebola [87]. IDOs can overwhelm the corpse processing system, leading to slow processing and increased infections in those who handle bodies [308-310]. Safety measures and protocols must be devised to reduce the possibility of transmission; handlers should be trained in safe corpse management and provided with PPE [309, 310]. Furthermore, different protocols should be put in place for different institutions handling human corpses, such as hospitals vs. funeral homes [172]. Protocols should be planned beforehand because the development of such protocols during an IDO is chaotic, as witnessed during the COVID-19 pandemic [172].

There is a need to fast-track burial licences and other related paperwork during IDOs [308]. The high number of deaths often requires digital systems to accelerate the documentation and processing of death certificates [309], and issuance of death certificates promptly requires adequate sharing of the personal details of the deceased [309]. Adequate and consistent documentation and labelling of victims' corpses to ensure prompt issuance of certificates should be the norm [309]. Traceability of the deceased's history also requires accurate registration when admitting the victim to hospitals, which highlights the need for adequate data entry at all stages [309]

High death rates during IDOs may require temporary storage and transportation of corpses [309], and such operations require adequate protocols to reduce infection spread [310]. This highlights the need for meticulous corpse preparation and transportation hygiene, both nationally and internationally [308]. Corpse handling protocols should also include safe burial guidelines. This is important because certain cultural practices, such as ceremonial washing and touching, increases transmission risk [87, 309]. Safe burial practices should be followed, whether the disease is confirmed or suspected, to minimise transmission risk [310] [309]. The involvement of the authorities may be needed to ensure workers follow safe burial practices [310]

3.3.3.5.1.3 Infectious solid waste. The COVID-19 pandemic showed that many countries, including developed ones, were not prepared to process solid infectious waste during a pandemic [311]. Infectious waste generation increased significantly during COVID-19. [199] reported that the Province of Hubei in China saw a six-fold increase in healthcare waste during the COVID-19 pandemic, and the same trend was observed in other countries. The high volumes of waste generated, coupled with limited capabilities to manage it, increased infections in the general population and workers in the waste management sector worldwide [311-313]. The lack of capacity to manage infectious waste caused illegal dumping, which further spread the infection [137]. The risk of spread may be magnified by the ability of certain pathogens to remain active on contaminated surfaces for long periods [137].

Many countries did not have infectious waste management plans for IDOs in place and started thinking about this challenge too late. In most cases, infectious waste handling was an afterthought that surfaced after authorities established testing centres, care provision and quarantine protocols during the COVID-19 pandemic [313]. This lack of planning led some countries to seek innovative solutions to manage infectious waste [136]. Cement plants were one of the alternative incineration methods the Spanish government recommended, for example. Norway allowed transferring waste to other locations to address the surge in volume [136].

Like many other planning tasks involved in pandemic management, planning for infectious waste management is a challenge. [264] highlighted that the safe handling of infectious waste is challenging because creating a segregated environment for infectious waste is necessary. This task requires close coordination between health authorities and the waste management sector [136]. One of the first issues that planners need to consider is that the number of infections during IDOs can fluctuate widely [199]. This is especially relevant in the case of medical waste, as dedicated processing facilities are usually designed to handle specific and steady quantities of waste, not surges [201]. Another challenge faced when devising waste management plans for IDOs is the constant movement and expansion of sources of infectious waste [137], including changes in location of quarantine centres, or even domestic travel of confirmed or suspected cases.

Highly infectious waste such as PPE generated by both HCFs and the public should be specially treated during all disposal stages, from segregation, collection and transportation, to its final destruction [198, 264, 311]. Infectious waste should be disposed of appropriately from its source to prevent contaminating other waste and to reduce overall volumes of infectious wastes. In fact, [199] argued that between 75%–90% of waste generated by hospitals is non-hazardous.

The need to segregate infectious waste at its source requires the introduction of infectious waste disposal education campaigns for both the public and HCWs [200, 314]. In a study conducted in Poland, [200] reported that some residents were unsure how to dispose of used PPE. [198] reviewed studies that showed how medical students and non-technical hospital workers lacked the knowledge to deal with biomedical wastes. The author also cited a study conducted during the COVID-19 pandemic, which reported that less than half of the HCWs in Pakistan knew how to dispose of infectious medical waste, such as used PPE, safely. This issue has also been faced in previous pandemics. [197] reported that many HCWs could not identify or follow regulations on the safe handling of medical and contaminated wastes during the 2014 Ebola epidemic in West Africa. Clearly, education should be part of preparedness efforts as, during a large IDO, news and instructions about safe waste handling are unlikely to be prominent media concerns [200].

The constant changes to waste collection points make organising infectious waste collection challenging [199, 311, 312]. During the COVID-19 pandemic, these changes increase the operating costs of waste collection companies and discourage some from following regulations [200]. The author also stated that only a few waste collection companies in Poland demonstrated correct procedures in following waste collection safety regulations [200]. In addition, the fear of exposure led to staff shortages in the waste management sector and increased burdens of care on the remaining staff [137]. The need to reduce infection risks, and staff shortages, led to calls to train waste management workers on infection prevention measures [198, 201, 315]. Some European governments retrained waste management staff during the pandemic [199].

The low capacity of the waste management sector to dispose of higher volumes of waste resulted in infections. A study by [136] recommended incineration. However, the same study stated that incineration facilities in some countries could not keep up with the high volumes of infectious waste during the COVID-19 pandemic. The lack of incineration facilities may have resulted in illegal dumping in locations near to water, contaminating it, and the further spread of infections is likely in this scenario [137, 199].

Recycling could be considered a method of final disposal of infectious waste. This method also has its risks, especially in developing countries because recycling in most developing countries is done by the private sector, which is hard to monitor [136]. In some countries, vulnerable workers, e.g., women and children, sort infectious waste manually at dumpsites, which increases the risk of infections [137]. Another issue faced in developing countries is that waste is sometimes dumped in the open, or in unsecured landfills, resulting in transmission to waste scavengers, livestock and wildlife, or contamination of nearby water sources [136, 199].

3.3.3.5.1.4 Infectious liquid waste. Liquid infectious waste, such as the bodily fluids of infected patients, is rarely mentioned in the literature. This is a high-risk type of waste as it is often carried by wastewater systems to other environments, where animals further spread the pathogen to humans [69]. Plans to manage liquid infectious waste and to disinfect wastewater to avoid disease transmission may be required for IDOs [229]. The risks are magnified because more than 80% of wastewater produced globally, and around 95% of that produced by developing nations, is discharged without treatment [229]. In fact, [264] argued that HCFs should plan for this kind of waste and that it should be neutralised before being discharged into the wastewater system. However, hospitals are only one of the potential sources of such waste. A widespread IDO caused by a highly infectious, water-borne pathogen may require converting large-capacity buildings, such as schools and hotels, into isolation and quarantine centres. Such an IDO can also result in people being isolated in their homes. Many buildings have poor plumbing and infrastructure, with no water disinfection capabilities, resulting in widespread wastewater contamination and infection spread [229]. Such a scenario may be even more catastrophic if, during the IDO, floods or blockages to the wastewater system occur [316].

Many scenarios could result in pathogen transmission through wastewater. These scenarios include direct skin contact; inhalation of droplets generated when wastewater flows experience force, such as driving vehicles or gravity; touching objects contaminated by those droplets; or washing up using contaminated water [201, 316]. Washing includes a massive collection of objects such as household items, bus stops, rails, doors, windows and many other items [316]. A famous case illustrating the seriousness of this transmission method occurred in 2003 in a large apartment complex in Hong Kong. A single case of SARS infected 321 residents via aerosols and droplets generated due to a combination of contaminated faeces and wastewater caused by a poor plumbing system design [229, 316].

Challenges arising from this type of transmission remain unaddressed, even by the WHO. The current wastewater recommendations by the WHO are aimed at wastewater disinfection at centralised wastewater treatment stations. These methods cannot address some of the scenarios highlighted above, and should be updated to suit decentralised wastewater disinfection [255].

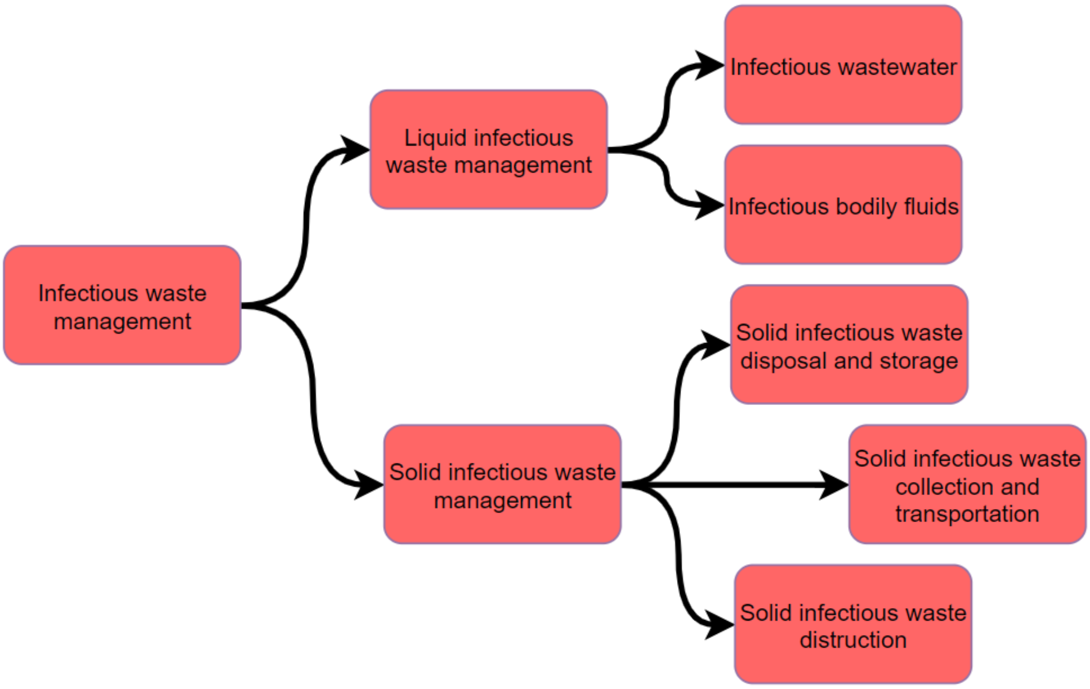

Figure 0-14 infectious waste management

Note. Figure 0-14 is the author's original work.

3.3.3.5.1.5 *Transportation.* Of the studies retrieved to support this research, the only one that discussed the transmission of infectious diseases on aeroplanes in detail was [317]. The study highlighted the role of aircraft ventilation systems in spreading infection between passengers. This happens because aircraft ventilation systems circulate air in a way that creates "air bubbles" shared between three seat rows. Thus, most passengers in an aircraft sit in overlapping air bubbles, resulting in a high risk of infection. [317] cited a study by [318], which stated that aircrafts with poor ventilation systems that park at airports with passengers on board for several hours yield high transmission rates. The study reported a specific case of an aircraft-generated flu transmission rate of 75%. Certain commercial considerations are a root cause of limited aircraft disinfection. Thorough disinfection takes time, which can reduce the profits of airline companies. In addition, frequent disinfection using strong chemicals damages internal components and cabin fittings, resulting in higher maintenance costs for operators [317].

A lack of training for check-in staff at airports also prevents the detection of infectious cases before they board the plane. Training limitations faced by other staff involved in air transport result in breaches of containment protocols when suspected cases arrive [317]. Furthermore, contact tracing is difficult to conduct due to legislation and data sharing challenges [317], e.g., limited cooperation between the airlines and public health authorities.

The high risk of infection on board cruise ships is exacerbated by their large passenger capacity and the duration of sea travel, which is significantly greater than aircraft [319]. In addition, their ventilation systems and cruise ships' airtight nature make them a high transmission risk. In most ships, ventilation is controlled by a central air conditioning unit, and the air inside cruise ships is circulated internally to save costs related to the heating and cooling of air taken in from the outside [319]. Inadequate IDO prevention and response measures on board cruise ships, including inadequate disinfection measures and truncated medical and testing capacities on board, magnify the risks [319, 320]. Reporting and surveillance on cruise ships can also be sparse, resulting in outbreaks extending to ports of call. Passengers on ships also avoid reporting diseases or visiting HCFs on board because they want to avoid isolation. A lack of knowledge of the disease reporting process among the ship's crew also results in poor reporting [320].

The inadequacy of current IDOs management methods used at ports is another issue that increases the probability of an outbreak infiltrating port operations [319]. The limitations faced at ports include inadequate disease data sharing with authorities [320]. Also, all ports' capabilities differ depending on the host country's capabilities. In some cases, coast guards do not have adequate emergency plans in place to respond to a fast-paced IDO containment order [319]. Containment challenges also arise from overlaps or gaps in the cruise ship management responsibilities [320].

Shared land transport, such as buses and metros, is one of the main ways infections can spread [166, 321]. The risks are influenced by shared ventilation systems and sporadic cleaning and disinfection of air conditioning filters [322]. Interventions that may be useful in reducing transmission on public land transport include:

- the disinfection of vehicles [215];
- a change to on-demand services [215];
- the education of passengers on safe practices [215];
- mandatory facemask wearing;
- the physical protection of the drivers;
- travel by reservation only;

- increasing customised bus routes to reduce the need for passengers to use more than one bus line to reach a destination;
- reducing the occupancy rates in busses; and
- regulating the demand for public transport to reduce crowdedness by promoting flexible working hours and remote working [322].

3.3.3.5.2 Challenges faced by HCSs. HCSs are the main tools we rely on during an IDO. Many past pandemics and epidemics have exposed inadequacies faced by HCSs, and these were experienced on a scale never seen before during the COVID-19 pandemic [43, 84, 87, 91, 225]. The challenges faced by the HCSs include an inability to cope with high workloads [36, 148], the high number of infections in HCFs [10, 279, 299, 300], shortages of supplies and supply-chain disruptions [10, 91, 180, 323], and shortages of human resources and equipment [88, 91, 169, 279, 301]. Figure 0-15

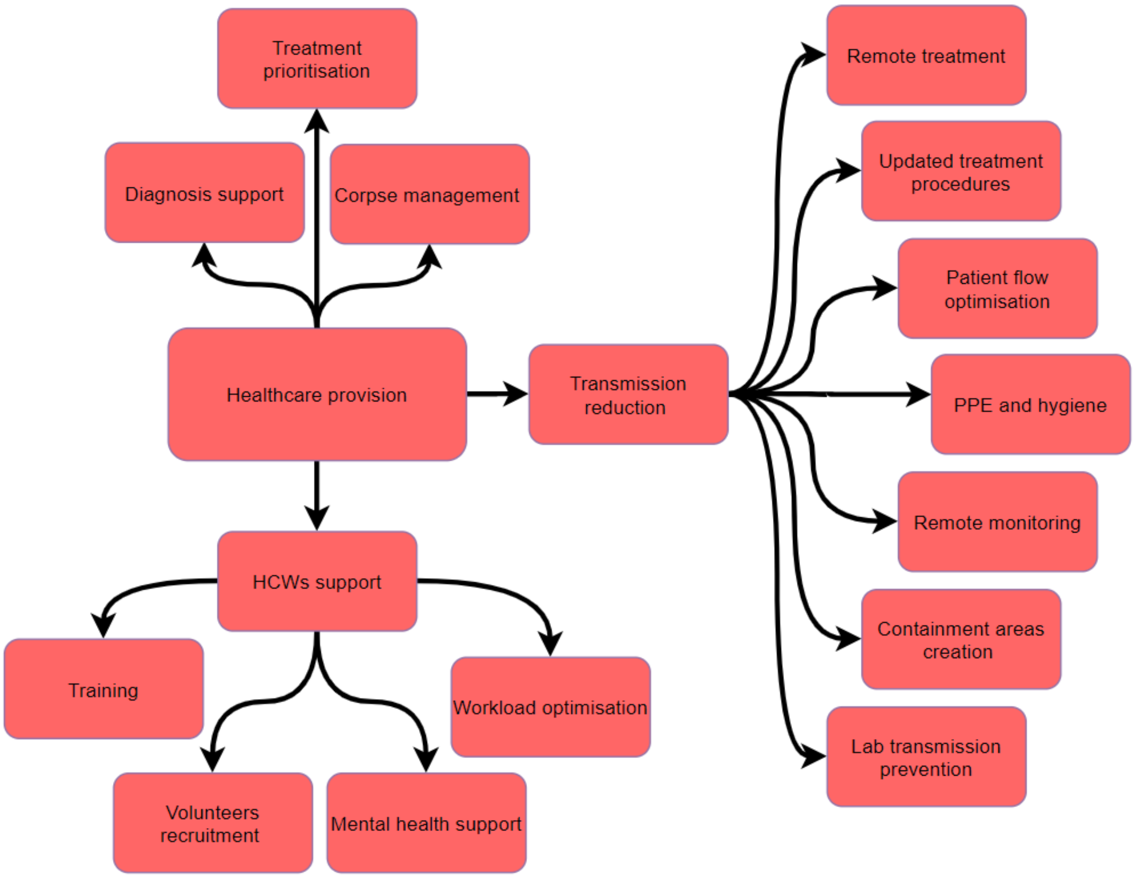

Figure 0-15 tasks involved in healthcare provision during IDOs.

Note. Figure 0-15 is the author's original work.

Abbreviations. HCW, healthcare worker; IDO, infectious disease outbreak; PPE, personal protective equipment.

3.3.3.5.2.1 High workload. The increased workloads generated by IDOs overwhelm HCSs and cause adverse outcomes for patients [88]. The Ebola outbreak in 2014 overwhelmed HCSs in Guinea, Liberia and Sierra Leone, which led to HCFs turning patients away [87]. This resulted in many deaths not directly related to the disease [157]. In fact, [36, 148] stated that high workloads in HCSs mean healthcare is often not available to individuals during most peak infection periods. This was the case during the COVID-19 pandemic in both developed and developing countries [68, 91, 279]. High workloads during this pandemic deprived both infectious and non-infectious patients of healthcare. Some patients were chronically ill [37, 272, 324, 325]. Furthermore, high workloads meant that HCWs were not available to treat other infectious diseases, such as malaria, resulting in an increase in malaria cases in certain countries [157]. This is an important issue as countries may, in the future, face two IDOs simultaneously.

High workload can force HCFs to take countermeasures to prevent systems from collapsing. One measure used during COVID-19 and previous IDOs is telemedicine [39, 49, 265, 279, 326, 327]. Telemedicine, aka telehealth, involves providing healthcare remotely using communication technologies and the IoT [75]. Telemedicine is a promising method of providing healthcare. However, the initial cost and training requirements hinder its application [39], and technological infrastructure and literacy levels in the general population also reduce the reach and usage of telemedicine [49, 326, 328]. Adoption rates and public trust are influenced by a lack of international regulations and ethical frameworks for telemedicine [166, 230, 327]. In addition, telemedicine does not allow the physical examination of patients [326, 327].

Another solution to reduce the HCS workload is the cancellation of elective procedures [325, 329]. However, this solution results in increased workloads within the HCS after the IDO has been addressed. It also results in non-IDO disease progression and increased deaths [24, 329]. Another issue highlighted by [329] is that the definition of “elective” is not clear, resulting in confusion and inconsistencies within systems employing this method.

The expansion of HCFs and care areas is an alternative solution to high demand [330]. This method deals only with the physical space limitations of HCFs and cannot address human resource shortages, however. In addition, facilities’ original physical layouts often complicate conversion processes [36]. [301] reported that, during the COVID-19 pandemic, when wards were converted to care for infectious cases, the dearth of PPE donning and offing spaces outside of infectious cases’ rooms was a problem. The logistics and organisation needed in care expansion is complex, too. When infectious cases increase beyond critical care capacity, gradually increasing an HCF's capacity in a step-by-step fashion to provide healthcare to non-infectious patients adds to the difficulties [88]. Recommended de-escalation strategies following the same principle are no easier [48]. Patient transfers to other HCFs may also occur, but this may be hard to achieve in case of large outbreaks as other areas are likely to be suffering from similar shortages of resources [182].

3.3.3.5.2.2 Workforce-related challenges. The human workforce is the core of the HCS [20]. Shortages and failures to ensure their readiness and well-being, be it physical or mental, often result in catastrophic outcomes during IDOs. The term HCW is used in this section to refer to *all* human workers involved in HCSs during pandemics, including physicians, nurses, auxiliary workers, maintenance personnel, security and laboratory technicians [165, 239, 331].

Shortages of HCWs are a favoured theme in the literature; for example, [10] argued that during a severe influenza pandemic, 40% of HCWs may be unable to perform their duties because they or a family member is infected. [332] reported that 43% of emergency medical services personnel are unlikely to work during an IDO. Furthermore, [88] reported that previous experience with pandemics shows that between 40% and 70% of HCWs may not be able to perform their duties. These HCW shortages were experienced during the COVID-19 pandemic in developing and developed countries alike [88, 169, 279, 301]. [33] reported that numerous clinics and wards had to stop providing healthcare and/or cease admitting inpatients because of COVID-19-related HCW shortages. Of course, the most common reason for HCW shortages during IDOs is infection transmission and quarantines required in response to infections [23, 88, 329]. [299] reported that a single COVID-19 outbreak in Tasmania's hospitals, with a total of 82 cases, forced 1,200 staff members to self-isolate. The same study reported that an estimated that 125,000 HCWs have been forced to isolate due to COVID-19 suspicion globally by April 2020.

Increased deaths can also cause shortages of HCWs during an IDO [10, 87]. A study by [10] reported that during the 2014 Ebola pandemic, an average of 7.5% of HCWs in Liberia and Sierra Leone passed away after contracting the disease. Certain groups of workers face increased risk of death because they are vulnerable to the pathogen causing the outbreak. Elderly HCWs rehired after retirement to aid during the COVID-19 pandemic experienced the highest mortality rate of the HCW age groups surveyed [88]. Based on COVID-19 pandemic data from the USA, 92% of HCWs who passed away after contracting the disease had underlying health conditions [88].

Unorganised lockdowns were another issue that prevented HCWs from working in some countries during the COVID-19 pandemic. [302] reported that lockdown rules in Saudi Arabia required HCWs to get travel permits to travel to work. The permit issue process was slow, however, resulting in some not being able to go to work, and others having to pay fines when caught travelling to work without permits. Direct absenteeism can also result in HCW shortages as absenteeism is fuelled by fear of infection. Insufficient PPE was cited as a reason for heightened infection fears resulting in absenteeism [10, 332].

Last-resort solutions include recruiting volunteers, transferring workers from different departments, reallocating HCWs from other facilities and managing the workforce more efficiently [48, 279, 331, 333]. Provision of motivational measures was also suggested by [333]. The application of these solutions may be hindered by the skill levels of recruits and volunteers, and their unfamiliarity with new workplace practices and layouts. Transferred HCWs require retaining on the new HCF's systems, training in local work practices and familiarisation with their new physical environment [33]. During IDOs, volunteers and recruits should be assigned specific tasks that align with their skill levels to overcome these limitations [331]. The combination of inexperienced recruits with experienced HCWs during the same shift is also a best practice [331]. The COVID-19 pandemic saw a severe shortage of ICU nurses, and long-term solutions proposed included the suggestion that governments should support nurses willing to upskill and retrain in ICU care [331].

3.3.3.5.2.3 Protection of HCWs. Yet, most solutions are all reactions to HCW shortages after they occur. Ensuring the well-being and the protection of HCWs before an IDO eventuates can help prevent those shortages before they happen. The protection of HCWs involves addressing and preventing mental health issues that lead to absenteeism, and the implementation of infection prevention measures to reduce the number of quarantined HCWs, and deaths among them. For example, measures taken at an HCF in Singapore included infection reduction methods and the protection of HCWs from transmission [306]. The facility followed a hierarchy of infection control methods originally presented by USA Centres for Disease Control and Prevention Figure 0-16 [334]. The hierarchy consists of five layers illustrating controls that can be used to address occupational hazards. It is used herein to present infection control methods that could be followed in HCFs, and to illustrate some of the challenges that can reduce the effectiveness of these solutions. The five hierarchical layers are: (1) the elimination of the hazard, (2) the substitution of the hazard, (3) engineering controls, (4) administrative controls, and finally, (5) PPE.

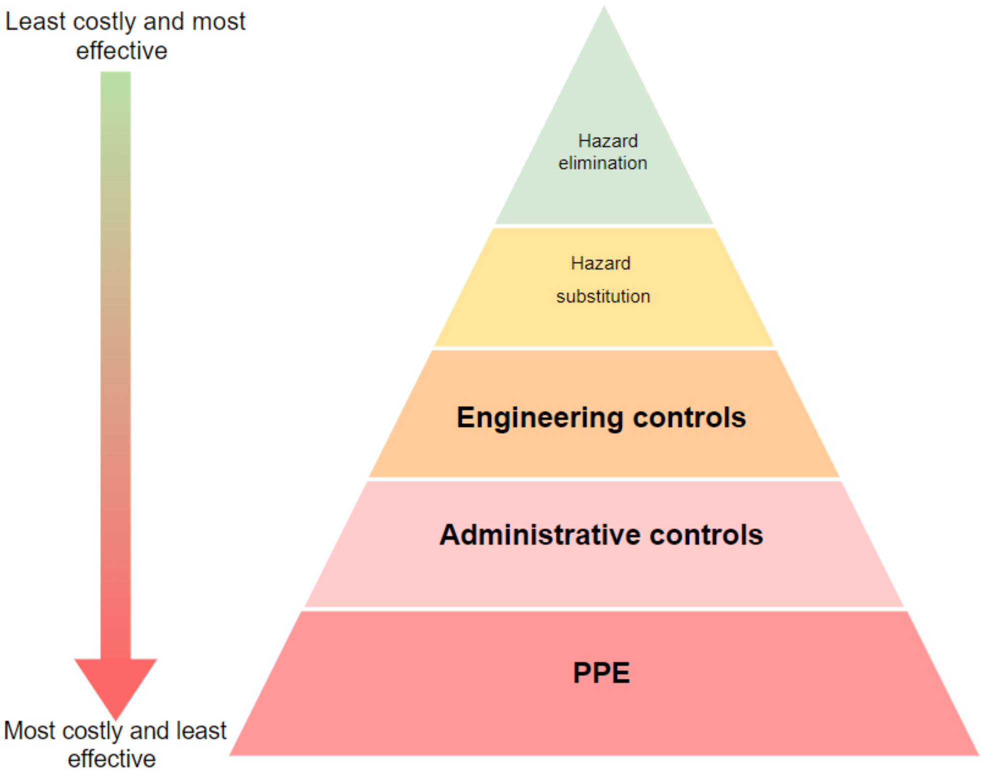

Figure 0-16 hirarcy of infection contorl methods.

Notes. Figure 0-16 hirarcy of infection contorl methods.Figure 0-16 is a duplicate of the figure presented by [334]

Abbreviation. PPE, personal protective equipment.

The elimination and substitution of hazards are the least costly, most effective and hardest initiatives to implement. Unfortunately, they do not apply to HCFs [306]. The description of hazard elimination herein refers to the prevention of hazards altogether [334], which could be understood as spark prevention and fending efforts. Hazard substitution refers to replacing high-risk substances or processes with less dangerous ones that are not fully applicable in the context of IDOs.

Engineering controls refer to actions taken to prevent hazards from reaching workers. These controls can be expensive and cumbersome to initiate, but are cheaper and more effective than administrative controls and PPE over the long term [306]. Examples of an engineering controls in a healthcare setting are remote monitoring and telemedicine. Telemedicine has been suggested by many scholars as a solution to reduce infections in HCFs and to protect HCWs [39, 49, 327]. The implementation of telemedicine has a high initial cost and training requirements. However, running expenses are lower than traditional, on-site care [39]. Other examples of engineering controls are air filtration systems and the disinfection of contaminated surfaces. The risk of transmission via droplets and aerosols is high in closed HCS spaces [229]. Air conditioning systems within HCFs may help limit spread indoors if they maintained and controlled properly [229]. Infectious pathogens spread when people touch contaminated objects and patient care equipment [225]. Examples of such objects include documents, hard surfaces, consumable supplies, medical equipment or even water taps used to wash hands [225, 305, 331].

Administrative controls refer to policies and actions taken by administrators to change work processes to reduce hazards [334]. The cost of the implementation is often cheap, but sustaining administrative controls over time is costly, and they tend to be less effective than engineering controls [306]. Examples in healthcare settings include changes to processes and protocols, such as strict and early patient triage [331, 335], the creation of containment areas [301] and changes to treatment protocols [336]. Indeed, triage is crucial for infection control [23]. This process involves identifying and isolating high-risk patients, transferring them to containment zones and assigning them separate HCWs [331]. The COVID-19 pandemic saw increased use of technology to perform patient triage checks, e.g., outdoors fever screening stations were used to identify suspected COVID-19 cases before they entered emergency departments [265]. Triage, however, can be hard to automate fully as there is a need to make decisions on a case-by-case basis. Two persons with the same symptoms may be triaged differently based on their social contacts or other non-medical reasons [302].

The creation of separate containment areas for infectious cases is a policy that is followed to prevent infections in HCWs to facilitate the continued provision of healthcare for non-infected patients [301]. The creation of such areas involves different sub-tasks, such as:

- training HCWs about isolation rules,

- ensuring HCWs follow separate transportation routes for infected and non-infected patients and use the correct elevators,
- ensuring the usage of assigned equipment and vehicles for the right class of patients, and
- enforcing the appropriate disposal of infectious wastes [337].

In addition to creating containment zones, addressing treatment protocols and patient flow updates can reduce infection rates inside hospitals. But communication about and implementation of updated protocols is challenging. [300] reported that ineffective communication with frontline workers affected the implementation of protocols devised during the COVID-19 outbreak, and [338] described nurses' difficulties in adapting to new ICU protocols.

The last control is PPE. Initial outlays are cheap but less effective than engineering controls, and sustaining PPE supplies is costly [306]. [299] reported that during COVID-19, the risk of HCW infections was three times higher than the risk in their wider communities when ex-hospital transmissions were low. The study argued that this figure indicates failures of infection prevention measures at hospitals, including PPE failures. In fact, PPE usage over a long time also results in physical and cognitive limitations for HCWs [339]. According to [340], wearing PPE for a long time causes headaches, fatigue and dizziness. In addition to physical effects, cognitive tasks such as decision-making and problem-solving may be impacted. [264] also argued that PPE affects manual dexterity and the perceptive faculties of HCWs, and it causes communication difficulties between HCWs and patients [306, 338].

PPE design limitations also limit the ability to reduce infections. [340] stated that infection rates in female HCWs were higher than those in males, which could be caused by sex-biased designs; indeed, PPE is more suitable for larger male features. Another hypothesis is that female and mixed-race medical students receive less guidance on using PPE than their white, male counterparts, which increases infections among them [341]. [303] reported that patients and their families' proper usage of facemasks in non-isolated areas in HCFs was around 73% during the COVID-19 pandemic. [314] argued that HCWs' PPE knowledge lacks depth, and that there is a need for increased awareness. Furthermore, [306] reported that around 15% of physicians involved in the COVID-19 response did not receive prior training on PPE use. During the COVID-19 pandemic, inadequate knowledge resulted in wasted resources, e.g., [300] reported that some HCWs double-masked or double-gloved, even though there was no proof at the time that these practices reduced infection risk.

PPE efficacy also depends on the correct sequence of donning and doffing, and on correct PPE combinations known to be effective against the pathogens causing the IDO [239, 339, 342]. [306] reported that 90% of HCF staff in Singapore did not follow the right donning sequence or use the appropriate PPE during the COVID-19 pandemic. Proper doffing is also crucial to prevent cross-contamination, an argument supported by [264], who advocated careful

PPE removal to prevent cross-contamination of other surfaces [264]. Efficacy concerns include inconsistent and conflicting PPE regulations and guidelines, too. [340] reported that the frequent changes to COVID-19 PPE guidelines resulted in confusion. The same comment was made by [343], who reported that different recommendations coming from different sources caused confusion.

In addition to the PPE design challenges, quality issues have been reported. Shortages of PPE during past IDOs resulted in counterfeit products being sold to and deployed in hospitals [34, 36]. Poor PPE quality was reported as one of the factors behind burgeoning infections in HCWs during the 2012 Lassa epidemic in Nigeria [86]. Furthermore, shortages of medical supplies, especially PPE, which can fuel fear of infections, were also reported to cause mental health issues for HCWs during IDOs [164, 331]. [307] highlighted that a lack of adequate PPE is a major source of stress, and that low-quality PPE causes low morale and affects HCWs' willingness to work during IDOs. This description was supported by [328, 338, 340].

Poor mental health leading to increased HCW absenteeism and burnout suggested that HCW protections need improvement [10, 332]. Knowledge barriers and uncertainties cause fear and psychological stress [164, 340, 344], and these negative emotions arise from conflicting information, frequent policy revisions and changes to the protocols [164, 172, 340]. This was witnessed during the COVID-19 pandemic, where knowledge barriers resulted in conflicting messages about crucial subjects, such as PPE access and guidelines [300, 341]. A study by [279] stated that providing HCWs with fit-for-purpose, up-to-date PPE and data about an IDO prevents psychological and emotional damage because uncertainties about the disease increase the fear of infection, which means more mental and emotional stress for HCWs [86, 164]. At the pandemic's start, uncertainties about COVID-19 transmission modes resulted in confusion among HCWs as to which PPE provided the best protection [302]. Inadequate training exacerbated the uncertainties [328, 340]. Studies by [328, 338] argued that the mental health of HCWs is affected significantly by their perception of how adequate their training and skills are in the face of an IDO. [170] reported that knowledge about PPE is a key factor influencing HCWs' stress levels.

Ethical barriers, and the hard moral choices some HCWs have to make during IDOs, also increase mental health issues. HCWs are trained to save all and any life. However, the situation may be different during an IDO. A scarcity of resources may force HCWs to make difficult decisions about which life to save [185]. Treatment prioritisation and resource rationing therefore cause severe emotional and mental health issues [31, 164, 182, 185]. In addition to the emotional pressure, treatment prioritisation processes result in a great cognitive load, leading to burnout. [338] stated that cognitive tasks require doctors to recall the levels of resources available while evaluating a patient's state against other patients, which means HCWs are forced to make untenable decisions they have to live with for the rest of their lives.

Another moral and ethical dilemma that impacts HCW mental health during IDOs is the conflict between their duties — the community vs. their families — which may be at odds during an IDO [340]. [332] found that approximately 90% of HCWs in the state of Delaware, USA, would report for duty during IDOs if asked; however, only 48% are willing to work if there is a possibility of transmission to a family member. Refusals are compounded by high workloads resulting from increased patient inflows during IDOs [88, 172, 331]. This challenge was frequently encountered during the COVID-19 pandemic [172, 340]. Inadequate HCW workload distribution further magnified the problem; a study by [300] reported that nightshifts were run using reduced staff, leading to increased workload and stress.

3.3.3.5.2.4 Resource-related challenges. Resource shortages have been experienced during past IDOs, and during the COVID-19 pandemic [10, 180, 323] and these shortages were evident even in high-income countries, like the USA [234]. Shortages greatly limited the provision of healthcare during the COVID-19 pandemic [88] and prevented the application of solutions, such as the expansion of HCFs [36]. Even HCFs in areas not badly affected by COVID-19 had to stop providing medical services when resources were transferred to other, highly impacted areas [33]. Basic supplies, such as paper towels, soap and infectious waste containers, were hard to get [345], which meant numerous clinics and wards in many countries could not provide healthcare [33, 165]. Shortages of medical supplies sometimes stepped the provision of intensive care [33].

Shortages of important drugs also plague IDOs, as was the case during the COVID-19 pandemic [35]. Patients with chronic diseases could not obtain their medications [273], or they got only substandard medicines [157]. Shortages of PPE, such as googles, masks and protective clothing, are frequently described in the literature [34, 239], in both developing and developed countries, with many of these reported during the COVID-19 pandemic [33-35, 164, 165, 185, 279, 300]. Lack of medical equipment, such as ventilators, also challenged healthcare providers [10, 36, 180]. This limits some ICU operations during large-scale outbreaks — which happened during the COVID-19 pandemic [33, 182]. The continuous flow of patients needing intensive care during the COVID-19 pandemic forced some HCFs to use anaesthesia machines as ventilators [36].

Resources shortages manifest themselves because of supply-chain challenges that arise during IDOs [289]. The healthcare supply chain is crucial to IDOs management [37], but managing it and ensuring the availability of response resources is extremely fraught during a global pandemic [20]. COVID-19 exposed a suite of difficulties when it caused unique and unprecedented supply-chain disruptions [143, 289], and even resources needed for other infectious diseases, such as malaria, did not reach their destinations [157]. Major supply-chain limitations highlighted by the situation include the fragility and inflexibility of these supply chains, meaning that they fail to meet IDO challenge [172], a failure embedded in the absence of resilience planning. Supply chains under normal operating conditions prioritise efficiency and cost reductions over robustness [234].

Countries reliant heavily on imports of medications suffer catastrophic consequences during a pandemic [272]. The division of labour in medication manufacturing processes also results in a high dependence on certain countries, increasing the possibility of shortages. The PPE shortages that arose during the COVID-19 pandemic were caused by certain countries confiscating PPE within their borders, even shipments heading for other countries [185]. In addition, IDOs' impacts on regions where raw materials come from also slow down production [37, 94]. Shortages of raw materials cause production challenges that are especially hard to address [217], and these disruptions cause global ripple effects that are hard to quantify or anticipate [217]. Raw material shortages also mean that even countries with huge manufacturing capabilities, such as China, are not safe [34].

Most supply-chain disruptions are not a direct result of IDOs; rather, they are side effects of interventions applied in response to IDOs. For example, physical distancing policies in factories result in production drops [217]. Lockdowns and quarantines in exporting countries, such as China, cause supply shortfalls in importing countries [94]. Lockdowns disrupt raw material supplies [289] and reduce the capacities of shipping and land transport industries significantly [157].

A critical issue that inhibits timely responses to supply-chain disruptions is the lack of accurate supply-and-demand data [289]. The unique nature of IDOs renders historical demand data invalid, as happened in the COVID-19 pandemic [289], when managers of many supply chains could not determine the magnitude of the pandemic's impact on suppliers and manufacturers [289]. Stock availability data were also inaccurate, and conflicted in some cases [300]. Clearly, the world needs improved integration of supply-chain information systems [37].

One non-manufactured consumable that could have benefited from better information systems was blood, often in short supply during IDOs, which makes rationing decisions difficult [329]. Blood is a perishable product with a short expiration time, and maintaining an inventory during pandemics is challenging [329]. Shortages are especially challenging in countries that suffer from low blood donations under normal conditions [286]. In addition, many countries have no emergency plans for blood transfusion services [286], which leaves blood banks facing the challenges of securing and protecting blood supplies during IDOs [287]. Therefore, a drop in blood donations means a shortage in blood supplies. Low donation rates are exacerbated by response interventions, such as lockdowns and physical distancing [287]. In addition, the number of donors drops due to infections, isolation and quarantine [329]. The COVID-19 pandemic saw the introduction of travel history screening, which meant further declines in potential donors [329]. Blood collection during COVID-19 was also reduced because some of the most reliable donor groups, such as older people, were considered vulnerable to the pathogen [329]. Even worse, supply chain disruptions and personnel shortages could also result in blood shortages. Supply chain failure could affect the availability of consumables needed for blood collection [286, 329] high infection rates in blood collection staff reduced blood collection capabilities [329].

Solutions to resource-related challenges include ensuring appropriate stockpiles and the close monitoring of these [239, 264, 273]. However, this solution cannot address IDO uncertainties, such as those experienced during the COVID-19 pandemic, and stockpiling can result in massive financial losses if products are not managed appropriately. This issue has been experienced in many countries, such as China, the USA and New Zealand. The latter once had to discard about 1.5 million doses of a flu vaccine with a retail value of about 110 million USD [346]. Another solution especially applicable to PPE is to change the workflow in HCFs to allow for the conservation of PPE. During the COVID-19 pandemic, certain HCFs resorted to minimising the number of HCWs assigned to each patient [36]. Admission protocols were also updated to minimise PPE usage [36]. [302] reported that one emergency department was divided into two sections, one for high-risk respiratory cases, and another for the remainder of patients, to preserve PPE.

A last-resort solution is resource rationing and treatment prioritisation [182]; these processes aim to maximise the benefits of the resources available [146, 182]. However, such processes are loaded with perplexing ethical dilemmas [164, 182, 185], and they can result in tragedies, which were witnessed in countries such as Italy, during the COVID-19 pandemic [31]. Yet, prioritisation and rationing are important parts of an IDO's response and should be planned carefully [31, 279]. Both extremes — ignoring prioritisation or being too stringent with resources — may result in needless losses of life [182]. Therefore, transparent protocols and decision support systems, infrastructure, legal protections and training are required [31, 182]. Lack of clear and transparent prioritisation and rationing during large IDOs decreases the population's trust in the authority and result in social unrest at critical times [31].

Unfortunately, uncertainty and variability in demand and capacity expose the impacts of knowledge and organisational barriers on prioritisation and rationing processes [31, 347], particularly because the processes depend on continuous updates that rely on quickly evolving data about availability and demand [31, 182]. Furthermore, the data required to support these processes derives from various domains and disciplines, posing another challenge [31], and the process itself requires adequate forecasting models to navigate the uncertainties posed by IDOs [193].

3.3.3.5.3 *Policymaking.* Policymakers are involved in all stages of IDO management, from preparedness to recovery [141]; preparedness and resilience building are largely in the hands of policymakers. The same applies to spark prevention and fending, which require the implementation of biosafety measures and EWSs. Responses to large IDOs depend mainly on NPIs, and even in cases where there is a vaccine available for the disease, suitable allocation and deployment policies are required [7, 193]. Furthermore, response de-escalation and restoration also depend on adequate and timely policy updates, and the same applies to recovery.

The involvement of policymakers in all IDO stages means that distinguishing between the policymaking component of the IDO's management and the entire process is difficult. The same can be said about the response phase. Policymaking can be seen as a component of the response phase, or the force orchestrating the entire response phase [49]. Consequently, this section deals only with the issues the literature has directly associated with the policymaking component of IDOs. The main tasks directly associated with policymakers are deployments and updates of interventions, the reduction of interventions' side effects, resource allocation, support of vulnerable populations and public management.

Intervention deployments and updates involve different subtasks; the first is response initiation timing [230]. Response initiation and the timeliness of response are among the main determinants of the success of a response. Policymakers must initiate the response rapidly and early as delays can quickly worsen the situation [146, 298]. Furthermore, early interventions significantly reduce the risk of local outbreaks turning into global pandemics [27, 236]. Response initiation requires accurate risk assessment and disease prioritisation methods to identify diseases to target [72]. This is challenging, especially when dealing with EIDs [72]. Furthermore, the prioritisation of infectious diseases involves assessing their impacts on domains other than health, which complicates the process further [72]. Yet, the prioritisation methods should be timely, transparent and repeatable [72]

Another subtask of intervention deployment is the identification of action thresholds. This is a considerable challenge as those thresholds are pathogen-dependent, and they differ depending on the interventions to be introduced [141, 146]. Furthermore, early implementation of interventions based on inaccurate thresholds often result in unnecessary resource wastage and expenses, while delayed implementation worsen IDO outcomes [141]. There is also a need to identify thresholds for updating, cancelling or reintroducing interventions. As an IDO progresses, certain interventions become less effective, requiring policy changes [37, 48, 153]. Inaccurate timing of these changes may renew the outbreak [37, 38]. A very intuitive example is the early lifting of lockdown measures [37]. Furthermore, [38] argued that one of the most challenging issues policymakers face is identifying a safe threshold for scaling down response interventions.

Accurate evaluation of intervention results can enhance IDO containment; however, this is another challenge faced by policymakers [38, 46, 146]. Monitoring intervention results is a process suffering from intrinsic delays as there is a time gap between the introduction of the intervention and its effects on the overall epidemiological situation [146]. In addition, it is hard to isolate the results of specific interventions during IDOs because, often, many interventions are implemented simultaneously [148]. Furthermore, intervention effectiveness differs based on the characteristics of the target population [193], and effectiveness changes over time due to the feedback loop between interventions and the pathogen's dynamics [49].

Other intervention-related questions that need to be answered by policymakers are:

- What are the outcomes of other, alternative interventions?
- What complications can arise when introducing this intervention?
- What is the probability of complications arising?
- What are the impacts of complications on related domains?
- What can be done to reduce the probability of complications?
- What can be done to reduce the impact of complications? [72, 193]

Interventions applied as a part of IDO response efforts have far-reaching and long-term consequences [44]. One of the main domains impacted by NPIs is the economy. NPIs impact economic growth and result in financial losses for different sectors and industries, e.g. lockdowns [148]. The costs and losses resulting from such interventions lead to conflicts between public health and economic goals, leaving policymakers with perplexing dilemmas [7]. Finding a way out of those dilemmas requires balancing public health and economic growth to minimise NPIs' side effects [146, 153]. One possible solution that may reduce economic losses resulting from NPIs is the introduction of targeted interventions, such as partial lockdowns [255], which are tailored to meet the specific needs of specific areas or groups of the population, instead of blanket-blind policies [37]. However, targeted interventions require accurate and timely mobility and healthcare data to succeed [37, 197].

Figure 0-17 illustrates policy challenges. The horizontal axis shows time progression, while the vertical axis shows infection case growth and resources consumed in the response. The red curve shows IDO growth, while the blue curve shows response escalation and resources consumed in the process. The main task for policymakers is to make the two curves overlap as much as possible — with the help of data and fast intervention updates. Response delays increase infections, while delays to de-escalation result in avoidable economic losses and resource consumption.

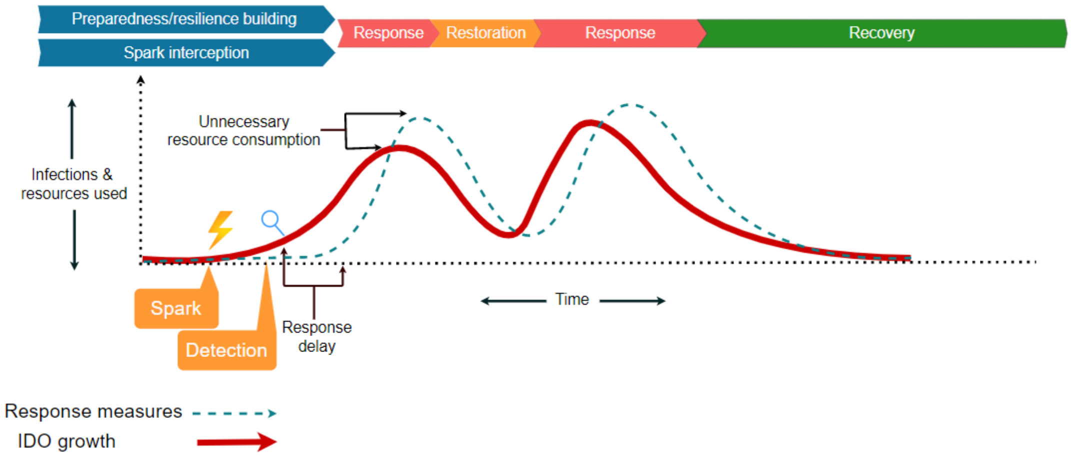

Figure 0-17 The challenges faced by policymakers during IDOs.

Note. Figure 0-17 is the author's original work.

Abbreviation. IDO, infectious disease outbreak.

The response phase during an epidemic or pandemic also involves resource allocation to minimise the effects of shortages. This task is challenging and should be performed carefully, as failure to do so can result in loss of lives and worsen the IDO burden on the whole of society [146, 148, 169, 223]. The difficulties of this process stem from data limitations and modelling inaccuracies. This is especially true at the start of IDOs, when data quality and model accuracy are low [88]. In addition, many available models cannot provide estimates of the IDO's impact on HCSs, which makes resource allocation processes reactive, rather than proactive [88]. Supporting the vulnerable population is a key task requiring resources during the response phase of an IDO [148, 193]. Policymakers' support methods may include vaccine prioritisation or special guidance [7, 45, 193, 267]. The fact that IDOs result in the population being pushed apart due to fear of infections means that vulnerable people need extra support as they could be facing difficulties alone [7, 30]. But policymakers need knowledge, resources as described in Section 3.3.3.1.4.2, and other resources, such as vaccines, to achieve the tasks mentioned above [196]. Furthermore, IDO management decisions are time-sensitive, requiring accurate and timely data [10, 39, 166, 169, 193, 208, 216, 230]. A study by [47] argued that during the COVID-19 pandemic, data scarcity was one of the major challenges faced by policymakers at multiple levels of policymaking, and in more than one county. With current surveillance capabilities, policymakers have two choices: (1) to act fast despite uncertainties, which is a significant concern for epidemiologists [48], or (2) to respond slowly to IDOs and risk wide-scale epidemics and pandemics [185]. One type of data needed for policymaking is accurate epidemiological surveillance data [23]. This could be mass detection data that provide a snapshot of the country's epidemiological situation, such as water-based surveillance [255].

Such data may help in determining accurate policy transition points [169]. Accurate and timely epidemiological data also helps policymakers evaluate the effectiveness of response interventions [43, 49, 193]. Such data also assists with employing adaptive management methods for IDOs, such as targeted and dynamic interventions [169, 197, 255].

The data are also required to generate other types of information required for policymaking. Other information includes data on preparedness and response spending, which illustrates gaps in preparedness and response capabilities, further assisting policymakers with resource allocation [10]. These data also provide insights into the cost-effectiveness of response measures, which guides policymaking and disease eradication campaigns [38, 148]. However, the data may be hard to interpret or use because response and eradication campaigns result in intangible benefits that are hard to quantify in dollars [38].

Resource allocation requires timely data about vulnerable populations (see Section 3.3.3.1, "Preparedness"), HCS capabilities [24, 43, 193] and other available resources [39, 72, 153, 166, 193, 239]. Resource allocation also requires data about high-risk areas [166, 193]. The connectedness of different regions economically and/or socially also needs to be considered when identifying them [38]. In addition, resource shortages result in counterfeit or substandard medical supplies being deployed and used [24], which adds the responsibility to monitor the quality and authenticity of such supplies to the policymakers' tasks. Adequate policymaking depends on epidemiological models [7, 50, 348] and forecasting techniques, which help policymakers estimate the effects of interventions before they are applied [72]; they are also useful when performing resource allocations [146].

The four management barriers mentioned in Section 3.2.2, "IDO management challenges and barriers", complicate the policymaking process, just as the many other tasks involved in IDO management do. In the case of policymaking, knowledge and ethical barriers can hinder the identification of correct intervention or actions to take. These barriers also make determining the scope and particulars of actions difficult. Political and organisational barriers prevent implementations, too. Finally, organisational and knowledge barriers stymie evaluations of the results.

Another task that can be considered the responsibility of policymakers is coordinating response efforts. Poor coordination dogged responses to the COVID-19 pandemic [169], when close coordination between state and local governments was required [211]. In addition, adequate coordination is crucial as dysfunctional interdependencies between systems and agencies involved cause ripple effects that hinder response efforts [40]. Coordination is also required at both the national and international levels, and coherent responses require cooperation from the start of the response phase [10, 48, 94-96, 268]. During the COVID-19 pandemic, uncoordinated national responses limited the success of interventions [165], for example, resource allocation and mobilisation [197].

International coordination of efforts is particularly crucial in the case of pandemics [94], which are transboundary threats requiring tools with an appropriate scope [177, 236]. The poor response of just one country can turn a local outbreak into a pandemic [7]. A lack of coordination was evident during the COVID-19 epidemic, even between neighbouring countries, which made controlling the spread [24, 169]; such coordination is crucial in the fight against vector-borne diseases [45].

Policymakers must communicate clearly and consistently with other stakeholders to ensure an effective response phase. The dynamic nature of the COVID-19 pandemic resulted in a highly evolving body of knowledge requiring frequent adjustments to recommendations, diagnoses and care policies [172]. Failure to navigate the changes and to provide consistent and clear information to HCWs resulted in confusion that hampered infection control efforts [164, 172, 230, 300]. [170] reported that nurses wanted clear, consistent and easy-to-understand knowledge about the pandemic, not mixed messages. Inconsistent messaging was also noted by [300]. Communication was made harder by delays in the translation of studies' findings, which sometimes resulted in outdated and conflicting information [47, 172].

Adequate information provision to the public is another task that falls on policymakers' shoulders during the response phase. Timely communication with the public is crucial to response efforts' success as it can determine the level of support for interventions [10, 146, 322, 345, 349]. Adequate communication with the public is also needed to counter pandemic fatigue, which can be defined as a decline in the public's adherence to response interventions when a pandemic persists for a long time [350]. Furthermore, proper communication policies are needed to address rumours and misinformation [10, 185, 197]. This was a major failed challenge faced during the COVID-19 pandemic, resulting in inaccurate health advice [34, 47, 68, 351]. Misinformation reduced the effectiveness of the response and vaccine acceptance rates [49]. Indeed, misinformation, the long duration of a pandemic and conflicting messages impact the public's trust in the authorities [7, 10, 177, 352, 353]. Incorrect information released to the public is difficult to retract, and re-establishing trust in the authorities after losing it is very hard [177, 185]. Yet, conflicting messages are also derivations of uncertainty and data limitations [7, 177, 185].

Inadequate communication strategies can also result in mass panic, which complicates any response [7, 10, 349]. Panic breeds unrest, or the targeting of specific groups which can be wrongly seen as responsible for an IDO by some [10, 350]. Panic also precipitates crowd surges and panic buying, which means increased infections and supply-related challenges [10, 166]. To ensure continued support for response measure, public communications should be conducted in a simple and understandable manner using suitable media channels [47, 174, 350, 352]. Policymakers therefore should involve anthropologists, sociologists, political scientists and theologians to improve communication and education campaigns [40]. Furthermore, certain population groups require more focused and consistent communications [174], which means targeted campaigns may benefit from data about different population groups' responses to interventions [350].

3.3.3.5.3.1 NPIs. NPIs are the main tools available to policymakers in IDO responses [210]. These tools can be used to control and contain the outbreak. They can also support resource rationing by keeping infections under certain levels manageable by HCSs [148]. Such interventions mainly aim to reduce infections by regulating interactions between people and by implementing biosafety measures and barriers [49]. Example NPIs are:

- facemask requirements;
- quarantine restrictions;
- self-isolation rules;
- limitations on gathering sizes;
- physical distancing;
- lockdowns;
- hygiene measures;
- the restriction of regional and/or international travel;
- event cancellations; and
- closures and postponements of non-essential venues/services [49, 148, 193, 210].

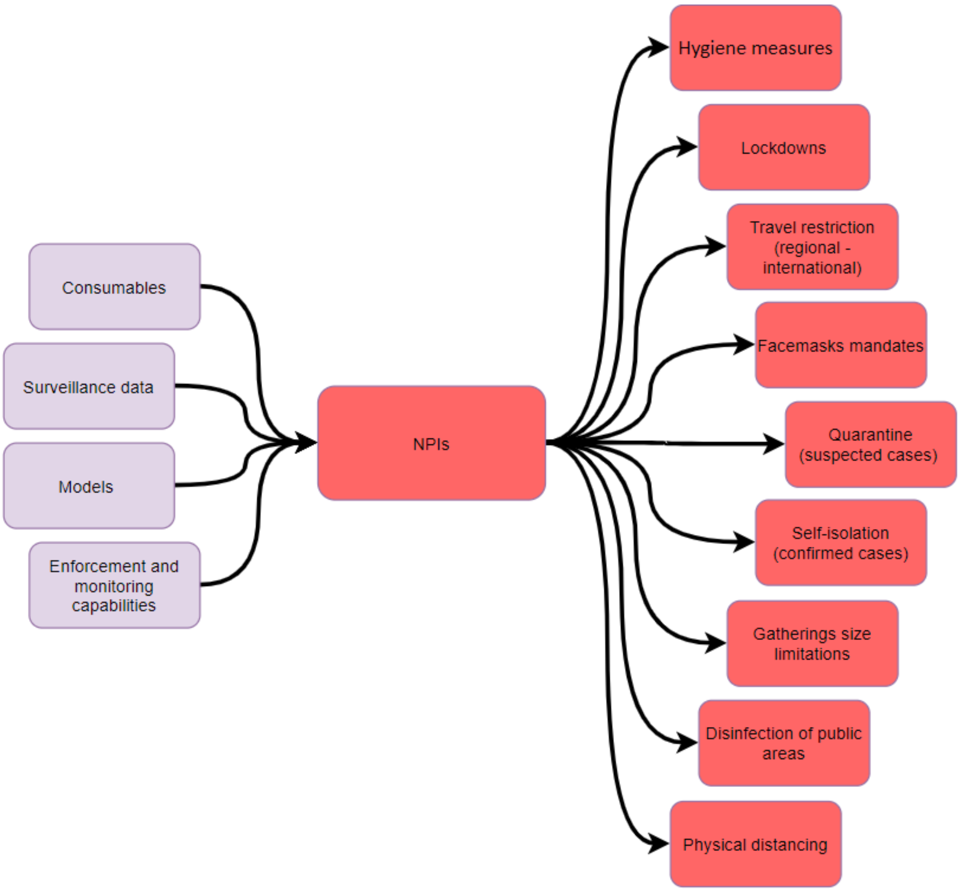

Figure 0-18 NPIs and their requirements

Note. Figure 0-18 is the author's original work.

Abbreviation. NPI, non-pharmaceutical interventions.

The drawbacks to NPIs include a lack of empirical data, which would facilitate their fine-tuning, and their high economic impact. [49] argued that only 15% of academic studies evaluating the effectiveness of NPI are based on empirical data, while 85% are theoretical. [10] reported on intervention costs per death prevented during the response phase; the lowest cost was associated with facemasks, while other NPIs, such as social distancing, quarantines and lockdowns, had high price tags per death prevented [10]. Indeed, NPIs' effectiveness at reducing infections or saving lives differs between IDOs, locations and populations. Factors influencing effectiveness include pathogens' characteristics, such as infectiousness and severity [348]. Effectiveness also depends on the context in which NPIs are employed. Context here refers to other NPIs employed, demographics and the economics of the region [148].

Facemask requirements and hygiene measures, such as hand washing and disinfection, are NPIs that can reduce infection spread. Facemasks are effective, as seen during the COVID-19 pandemic [210]. However, the public's adherence to facemask mandates is affected by multiple factors (see Section 3.3.3.1.4.2, "Challenges faced by HCSs", for more detail). Reasons for ignoring facemask and hygiene mandates include beliefs, values and certain medical conditions [40, 303]. Such mandates are harder to follow in developing countries due to their lack of infrastructure, such as clean water and hygiene facilities [313, 345].

Lockdown NPIs were employed extensively during the COVID-19 pandemic. Lockdowns must be implemented early in IDOs to be effective. These are a powerful NPI; however, they can be hard to implement for long periods as they result in economic and social hardships [10, 37, 148, 255], and their high costs mean governments resist using lockdowns [185], or lift lockdowns prematurely, which should be avoided [37, 185]. Furthermore, lockdowns disrupt many of the services needed in an IDO. For example, lockdowns implemented in response to the COVID-19 pandemic disrupted the production of PPE, testing kits, medications and raw material supplies [289], and reduced shipping and transport industry capacities significantly [157]. Lockdowns also cause increased health problems for some groups, such as patients with chronic health issues, who cannot access healthcare during lockdowns [302, 354]. Lockdowns even affect healthcare provision for other infectious diseases; for example, [157] argued that lockdowns during COVID-19 resulted in people with malaria not being able to access treatment.

Physical distancing is also available to policymakers, but it is costly and imprecise [203]. Physical distancing is difficult to implement due to cultural, economic, population density and environmental factors [283]. For example, shared facilities such as water collection points makes physical distancing impossible [250, 313]. Low-income individuals and families also find it hard to practice physical distancing because financial needs force them to work [172, 250], thus exacerbating economic inequalities that are reflected as health inequalities, too [172].

Self-isolation, another NPI, refers to the restriction of the movement of confirmed cases [153]. The strictness of the isolation measure required differs depending on pathogen characteristics; certain pathogens, such as Ebola, require strict isolation [45]. Like other NPIs, self-isolation requires adherence, and economic hardships make adherence to self-isolation without government support unachievable [250, 313]. Quarantine is similar to self-isolation, but it involves restricting the movement of suspected infectious cases, rather than the confirmed [153]. This NPI is most effective at end-stage pandemic control and disease elimination [348]. The success of quarantines depends on the speed and accuracy of case identification [146, 348], but the precise identification of cases is not always necessary as leaky, or partial, quarantine is enough to increase the immunity of whole societies [348]. Both quarantines and self-isolation require support services to deliver food and medications to suspected and conferment cases [250, 273], which highlights the need for coordination between stakeholders [10]. Delivery of items must be done safely to prevent infection spread, which would defeat the purpose of the quarantine [250].

The first measure countries often take when facing pandemic risks is to impose travel restrictions and close their borders [37]. This is a crucial step in preventing cross-border transmission and reducing the probability of a global pandemic [27, 45, 223]. The closure of borders should be followed by the identification of suspected cases that managed to enter the country before travel restrictions were in force [37]. The effectiveness of travel restrictions depends on the pathogen's characteristics. Asymptomatic pathogens with long incubation periods are difficult to outwit [10, 141], and surveillance systems are limited [7]. The most widely used surveillance methods in this domain, such as thermal scanners, are ineffective in the case of asymptomatic infections [153].

In addition to international travel restrictions, it may be necessary to impose regional travel restrictions. However, implementing regional travel restrictions is even more challenging, as witnessed during the COVID-19 pandemic in Australia [166]. Clearly, internal travel restrictions should be implemented carefully alongside panic control measures, which may forestall mass and rapid population movements [10]. Furthermore, regional travel restrictions require support for crucial cross-regional services, such as the transport of basic supplies [321]

Infections in livestock also require NPIs to curb spread to humans. Such interventions may mean:

- the mandatory slaughter of infected animals and specific corpse disposal methods;
- zoning areas based on infection stages;
- spot checks on animal trading and the sale of animal products;
- monitoring or restricting the movement of humans, animals and vehicles;
- mandating the disinfection of vehicles and equipment used to transport and process animal products; and
- the vaccination of livestock [134].

3.3.3.5.4. PIs (Vaccines). Vaccines are an IDO management tool applicable in more than one phase of the PMC [45, 84, 208]. Vaccines are used primitively as a spark fending measure to reduce the spread risk of infection in HCWs and/or the general population, or as a response tool to contain an epidemic/pandemic. Vaccines can be a very effective method of saving lives as they increase immunity and reduce the number of people vulnerable to a pathogen [146, 227]. Despite their versatility, vaccines are high-cost items: the high costs of research, production and distribution limit their effectiveness [355]. Vaccines must be preserved at specific temperatures because extreme heat or cold affect most vaccines [355]. Their temperature sensitivity requires costly cold-chain distribution [277, 339]. [355] argued that even when suppliers sell vaccines at a reduced cost, transportation and distribution costs can are still a significant barrier to deployment in developing countries.

Costs also increase due to wastage [355]. Poor management of stockpiles results in wastage and additional costs to destroy expired stockpiles [356]. The management of stockpiles is a complex task as different pathogens require different stockpile sizes [356]. Certain vaccines require more than one dose, which further complicates distribution and stock management processes [355]. Poor stockpile management also results in the depletion of reserves, posing a considerable risk that affects the success of vaccination campaigns [356]. About 30% of countries representing all national income levels have reported vaccine stockpile depletions for an average of 37 days due to poor stock management [356]. These “stockouts” are also caused by poor forecasting and funding delays [356].

Furthermore, vaccines require long timeframes for research and development (R&D), which affects IDO response speeds [10]. Vaccine research is a reactive process that attempts to “catch up” with pathogens and their evolution, especially in the case of EIDs [134]. The vaccine research process may take several years [37]. Certain diseases still have no vaccines, even after decades of research, for example, the acquired immune deficiency syndrome (AIDS) [7], Zika and dengue [45]. Furthermore, even if vaccines are available within 6 months after the start of an IDO, the quantities available will be limited [7], and newly developed vaccines are likely to have low efficacy [7, 10]. Furthermore, pathogen mutations often reduce vaccines' effectiveness [37, 357]. Mutations can be a significant issue in the case of a global pandemic, especially if developing countries have no access to vaccines [10, 178].

Another issue that limits vaccine effectiveness is their coverage rate, which is impacted by difficulties in reaching people who live in remote locations or lack permanent addresses, as in the case of homeless people [38, 167, 269]. Security challenges in certain countries may result in risks to vaccination teams, which affect coverage rates [271]. A population's acceptance of vaccines in general also compromises coverage [68, 232]. Vaccine coverage can be low in developing nations due to a shortage of trained HCWs who can administer vaccines [355]. [355] argued that smallpox eradication was achieved only because there was little need for trained HCWs to administer the smallpox vaccine.

3.3.3.5.5 *Research.* Another task that may be carried out during the response phase is the support of research efforts. Research, in general, is a reactive process that is performed to address an existing problem [185]. In addition to its reactive nature, which causes delays, certain research fields face additional delays due to preparatory requirements. A study by [358] reported that the average period required for disease-specific research start-ups is between 188 and 335 days. In addition, low market values for some vaccines and antivirals can reduce pharmaceutical companies' research incentives, which necessitates government intervention, such as support for those companies, or a stronger involvement of the academic community to kick-start research [197].

Start-up delays, in addition to the time-sensitive nature of IDO management, place researchers in fields related to IDO management under considerable time pressure [163]. Time pressures are often magnified depending on the disaster phase the research addresses and in which it is conducted [163]. One of many deadline-related challenges scientists face is the duplication of work, or "scientific waste" as it is called by [185]. The time pressures faced during pandemics also result in scientists bypassing normal checks on the validity of their results, or even resorting to mediums such as social media to address problems [185]. One of the effects of bypassing scientific checks was seen in the increased retraction rate studies produced during the COVID-19 pandemic suffered [68]. Clearly, there is a need to examine ways to enhance the research process and address obstacles that slow it down, without sacrificing scientific integrity. A possible solution to this problem is a global research governance system that can provide an overview of the current state of research [178, 185].

Furthermore, accelerating the research process requires addressing the problems in data collection and sharing (see Section 3.2.2.3.1, "Data quality and sharing", for more details), such as privacy concerns [49]. However, other data-sharing challenges specific to the research process that need to be addressed include the "publish or perish" mentality in academia [46]. This problem limits data sharing, and it is indirectly incentivised as academic organisations are judged based on their publication rates [46]. The reluctance to share data is also motivated by commercial incentives and competition [205]. Furthermore, the reluctance may also be a state-level issue; the feeling that some countries are not benefiting from the data they share may hamper necessary global data sharing [178]. For example, Indonesia shared H5N1 (bird flu) sequence data with the WHO. The WHO then passed the data to pharmaceutical companies, who ended up selling the vaccine they produced from using the shared data to Indonesia. This swindle resulted in Indonesia suspending information-sharing with the WHO [7, 178]. Political barriers cause research obstacles and data-sharing challenges, as evidenced in the COVID-19 pandemic, when researchers from around the world cooperated at its initial stages, even where there was political strain between their countries, but later on, cooperative efforts soured because politicians made accusations about the origin of the virus [178].

Biases in existing data can reduce the effectiveness of research. Most research produced during IDOs is based on data collected from developed countries [10], including management practices and patient protection guidelines. Such research findings may be unsuitable for guiding IDO management in developing countries [307].

3.3.3.6. Eradication and elimination. Disease elimination and eradication are the last tasks in a successful response phase. The strategy required these tasks may differ significantly from that of the response, leading to unique challenges for those involved [38]. Elimination stands for reducing incidences of a certain pathogen in a *given area* to zero cases. In contrast, eradication means wiping out the pathogen *globally*, and reducing the number of active cases to zero [38].

Eradication requires political commitment, sustained investment and population support [7, 38, 45, 359]. Sustained commitment is difficult to garner because the cost-effectiveness of disease eradication is hard to determine. This is mainly because eradicating a specific disease comes with many intangible effects that are hard to quantify [38]. Furthermore, the cost of eradication can vary widely between diseases. According to available estimates, the smallpox eradication programme cost 300 million USD, while the malaria eradication programme cost more than 14 billion USD up to 2011 [359]. The variations in cost depend on the difficulty of the eradication process, which in turn, depends on pathogen characteristics [38], e.g., lifecycle, susceptible hosts, persistence in the environment, symptoms and accuracy of diagnostic tests, among many other factors [38].

Although eradication campaigns differ according to pathogen characteristics, they share several common challenges, such as the increasing cost of interventions and surveillance as the eradication campaign progresses. One cost driver is the difficulty in identifying the last of the susceptible population; detecting low-level infections requires highly sensitive surveillance systems [45]. Furthermore, evolutionary pressures on the pathogen closer to the eradication point often cause mutations that require rapid, frequent updates to surveillance methods [45].

3.3.3.6 Phase 6: De-escalation and restoration

According to [24], IDOs can be classified into two types based on the response strategy: (1) mitigated IDOs, and (2) unmitigated IDOs. Mitigated IDOs are those which are managed using PIs and NPIs, and these come in multiple waves depending on the timing of intervention, the relaxation of interventions, and/or cross-border infections [8, 15]. On the other hand, unmitigated pandemics spread through the population and eventually fade out naturally, either by the hosts passing away or gaining immunity to the pathogen [24]. Both of these scenarios involve a decline in infections after a peak.

Determining whether a decline signals the end of the pandemic, or simply an end of an infectious wave, can be challenging due to the issues described in Section 3.2.2.1.1, “Knowledge barriers” [161]. [146] highlighted the difficulty in detecting new waves of infection. In the case of EIDs such as COVID-19, historical seasonal data is lacking.

Determining a population's immunisation also poses problems due to asymptomatic infections, and because determination of viral infectiousness differs over time and space [146]. Furthermore, pandemic declines may be gradual, over a long period of time. [30] argued that identifying the end of the response phase is difficult as "the end" is unclear and fuzzy. The end's fuzzy nature means that some disaster management frameworks built on the assumption of a clear cut between response and recovery phases cause confusion. Rigid frameworks also result in managers overlooking challenges that need addressing during transitions from the response to the recovery phase.

At a practical level, the inability to determine disease decline, and its gradual nature, result in an overlap between the recovery and the response phases, when tasks need to be carried out simultaneously [30]. These tasks include restoring interrupted services and allowing those involved in response efforts to rest and recover should there be another wave. In addition, the gradual de-escalation of response efforts, which aims to maintain readiness for another wave while lifting and easing response measures, must be considered. Gradual de-escalation is required as hastening this process may cause a resurgence of infections, or new outbreak waves [48]. A logical, scientific and safe approach is therefore needed to guide de-escalation efforts [48]. Questions managers often ask are:

- What is the safest way to de-escalate measures such as lockdowns while minimising infection spread?
- How slow does the de-escalation need to be?
- How long do we need to hold the line before starting the full recovery phase [38]?

These de-escalation decisions should be guided by data collected during the outbreak [48]. Determining a population's immunity is useful in guiding de-escalation efforts [48]. A review of case detection and identification methods, such as contact tracing, may be necessary before de-escalation to maintain control and contain outbreaks should they happen during the de-escalation [48]. De-escalation can be especially challenging for HCSs [88]. HCSs need to be ready to reinstate response measures in case of a new wave, but there is also a need to catch up with delayed surgeries and tend to the needs of individuals who could not access healthcare during the IDO [146, 360].

The ideal de-escalation allows for performing some of the actions that fall under this phase's restoration component, e.g., measures aimed at HCS recovery. HCWs face the possibility of exhaustion and burnout during the response phase [30], so a de-escalation including HCW training to perform tasks that are in demand is vital. Restoration efforts should also include enforced rest for HCWs to reduce the possibility of burnout, including enhanced access to mental health support services for both the population and HCWs [193]. Restoration efforts may also include resource replenishment measures, such as the recovery of the supply chain or ramping up production, or collection of non-manufactured consumables, such as blood supplies.

3.3.3.7 *Phase 7: Recovery*

Recovery in this study refers to actions taken after the elimination or eradication of an outbreak to return society and services to pre-outbreak conditions [20, 147]. The key point here is post-elimination, or eradication, in which actions include long-term recovery efforts that span different domains such as the political, economic, social, health and infrastructural elements [30]. Some of the challenges traditionally considered part of the IDO recovery phase are included in the restoration and de-escalation sections of this thesis. The remainder are out of this study's scope as they deal with the side-effects of IDOs, rather than direct challenges that can result in resurgence, or reintroduction, of the pathogen. However, it is crucial to note that this does not mean recovery is to be neglected. In fact, a key challenge mentioned in the literature is the under-rated and under-resourced nature of the IDO recovery phase [30]. One of the few studies investigating recovery challenges [30] argued that adequate recovery planning is another aspect of resilience building and should not be neglected. The study also highlighted the need for R&D to develop detailed IDO recovery maps [30]

Some of the general challenges in recovery include the inability to transfer recovery plans between countries as these plans are context-dependent, and the outcomes of an IDO may differ based on the country or its population. This complexity results in recovery being a nonlinear process that can progress unevenly in different social domains [30]. Of course, different pathogens require different recovery plans; after a flu outbreak, the members of the society who survive the outbreak will not require supporting healthcare services most of the time; however, for a disease like Zika, children born during the outbreak will need support due to teratogenic neurological deficits caused by the disease [30].

APPLICATIONS OF IOT AND RFID IN IDO MANAGEMENT

This chapter presents the findings of an SLR conducted to elucidate applications IoT and RFID technologies in IDO management. The chapter starts with a methodology section (Section 4.1) explaining the protocol followed when conducting the review. This section is then followed by the findings section (Section 4.2), which presents the results of this SLR.

4.1 METHODOLOGY

This SLR aims to identify current and suggested IoT and RFID technologies applicable to IDO management. The SLR begins with an identification and evaluation of the search string, followed by a description of data collection and filtration. The final stage of the discussion involves data extraction and analysis. Each one of the stages is discussed in Sections 4.1.1–4.1.3 below.

4.1.1 Search string

The search string for this SLR was partially based on the search sting used in the first SLR because both SLRs shared a common field of inquiry: IDOs. Therefore, the first part of the search string used in the first SLR was used in this SLR, too. This section of the search string was also updated to increase its coverage. Terms added were "disaster", "disaster management", "infectious disease", and "infectious diseases". The second part of the search string was devised based on the aim of this SLR, which was to identify IoT/RFID applications. Based on the goal, and after consulting librarians at the AUT, and other researchers working in the field, the default search string was created:

(“Disaster” OR "disaster management" OR "disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR “epidemic” OR “pandemic” OR “outbreak” OR "infectious disease" OR "infectious diseases" OR "communicable disease" OR "communicable diseases")

AND

(“IoT” OR "internet of things" OR “RFID” OR "radio frequency identification")

4.1.2 Data collection and filtration

Databases primarily focusing on health, computer science, disaster and emergency management, health and health informatics were searched. These included PubMed, IEEE Explorer, PLOS and Science Direct. These databases were determined based on AUT's databases list [129] for computer science and healthcare, and after consultations with librarians. Google Scholar was also searched as it is a multidisciplinary database.

The databases selected influenced the search process in many ways. For example, index terms were not used in the search process because not all the selected databases supported index terms. The different syntaxes used in the databases necessitated tailoring the search string to address idiosyncrasies. For example, the maximum length of a search string that Google Scholar can process is 256 characters long [130]. This limitation was addressed by breaking the default search string into three substrings used to perform the search. Appendix B describes the databases, the search strings used and the reasons for string changes in detail.

Search stopping criteria were determined before the commencement of data collection based on guidelines provided by [117, 131]. The stopping criteria were 10 consecutive articles with two or fewer articles relevant to the SLR aims. Once this condition was met, a search on a particular database was discontinued.

The data collection was conducted in two stages. The first of those stages covered articles published in English from 2010 until the end of March 2021. This round was followed by another that targeted studies published between the ends of March 2021 and December 2021. The reason behind the staging was the desire to include the maximum possible number of studies proposing IoT/RFID systems to manage the COVID-19 pandemics. Figure 4-1 shows the records collected at each stage, and the updated count after each screening step.

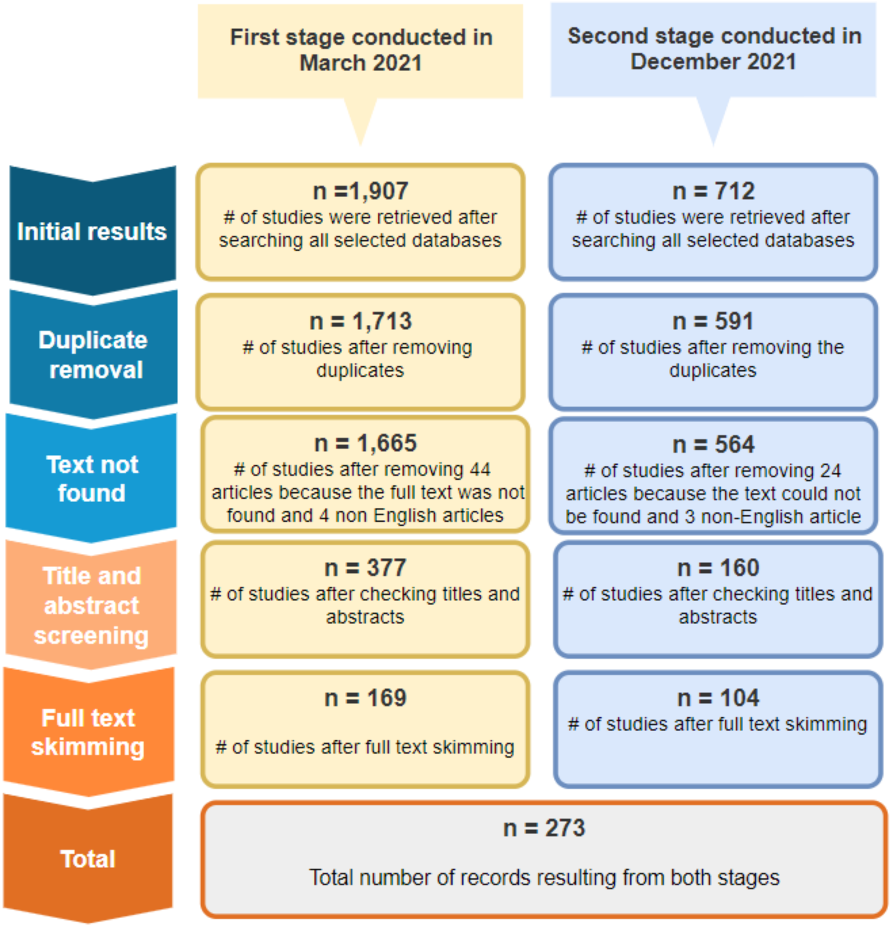

Figure 0-1 Number of studies retrieved and the number of those excluded at each stage of the filtration process.

Note. Figure 0-1 is the author's original work.

The screening protocol illustrated in Figure 0-2 was employed during both stages. The screening process started by excluding duplicates, non-English articles and studies that did not offer open access to the full text. This step was followed by screening the titles and abstracts, and excluding studies discussing applications of IoT/RFID in domains other than epidemics, pandemics or IDO management. This stage also involved the exclusion of perspective and opinion pieces, and theses and dissertations, due to the time limitations of this project. This stage was then followed by the third and final screening stage, which involved skimming the studies' full texts. Studies focusing on technical issues, such as security or software architecture, were removed. Studies focusing on applications of IoT/RFID to remedy IDOs' side effects not directly affecting IDO management, such as remote working facilitation or economic recovery, were also excluded. Studies focusing on AI and ML, with little or no attention to IoT/RFID, were also excluded from the results at this stage.

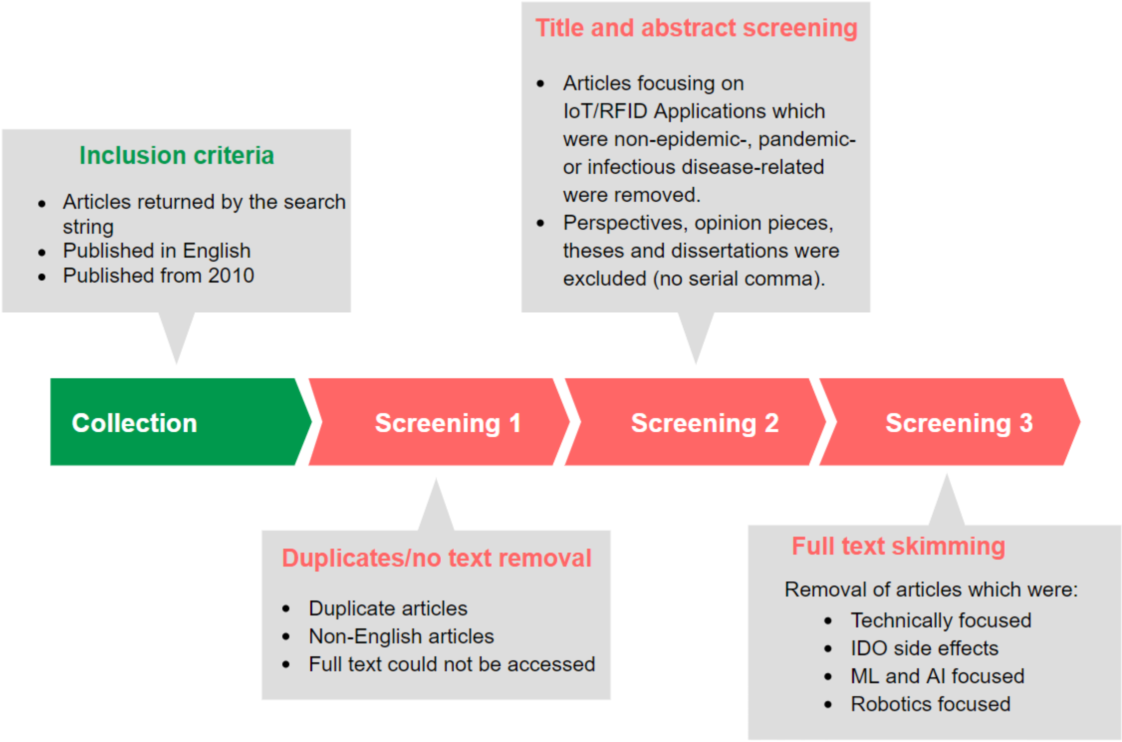

Figure 0-2. Overview of the inclusion and exclusion criteria employed in this SLR

Note. Figure 0-2 is the author's original work.

Abbreviations. AI, artificial intelligence; IDO, infectious disease outbreak; IoT, Internet of Things; ML, machine learning; RFID, radio frequency identification.

4.1.3 Data analysis

The data analysis method used in this SLR was built on the results of the first SLR. The thematic analysis method used in the first SLR was also used in this SLR. Furthermore, the themes identified in the first SLR were used to generate suitable themes for this SLR. These decisions were made because they allowed us to combine the results of both SLRs to highlight unaddressed IDO management challenges. Furthermore, applications of IoT/RFID that could not be directly associated with the challenges identified were added to newly created themes. This process was performed using the same software employed in the first SLR, which is known as NVivo.

4.2 Findings

This section presents the findings of the SLR conducted to identify current and suggested applications of IoT/RFID technologies in IDO management.

4.2.1 CDI

Error! Reference source not found. shows the studies that proposed applications for CDI t asks, which were discussed in Section 3.2.2.3.3. These include horizon scanning, syndromic surveillance, enhanced reporting, event-based surveillance support, enhanced PoC and contact tracing. Contact tracing systems suggested were of two types. The first of these types collects case path data, which is then used to generate a contact list by identifying path and time overlap between cases. The second type of data collected, such as body proximity, directly indicates contacts.

Table 0-1 Suggested applications of IoT/RFID in CDI.

Application	Studies
Climate and environment monitoring — horizon scanning	[361-368]
Vector density monitoring	[367-370]
Vector disease surveillance, climate-vulnerable hosts, mosquito breading sites	[369, 371, 372]
Vector type detection	[373, 374]
Livestock behaviour and movement tracking	[73, 375-377]
Livestock syndromic surveillance	[365, 375]
Cluster and hotspot identification	[56, 368]
Event-based surveillance	[59]
Event-based surveillance/medical resource usage	[378]
Enhanced reporting	[233, 379]
IoT enhanced PoC testing	[73, 74, 365, 372, 380-398]
Point-of-exposure detection	[399, 400]
Syndromic surveillance	[52, 57, 59, 75-82, 194, 365, 367-369, 371, 373, 374, 379, 393, 399, 401-475]
Syndromic surveillance (voice detection and diagnosis)	[59, 421, 459, 476, 477]
Syndromic surveillance — cross-border spread control	[416, 431, 462, 478, 479]
Drone syndromic surveillance	[393, 452, 480-482]
General contact tracing	[54, 57, 59, 82, 376, 379, 399, 406, 411, 412, 421, 422, 429, 438, 440, 443, 444, 447, 449, 452, 454, 461, 472, 476, 479, 483-497]
Indoors path tracking	[377, 402, 487, 488, 490, 497-504]
Indoors contact tracing	[56, 75, 79, 402, 414, 423, 458, 462, 487, 490, 497, 499-501, 503, 505-510]

Abbreviations. IoT, Internet of Things; RFID, radio tracking identification.

The majority of the applications suggested are related to syndromic surveillance. Vital signs monitored by these systems include body temperature monitoring, pulse oximetry, blood oxygen levels, respiratory rate, electrocardiograms and photoplethysmography, among others. Furthermore, a few studies suggested surveillance systems based on voice and cough detection and classification. Certain applications were suggested for controlling cross-border infections, mainly based on thermal scanning. A few studies also combined syndromic surveillance and drone capabilities to achieve mass syndromic surveillance (Table 0-1)

4.2.2 HCS support

Many studies suggested IoT/RFID applications to support HCSs during IDOs (Table 0-2). Some of these applications were aimed at supporting HCS management, including prioritisation and allocation of resources and treatment, and the optimisation and the automation of patient flows in HCFs to reduce infections and increase HCS efficiency. IoT/RFID technologies were also suggested to ensure accurate patient identification and proper healthcare record-keeping.

IoT and RFID were also suggested as a solution to manage and organise the workforce in HCFs, including HCWs and ambulances. Furthermore, bed space tracking and management in hospitals using IoT/RFID technologies were ideas suggested. These technologies were also suggested to support HCSs infrastructure when expanding HCFs and creating isolation wards (Table 0-2).

Table 0-2 Suggested applications of IoT/RFID in HCS management.

Application	Studies
Treatment and resource prioritisation	[59, 82, 390, 414, 428, 430, 470, 486, 510-515]
Ambulance allocation	[56, 484]
Care path optimisation	[494, 510]
Patient flow automation	[83, 393, 430, 472]
Patient identification	[378, 423, 516]
Patient tracking to accelerated healthcare	[402, 423]
Smart healthcare records	[373, 377, 414, 430, 440, 516, 517]
Coordination of HCWs	[471, 486, 517, 518]
Tracking of HCW activity to improve productivity	[377, 414, 430]
Tracking of ambulances	[401, 414, 448]
Hospital bed space tracking and management	[133, 461]
Scaling HCS infrastructure	[519]
Ward isolation	[377, 431, 516, 520]

Abbreviations. HCS, healthcare service; HCW, healthcare worker; IoT, Internet of Things; RFID, radio tracking identification.

IoT/RFID applications were also suggested to support HCWs during IDOs (Table 0-3). These applications aimed to improve knowledge and data sharing with HCWs and reduce medical errors. One recent study suggested using those technologies to ensure the proper section of PPE. A few studies suggested those technologies to monitor the mental health and stress levels of HCWs. These technologies were also suggested to support HCWs' allocation and transfer decisions and facilitate remote training of HCWs. Two studies suggested using those technologies to support the communication between patients and HCWs during IDOs.

Table 0-3. Suggested applications of IoT/RFID in HCW support.

Application	Studies
Improve knowledge sharing with HCWs	[82, 374, 430, 480]
Improve data sharing, including health data	[390, 414, 430, 452, 515, 521]
Improve patient data access for HCWs	[423, 430]
Human expert support for first aid staff	[413, 522, 523]
Medical error reduction	[78, 480]
Appropriate selection of PPE in HCFs	[520]
Stress and mental health management	[79, 82, 365, 399, 447, 461, 462, 472, 486, 491, 524-527]
HCW transfers and allocations	[528]
HCW remote training	[470, 529]
Communication: patient–HCW	[430, 517]

Abbreviations. HCS, healthcare service; HCW, healthcare worker; IoT, Internet of Things; PPE, personal protective equipment; RFID, radio tracking identification.

Scholars suggested the use of IoT/RFID technologies to reduce and control infections indoors, including in HCFs (Table 0-4). Applications mooted included using IoT/RFID to support and automate indoor disinfection, and to monitor and control airflow in hospitals. These technologies were also suggested to support the touchless operation of objects that can spread infections in HCFs, such as light switches and elevators. Finally, IoT/RFID applications were recommended to support and automate the collection, tracking and transportation of infectious specimens (Table 0-4).

Table 0-4. Suggested applications of IoT/RFID for indoors infection control.

Application	Studies
Indoors disinfection	[79, 133, 401, 406, 413, 428, 430, 439, 446, 447, 452, 459, 461, 462, 470, 472, 481, 484, 486, 524, 528, 530-532]
Disinfection duty allocation and requests	[75, 462, 486]
Indoor air monitoring and control	[56, 399, 424, 438, 448, 472, 520, 533-535]
Touchless equipment	[393, 439, 471]
Specimen collection	[447, 452]
Specimen tracking	[378]
Specimen transportation	[428]

Abbreviations. IoT, Internet of Things; RFID, radio tracking identification.

Many studies suggested IoT/RFID technologies to support telehealth, and to support and automate diagnoses (Table 0-5). Patient monitoring, whether outside HCFs or the continuous monitoring of those inside HCFs, especially in ICUs, was also suggested by a few authors. These technologies were also proposed to support remote treatment, and in some cases, with the added use of robotics. Systems to support drug dispensing, administration, adherence and verification were also presented in some studies (Table 0-5).

Table 0-5. Suggested applications of IoT/RFID in telehealth.

Application	Studies
Diagnosis support	[55, 57, 59, 76, 80, 362, 368, 401, 403, 409, 422, 425, 429, 430, 433, 444-447, 451, 452, 461, 462, 467, 471, 472, 479, 480, 484, 494, 514, 521, 525, 534, 536-544]
Remote monitoring	[452, 484] [55, 57, 59, 75, 76, 79, 80, 82, 133, 194, 361, 365, 369, 371, 373, 377-379, 381, 385, 389, 393, 395, 399, 401-403, 405, 406, 409, 413, 415, 417, 421-425, 428, 430-432, 438, 439, 441, 444, 447, 448, 451, 452, 457, 461, 462, 465, 467, 470-472, 477-479, 481, 486, 491, 494, 500, 504, 508, 510-512, 514, 515, 517, 519-522, 524, 526-529, 535, 536, 541, 544-570]
Continuous patient monitoring	[79, 374, 380, 390, 430, 452, 522, 547, 571]
Remote treatment and case management	[59, 73, 75, 82, 380, 401, 406, 415, 428-430, 440, 441, 447, 452, 461, 470, 477, 480, 484, 522, 524, 529, 535, 540, 541, 561, 568]
Robot-assisted remote treatment, case management and communications	[428, 470, 480]
Drug administration and verification	[79, 194, 371, 377, 386, 423, 447, 500, 516, 529]
Drug dispensing and adherence	[133, 406, 428, 430, 469, 517]

Abbreviations. IoT, Internet of Things; RFID, radio tracking identification.

4.2.3 Resource management

Applications of IoT/RFID in the field of resource management were frequently mooted in the literature. These applications included equipment maintenance and sterilisation tracking, in addition to allocation and usage optimisation (Table 0-6).

Table 0-6. Suggested applications of IoT/RFID in equipment management.

Application	Studies
Equipment maintenance tracking	[377, 448]
Equipment sterilisation monitoring	[377, 572]
Equipment tracking and allocation	[56, 377, 378, 414, 423, 469, 510, 516, 517, 528]

Abbreviations. IoT, Internet of Things; RFID, radio tracking identification.

Scholars' suggested applications also included the management of blood supplies and medical inventory (Table 0-7). Studies proposed IoT/RFID technologies to verify the authenticity of supplies. IoT and RFID were also suggested as a solution to support supply-chain management during IDOs. A few studies also suggested using these technologies to support autonomous supply delivery with drones and robots (Table 0-7).

Table 0-7. Suggested applications of IoT/RFID in supply and resource management.

Application	Studies
Blood supply management	[82, 401, 423, 516, 517]
Monitoring medical inventory (quantity and shelf life)	[233, 377, 423, 441, 494, 500, 516, 517, 520, 528] [448, 517]
Product authenticity verification	[377, 517, 520]
Supply-chain management	[82, 377, 406, 423, 448, 469, 520, 573]
Autonomous medical and non-medical supply delivery (drone and robot)	[56, 57, 59, 75, 77, 79, 82, 133, 377, 393, 402, 428, 430, 436, 439, 443, 446-448, 451, 452, 461, 470, 471, 480, 481, 506, 544, 574, 575] [390]

Abbreviations. IoT, Internet of Things; RFID, radio tracking identification.

IoT/RFID can also be used to support vaccination processes and campaigns (Table 0-8). These technologies could be used to improve cold supply-chain management, which is necessary for most vaccines. Furthermore, IoT/RFID have been suggested as methods to track the progress of vaccination campaigns, manage vaccine inventory and monitor and ensure vaccine quality (Table 0-8).

Table 0-8. Suggested applications of IoT/RFID in vaccination campaigns.

Application	Studies
Cold supply chain management	[82, 133, 446, 461, 528]
Vaccination history tracking	[516]
Vaccine inventory management	[472]
Vaccine quality control	[576]

Abbreviations. IoT, Internet of Things; RFID, radio tracking identification.

4.2.4 Policymaking support

IoT/RFID can also support the process of policymaking (Table 0-9). The data collected by these technologies may, as scholars have suggested, significantly enhance the modelling necessary for policymaking. A few studies recommended using IoT/RFID in combination with drones to communicate with the public and to broadcast notifications. Furthermore, some authors suggested using the two technologies to collect data to enable the evaluation of interventions and to support targeted interventions. One study suggested the use of IoT/RFID to support the gradual de-escalation of lockdowns (Table 0-9).

Table 0-9. Suggested applications of IoT/RFID to support policymakers.

Application	Studies
Improved forecasting and modelling	[52, 233, 476, 479, 508, 577]
Public communication enhancement	[52, 59, 79, 413, 428, 430, 436, 447, 575, 578]
Improved data-sharing	[479]
Intervention evaluation	[428]
Targeted intervention support	[506]

Application	Studies
Gradual de-escalation of lockdown	[574]

Abbreviations. IoT, Internet of Things; RFID, radio tracking identification.

These technologies were also suggested for use in NPIs. The main application mooted was the enforcement of adherence to rules governing physical distancing, lockdowns, facemask mandates, quarantines and self-isolation. In addition, scholars recommended IoT/RFID applications to service and support quarantined individuals, e.g., the autonomous delivery of supplies and medication (Table 0-10).

Table 0-10. Suggested applications of IoT/RFID to support NPIs.

Application	Studies
Physical distancing adherence	[59, 75, 79, 82, 133, 393, 399, 401, 406, 411, 413, 424, 426, 428, 436, 438, 446, 447, 452, 456, 461, 465, 471, 472, 474, 477, 478, 497, 519, 520, 522, 547, 565, 575, 579-585]
Lockdown enforcement	[59, 79, 406, 575, 586]
Mask adherence	[57, 79, 82, 395, 436, 437, 439, 445, 477, 478, 519, 521, 565, 583, 587, 588]
Quarantine enforcement	[56, 79, 82, 133, 194, 393, 395, 413, 417, 421, 425, 428, 429, 439, 440, 444, 446, 447, 451, 461, 470-472, 480, 482, 484, 508, 544, 589]
Self-isolation adherence	[399]
Robotic support for quarantined individuals	[429]

Abbreviations. IoT, Internet of Things; NPI, non-pharmaceutical intervention; RFID, radio tracking identification.

4.2.5 General transmission reduction

Several studies proposed using IoT/RFID for transmission reduction in general (Table 0-11). The applications suggested included face-touch alert systems, hygiene adherence monitoring, human body disinfection, identifying and alerting individuals to high-risk areas, tracking positive cases and the disinfection of open locations outdoors. Certain studies also suggested new technologies to reduce transmission in transport industries by supporting the upscaling of services, identifying cases through syndromic surveillance, and controlling and disinfecting aircraft/bus airflow systems (Table 0-11).

Table 0-11. Suggested applications of IoT/RFID to support pathogen transmission reductions.

Application	Studies
Face-touch alert	[461, 511]
Hygiene adherence monitoring	[81, 431, 451, 461, 510, 516, 520, 528, 590-592]
Human body disinfection	[572, 593, 594]
Avoiding high-risk areas	[393, 595]
Disinfection outdoors	[59, 75, 79, 393, 401, 413, 428, 436, 439, 446, 447, 452, 544]
Positive case tracking	[406, 409, 440, 464, 480, 517, 520, 540, 587]

Application	Studies
Transport — demand forecasting	[82, 596]
Transport — in-cabin environmental control	[472, 534]
Transport — syndromic surveillance	[519]

Abbreviations. IoT, Internet of Things; RFID, radio tracking identification.

4.2.6 Infectious waste management

A few studies suggested using IoT/RFID to support infectious waste management (Table 0-12). One study suggested using these technologies to enforce and monitor the correct disposal of PPE. Another paper promoted the use of IoT/RFID to monitor the level of waste in bins. Scholars also proposed IoT/RFID to monitor temporary infectious waste storage sites, and one study focussed on IoT/RFID solutions to dispose of bodily fluids safely. Coordination of the collection and monitoring of the final destruction and sterilisation of facemasks was also suggested in the literature (Table 0-12).

Table 0-12. Suggested applications of IoT/RFID to support safe infectious waste management.

Application	Study
PPE disposal monitoring	[520]
Notification of full bins	[461]
Monitoring waste storage sites	[597]
Autonomous waste collection	[428, 431]
Safe bodily fluid disposal	[535]
Coordination and monitoring of waste collection trucks	[448, 597]
Sterilisation of facemasks	[598]
Sterilisation of waste	[448]
Final destruction monitoring	[597]

Abbreviations. IoT, Internet of Things; PPE, personal protective equipment; RFID, radio tracking identification.

THE DELPHI STUDY

Chapter 5 presents the Delphi component of the study. It outlines activities conducted as a part of this phase and reports the results collected from the two rounds of questionnaires.

The main aims of the Delphi component of this project were to:

- assess the suitability of IoT/RFID to address management barriers identified in section 3.2.2.1 IDO management barriers.
- assess the suitability of IoT/RFID to overcome challenges to employing resources, processes and systems to manage IDOs.
- identify experts' views on the differences between IDOs and other disasters.

5.1 DELPHI METHOD USED IN THIS RESEARCH

The steps taken to conduct the Delphi component of this project are presented in this section. The section starts with an overview of the preparation for the first round of the Delphi study, and it is followed by a description of the tasks carried out while executing the study. The preparation tasks involved in the second round are outlined next, followed by a description of second-round execution.

5.1.1 First-round tasks

The following tasks comprise the preparation stages in most Delphi studies. The preparation stage is followed by the Delphi execution stage, which includes questionnaire dissemination, response collection and analysis, formulation of the second questionnaire, dissemination of the first-round findings and the second questionnaire. These last two steps can be repeated until termination conditions are reached. Figure 0-1 illustrates the flow of these tasks.

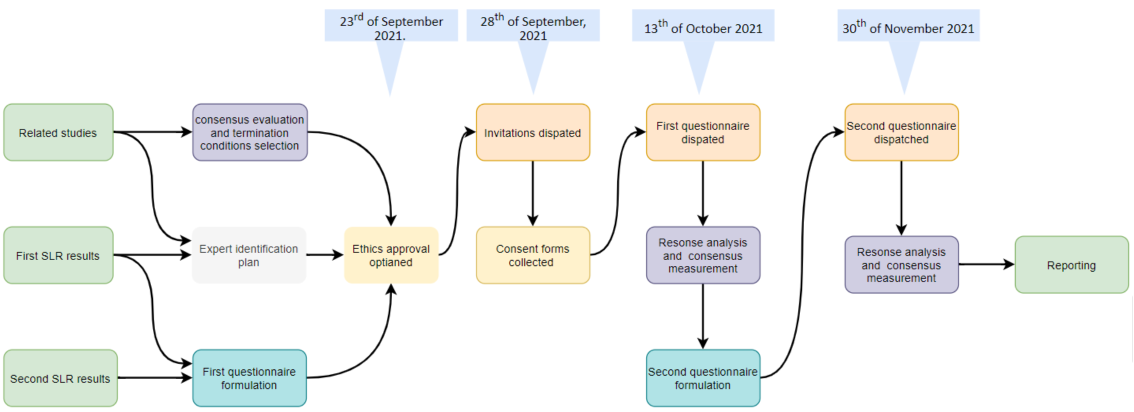

Figure 0-1. The flow of first-round tasks completed as part of this project's Delphi study.

5.1.1.1 First-round preparation phase

As stated in Chapter 2, Delphi studies start with formulation of an initial questionnaire, followed by the establishment of consensus evaluation methods, study termination conditions and participant recruitment processes [126].

5.1.1.1.1 First questionnaire formulation

The findings from the first round of the first SLR resulted in identifying IDO management barriers faced at all phases of the management process. These barriers were used to generate some of the questions presented in the first questionnaire. The questions were designed to evaluate the ability of the IoT and RFID technologies to alleviate the barriers.

The first SLR also identified other challenges affecting specific resources, processes and systems. Challenges that were not addressed by IoT/RFID systems identified in the second SLR were used to formulate some of the questionnaire's components. These questions aimed to evaluate the potential of IoT/RFID technologies to overcome challenges not addressed by IoT/RFID technologies.

The questions designed to evaluate the barriers and challenges identified were presented as five-point Likert-scale questions, shown in Figure 17 [599, 600]. The idea was to capture the participants' level of agreement with a statement proposing the use IoT/RFID technologies to overcome the barrier or challenge in question.

Figure 0-2. The five-point Likert scale used in this project.

Notes. Strongly disagree (dark red) = 1; disagree (bright red) = 2; neutral (blue) = 3; agree (light green) = 4; strongly agree (dark green) = 5.

Since IDO management is a data-intensive process, with its outcomes dependent on data quality attributes [6, 39-42], the desired data quality attributes identified in the first SLR were used to formulate some of the questionnaire's components. The questions were designed to get the experts to evaluate the suitability of specific solutions to collect data with the desired quality attributes. These experts were given three options: (1) IoT/RFID technologies, (2) traditional data collection methods or (3) a neutral option. The experts were also given a choice to present other solutions they saw as suitable for collecting data with the desired attributes.

Open-ended questions were also included in the first questionnaire to allow expert participants to steer the conversation, if necessary, rather than just responding to prompts. These open questions were designed to collect comments on the questionnaire itself, or to give experts the opportunity to suggest other technologies that could help overcome some of the stipulated challenges. A group of questions was also designed to collect experts' opinions on the differences between pandemics and other disasters, which could be used to evaluate the need for future studies investigating disaster management practices and related policymaking activities. These questions were also added to evaluate experts' views on the DMC, and, in light of recent criticisms resulting from the COVID-19 pandemic, the generic view of disasters.

After the formulation of the first questionnaire, it was sent to academics in related fields to be evaluated. One of the evaluation team members raised some points regarding clarity and linguistic expression. These were addressed, and the questionnaire was finalised. The first round questionnaire is presented in Appendix G

The first questionnaire was then transcribed using an online survey tool called Qualtrics [601]. This tool was used to compose and distribute both questionnaires included in this study. In addition to these services, this tool provides certain data analysis services, which were used to some extent in the analysis process. However, evaluations of expert consensus were done using a script written in Java as this exercise was not possible using Qualtrics services.

5.1.1.1.2 Consensus evaluation

The establishment of expert consensus is one of the main components of the Delphi method. Despite this, there are no set rules for consensus evaluation, and different studies follow different methods according to their objectives [602]. One of the most common methods depends on the frequency distribution of responses [11]. However, when analysing quantitative findings of Delphi studies, different frequency thresholds have been used as an indicator of consensus in different studies. For example, [603] considered that 51% of responses in one category were adequate to signal consensus.

On the other hand, [604] used a 5-point Likert scale and a 60% threshold to indicate the participants' consensus. A similar study [11] with close similarities to this project used a frequency-based approach with a threshold of 51%. The approach involved considering both the "strongly agree" and "agree" responses as a single positive bucket. The "strongly disagree", "disagree" and "neutral" responses were considered to be a single, negative bucket.

This study uses a novel consensus evaluation method, which will be referred to as the "conditional consensus evaluation approach". This approach was used to overcome some of the noted limitations of frequency-based approaches while analysing the data. Instead of considering the neutral responses as negative, the conditional approach classifies these as undefined. This approach was followed because some experts selected natural responses during the validation phase of this questionnaire when the question wording was not clear to them. So, the conditional approach was used to reduce the possibility that the consensus reached on a particular question was not due to misunderstanding or unclear questions.

Another reason behind this modified approach was that the final number of participants in this study was odd. This meant that applying the frequency-based method with its 51% threshold would result in consensus for all the questions presented. This can occur when the number of participants is odd because it is impossible to divide the experts into two groups equally, which means the consensus reading is always above 50%.

In addition, three conditions were used as the consensus measurement scheme to avoid this scenario. If one of these conditions was met, the questions were rephrased and carried forward to the second questionnaire. These conditions were coded in Java, and the responses were evaluated using a small computer program written for this purpose. The source code, inputs and outputs are shown in Appendix I, J, K, and L. The logic behind the program is presented in *Figure 0-3*.

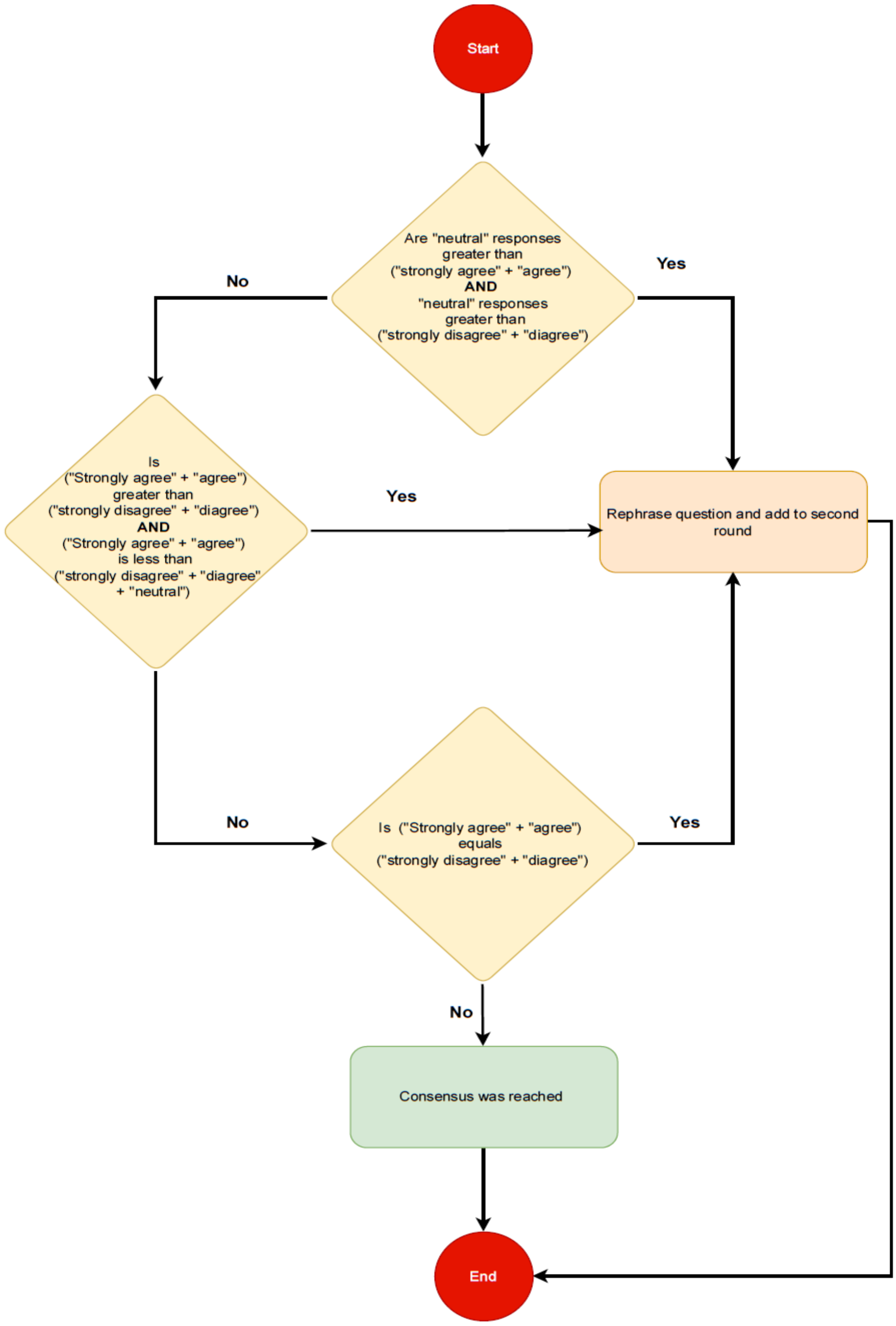

Figure 0-3. The logic flow of the conditional consensus approach used in this study.

The first condition was designed to select questions that received more “neutral” responses than negative and positive responses. This condition can be expressed as follows.

If (neutral > agree + strongly agree) & (neutral > disagree + strongly disagree), then rephrase the question and carry forward to the next questionnaire.

The second condition was to select questions where consensus was researched because “neutral” responses skewed the results, favouring the negative responses category. This condition can be expressed as follows.

If (agree+ strongly agree > disagree + strongly disagree) and (agree + strongly agree < disagree + strongly disagree + neutral), then rephrase the question and carry forward to the next questionnaire.

The third condition was added to find answers that attracted an equal number of negative and positive responses, regardless of the “neutral” response count. This condition can be expressed as follows.

If (agree + strongly agree) = (disagree + strongly disagree), then rephrase the question and carry forward to the next questionnaire.

It should be highlighted that once the Delphi study was finished, the collected Likert scale data was evaluated using the three consensus evaluation methods as described in this chapter. This evaluation was used to check for the validity of the conditional consensus evaluation method. More importantly, some of the outputs of the frequency-based approaches were not consistent with the results of the second questionnaire. In some cases, the frequency-based approaches showed that a question was answered, and expert consensus was established for bucket “x”. However, the second round's rephrased questions yielded results showing that consensus was established for bucket "y" when using conditional, or frequency-based, approaches. This discrepancy could indicate inaccuracies in frequency-based approaches; however, further investigation and dedicated studies are needed to confirm this.

5.1.1.1.3 Delphi termination conditions

This Delphi study had two termination conditions, and if one of those was met, the study was to be concluded. The first of those conditions was the generation of expert consensus on more than 90% of the questions. The second condition was the inability to research a consensus on more than 90% of the questions after a third round. The first round included 41 Likert-scale and multichoice questions. Of those, when using the conditional consensus evaluation method, 12 questions did not generate consensus. Based on this, only 70.7% of the questions generated consensus, which indicated the need for a second round. The second-round questionnaire included 41 questions, out of which four did not generate consensus among the experts. Based on this, 90.2% of the questions resulted in consensus among the experts, and thus, the study was terminated after the second round.

5.1.1.1.4 Methods used to identify experts

The creation of a qualified panel of experts is a determining factor in the success of a Delphi study because the panel is an indicator of study reliability [605]. The main aspects of the panel that needed to be determined at this stage were the number of panellists and their level of experience. The expert selection process followed in this study is a modified version of that followed by [11] due to the close similarities between the two studies.

The process followed by [11] started with conducting literature reviews to identify the disciplines and skills suitable for this project. This was followed by identifying organisations and groups with potential participants. Individuals with relevant experience were then identified. A search for publicly available email addresses was then executed. Participants with relevant experience and publicly available, valid email addresses were then approached and invited to participate in this study.

It was decided that 5–10 experts constituted a suitable size for the panel. Different recommendations for the number of experts to recruit for a Delphi study suggest ranges from five to 100 recruits [126]. These recommendations differ based on the requirements of different types of problems and domains [126, 128]. However, some studies suggested that 5–10 is a good starting number [126], a recommendation followed in this study. This number was also used by [11], who investigated a similar problem as mentioned in the paragraph above.

Other conditions of recruitment included the experts' ability to communicate in English and their knowledge in fields related to this study. The experts recruited needed to demonstrate practical experience or academic achievement in one or more of the fields of:

- disaster management,
- disaster medicine,
- disaster e-health,
- crisis management,
- IoT, and/or
- RFID.

In this study, two methods were followed to identify experts. The first of these was through the literature surveyed in the first SLR, and the second was through the identification of organisations involved in fields relevant to this study. Authors of studies most relevant to this research were identified while conducting the first SLR.

Two organisations were identified as involved in the fields relevant to this study. The first was the Disaster e-Health Community of Interest (DECOI). This group was used by [11] to recruit experts to participate in their study investigating the applications of IoT/RFID in e-health and disasters. The group was founded to connect international experts and researchers in the fields related to disaster e-health, which share many similarities with IDO management. For more information about this group, refer to [606]. Experts from this group were identified, and their email addresses were collected through an online search. The second organisation that was identified as relevant to this research was the New Zealand IoT Alliance [607]. This alliance consists of organisations and individuals working in IoT development and research in New Zealand. This alliance represents almost 500 organisations working in fields related to IoT [608]. The expert recruitment process followed in this study is presented in Figure 0-1

5.1.1.1.5 Ethics approval

Once the four preparatory tasks outlined above were completed, an application requesting ethics approval was sent to the Auckland University of Technology Ethics Committee (AUTEC). After specific AUTEC requirements were fulfilled, approval was granted on the 23rd of September, 2021 (Appendix C).

5.1.1.2 First-round execution

The expert identification stage was followed by sending invitations to participate in this project. Email addresses of scholars identified during the first SLR, and those involved in the DECOI, were collected and added to an invitation list. An invitation email was sent to these experts on the 28th of September, 2021. The invitation email contained project information, and attached to it was a project information sheet and a consent form. Another email was sent to an organiser at New Zealand IoT Alliance with details of the study. The organiser dispatched this email to potential participants. Both of the emails contained details of the ethics approval granted by AUTEC.

A total of 18 participants expressed an intention to participate in the project, all of whom met the conditions to participate. A reminder email was sent two weeks later. Out of the 18 participants, 14 replied with completed consent forms. None of the experts who replied was excluded as it was expected that some would not complete the questionnaires sent, which was the case.

Once the 14 consents were received, an email containing participation instructions and a link to the first questionnaire was dispatched to these 14 recruits on the 13th of October, 2021. A reminder email was sent out on the 28th of October to participants who did not complete the questionnaire. The questionnaire was closed on the 3rd of November, 2021, with a total of nine responses which falls within the recommended number for experts according to [126].

5.1.2 Second-round tasks

Once the first round was concluded and the data collected was analysed, the second round commenced. This started with the preparation phase, which included questionnaire formulation and an ethics approval request to conduct a second questionnaire. These activities were followed by the execution of a second round.

5.1.2.1 Second-round preparation phase

The second-round preparation stage consisted of formulating the second questionnaire and submitting an amendment to the ethics approval application to execute the second round of the Delphi component.

5.1.2.1.1 Second questionnaire formulation

Responses generated from the Likert-scale questions in the first questionnaire were evaluated using the conditional consensus evaluation method. A total of 12 Likert-scale questions did not meet the consensus evaluation condition. These questions were rephrased and included in the second round. Comments and responses to open-ended questions were also analysed, and points raised were used to either improve the Likert-scale questions or generate new questions to investigate issues further. The complete results of the first round are presented in section 5.2.1 Results from the first questionnaire

5.1.2.1.2 Ethics approval

Once the second-round questionnaire was composed, an amendment was logged to obtain the permission of AUTEC to execute the second round. The amendment was logged on the 26th of November, 2021, and the approval was obtained on the 30th of November, 2021. The approval letter is included in appendix D.

5.1.2.2 Second-round execution

The second questionnaire was dispatched as soon as the ethical approval to carry on with the study was obtained. The same methods that were used to dispatch the first questionnaire were followed during this task. Due to the low response rate and the holiday season, the questionnaire was left open for an extended period. An email reminder was sent on the 13th of January, 2022, which resulted in all the remaining participants completing the questionnaire. The questionnaire was closed on the 20th of January, 2022 (Appendix H).

5.2 DELPHI DATA ANALYSIS

Section 5.2 presents the results from both rounds of this study's Delphi component. The scheme used to organise the questionnaires was based on the four phases of the DMC. The DMC was used instead of the PMC (see Section 3.2.1) as it was likely that participants were more familiar with the DMC.

Both questionnaires included Likert-scale questions. The responses to these questions are presented tables in sections 5.2.1 Results from the first questionnaire and 5.2.2

Results from the second questionnaire. Each table has eight columns. The columns' labels are:

- "#" for the question identifier;
- "questions" for the question text;
- "SA", representing the number "strongly agree" responses;
- "A", representing the number of "agree" responses;
- "N", representing the number of "neutral" responses;
- "D", representing the number of "disagree" responses;
- "SD", representing the number of "strongly disagree" responses; and finally,
- column "C", showing the results of the conditional consensus evaluation.

The C-column cells are coloured in green, red or orange. Cells coloured in green indicate that consensus was reached and that most experts agreed with the statement. Cells coloured in red show that consensus was reached and that most experts disagreed with the statement. Cells coloured in orange show that consensus was not reached on this question, and that it was transferred to round two of the Delphi study.

Both questionnaires one and two included open-ended questions and text entry fields constructed to collect participants' comments. The answers and comments left by the panellists are presented in additional tables. These tables have three columns each. The column labels are "#", which holds the response identifier; the "question" column, which presents the text of the question; and the "comment" column, which shows the panellists' responses.

5.2.1 Results from the first questionnaire

Section 5.2.1 presents the results of the first questionnaire deployed as a part of the Delphi study. The questionnaire consisted of five main sections. The first section contained demographic questions designed to collect data about participants' backgrounds. This section was followed by four others, one per DMC phase.

5.2.1.1 Demographics section

The questionnaire's first section was dedicated to collecting demographic information about the participants. Table 0-1 shows the participating experts' countries of residence.

Table 0-1. Participating experts' countries of residence.

Country	No. participants
Norway	1
New Zealand	1
Canada	1
France	1
United States	1
Australia	1
United Kingdom	1
Germany	1
Sweden	1

Abbreviation. No., number of.

Table 0-2 shows the experts' qualifications at the time of this study. As can be seen, eight participants had PhD degrees in fields related to this research. It should be noted that participants had the chance to select more than one option for this question.

Table 0-2. Educational levels of the expert participants.

Degree	No. participants
Doctorate	8
Master's degree	0
MBA degree	0
Bachelor's degree	1
Other	0

Abbreviations. MBA, Master of Business Administration; no., number of.

Based on Table 0-1and Table 0-2, this research was supported by a good selection of experts from different countries, which provided a global perspective on research findings. As most of the participants held doctoral degrees, they presented a good level of expertise and knowledge.

Table 0-3 shows the sectors the experts worked in. It should be noted that participants had the chance to select more than one option for this question. As can be seen, most of the participants had academic experience. Three out of the experts had practical experience in disaster management. Healthcare sector representatives were also three experts in this study.

Table 0-3. The sectors in which participating experts were employed.

Sector	**No. participants**
Academia	7
Research	4
Consulting	0
Government	0
Healthcare	3
Healthcare IT	2
Disaster medicine	1
Disaster management	3
Other (e-health/digital health)	1

Notes. Several participants selected more than one sector.

Abbreviations. IT, information technology; no., number of.

Table 0-4 shows each expert's total years of experience. More than half of the experts had ten years of experience. This total year of experience of our participants gives us a wealth of knowledge of the field and enhances the credibility of the research finding.

Table 0-4. Participating experts' length of service in fields relevant to this research.

Experience (total years)	**No. participants**
0–5	1
6–10	3
11–15	1
16–20	0
21–30	4
> 30	0

Abbreviation. No., number.

5.2.1.2 Preparedness

The second section of the questionnaire consisted of three types of questions. These were (1) Likert-scale questions, (2) multichoice questions and (3) open-ended questions. The Likert-scale section contained four questions. The questions aimed to evaluate the suitability and the flexibility of the IoT/RFID data collection systems used to provide data needed to evaluate IDO management capabilities and support preparedness efforts.

These four questions met the conditional consensus criteria outlined earlier, except for question 1. This question was revised and carried forward to the second-round questionnaire based on comments provided by the participants. The results from the Likert-scale questionnaire component are presented in Table 0-5.

Table 0-5. Results from the Likert-scale preparedness component of the first questionnaire.

#	Question	SA	A	N	D	SD	C
1	Deducing benchmarks and indicators to evaluate early warning systems is more likely to be achieved using data collected by IoT/RFID early-warning systems than data collected using traditional systems.	0	4	3	2	0	
2	IoT/RFID-based early warning systems are easier to evaluate and monitor than those using traditional data collection methods.	1	4	3	1	0	
3	IoT and RFID-based early warning systems are more flexible than traditional early warning systems.	2	4	2	0	1	
4	The evaluation and monitoring of IoT/RFID-based surveillance systems can be automated and conducted routinely.	4	5	0	0	0	

Notes. Four questions comprised the Likert-scale component. Nine expert participants responded. Column headers: #, question number; questions, question text; SA, number of "strongly agree" responses; A, number of "agree" responses; N, number of neutral responses; D, number of "disagree" responses; SD, number of "strongly disagree" responses; C, results of conditional consensus evaluation, with green representing an agreement consensus, and orange representing no consensus either way. Note the absence of red, representing a disagreement consensus, in column C.

Abbreviations. IoT, Internet of Things; RFID, radio frequency identification.

The preparedness section of questionnaire one contained the only multichoice question included in this Delphi study. This question aimed to evaluate the capabilities of data collection systems to provide data during an IDO with the desired quality attributes. The question presented to the panellists was: "Pandemic management requires data with certain attributes. Please indicate whether IoT/RFID-based data collection systems or traditional data collection systems are more capable of delivering data with the following quality attributes."

The nine experts' responses are presented in Table 0-6. The column headers are: "#" for the identifier indicating a discreet quality attribute (six sub-questions); "data attribute", a textual description of the data quality attribute in question; "IoT/RFID", the number of responses indicating that IoT/RFID were more suitable for collecting data with the desired attributes; "neutral", indicating neither agreement nor disagreement; "traditional", the number of responses favouring traditional methods of data collection over IoT/RFID.

Sub-questions 1 and 4 failed to generate consensus among the experts. Those sub-questions were revised and included in the second-round questionnaire as Likert-scale questions. One explanation for the high number of "neutral" responses can be found in comment "f" in Table 0-7. The results for the preparedness section of the questionnaire are summarised in Table 0-7 below.

Table 0-6. Data quality requirements, questionnaire one.

#	Data attribute	IoT/RFID	Neutral	Traditional	C
1	Accuracy	4	5	0	
2	Balanced (unbiased)	6	2	1	
3	Completeness	5	3	1	
4	Granularity	2	7	0	
5	Standardisation	5	3	1	
6	Timeliness	7	2	0	

Notes. One question with six components (sub-questions) comprised the preparedness portion of the questionnaire. Nine expert participants responded. Column headers: "#", the identifier indicating a discreet quality attribute; “data attribute”, a textual description of the data quality attribute in question; “IoT/RFID”, the number of responses indicating that IoT/RFID were more suitable for collecting data with the desired attributes; "neutral", indicating neither agreement nor disagreement; "traditional", the number of responses favouring traditional methods of data collection over IoT/RFID; C, the results of the conditional consensus evaluation, with green representing an agreement consensus and orange representing no consensus either way. Note that red, representing a disagreement consensus, is absent.

Abbreviations. IoT, Internet of Things; RFID, radio frequency identification.

Six additional, qualitative questions were included in the preparedness section of the first questionnaire. These questions generated 22 comments and answers. The first question aimed to identify any data needed for evaluating EWSs that IoT/RFID surveillance systems cannot collect. The items mentioned included data collected by healthcare providers, data from communities with low technological capabilities, data that captures the usability of EWSs and data that could help identify which stakeholders should receive an early warning. Three experts left comments that showed the question was not clear enough.

Comment “b” suggested that benchmarks should be determined before designing and implementing EWSs. However, the idea behind the question was that benchmarks are continuously evolving based on data collected by different systems, and that they are used not only to guide the implantation of new systems, but also to improve the performance of current systems. Comment “c” indicated that the one expert answered the question assuming that the EWSs being examined were general systems and applied to all disasters, not only IDOs.

The second question aimed to identify possible strategies and technologies that could be used to routinely evaluate surveillance systems other than IoT/RFID. This question was included because the evaluation of surveillance systems is a challenge frequently mentioned in the literature. This question generated two comments. Comment “e” expressed the same misunderstanding outlined above by comment “b”. Comment "f" proposed using call logs to record calls made to healthcare providers; however, the idea presented by the expert was not clear. It is possible that their idea was to compare the data collected from those call logs with data collected by surveillance systems to determine the effectiveness of those systems.

The third qualitative question aimed to collect suggestions about other potential technologies that could be used to collect data with the desired quality attributes. Some suggestions included testing, call logs to healthcare providers, telehealth or e-health. Comment “g” highlighted that the expert had selected "neutral" as a response for more than one item in the multichoice question because the systems depended on programmers. The expert added that the neutral responses would transfer to IoT/RFID systems if the systems were implemented appropriately.

The fourth question aimed to collect experts' comments about the preparedness section of the questionnaire. Comment "j" expressed the need for more details about the questions’ context, a comment considered when devising the second-round questionnaire. Comment “k” demonstrated inconsistent definitions of DMS phases between disciplines, or possibly, the unfamiliarity of expert respondents with those terms. This confusion was clear as case detection, a part of the mitigation phase, was considered by one expert to be part of the preparedness phase. Definitions of terms were presented at the start of the questionnaire. However, keeping the questionnaire short meant that complete, detailed definitions were hard to include. The same comment “k” questioned the current capabilities of IoT/RFID sensors to deliver the needed functions. This point was addressed in the second questionnaire by presenting a clear explanation of how a sensor can be used to achieve a specific function. Comment “l” highlighted confusion caused by the phrase "evaluation of the systems". The expert expressed their uncertainty about whether this meant the evaluation of the system or the data generated by the system. All of those comments were taken into consideration when the round two questionnaire was formulated.

The fifth question aimed to identify the differences and similarities between preparedness for IDOs vs. biological attacks, which could be seen as a similar type of disaster. Comments “m” and “r” considered these disaster types to be similar. Comment "r" added that this was especially true if the data needed was available in both cases. Comment “n” pointed out the need to improve question clarity. Comment “n” also highlighted that biological attacks are more geographically focused and sudden than pandemics, which means there is more time to organise a response in the case of pandemics. The differences in spread and coverage of pandemics vs. biological attacks were pointed out in comments "n" and "s". Comment “o” argued that pandemics are frequent, making them more familiar. This comment contradicted comment "p", which argued that pandemics pose more uncertainties than biological attacks, which have occurred before, and that managers have more experience with biological attack management.

The sixth open-ended question aimed to identify barriers that could prevent practitioners from using the same EWS for different pathogens and IDOs. This question generated four comments. The first of these, comment "t", argued that technically, there are no barriers, but that on a practical level, multi-use is only possible if sensors are set up to collect the same signs, or indicators, of more than one disease, and if the capability to differentiate signals from noise is adequate. Comment "u" stated that analysis algorithms and installed sensors may hinder EWS use for more than one disease. Comment "v" stated that overlapping symptoms might make it challenging to identify different diseases using the same EWS. Comment "w" stated that infrastructure issues in adopting EWS solutions could be an obstacle. However, infrastructure issues constitute a general obstacle, not an issue that will limit EWS' usability in detecting and monitoring more than one pathogen. Questions and the comments are presented in Table 0-7.

Table 0-7. First-round qualitative questions and answers on the subject of preparedness.

#	Question	Comment
a	Please mention any data required for defining EWS benchmarks and indicators that cannot be collected using IoT/RFID systems.	*Survey data resulting from contact tracing in communities without high levels of technology access, data collected by healthcare providers.*
b		*Again — perplexed. Desirable benchmarks and indicators should be determined ahead of time, and then the data collected. It seems as though your desire is to simply capture all of the myriad data available from the IoT/RFID capture, and then 'fish' to see if some of it seems relevant. The disaster could have come and gone during this process, whereas knowing the leading indicator ahead of time and specifically monitoring for that may have prevented/moderated the disaster.*
c		*Tsunami early warning systems (seismic activity underwater)?*
d		*Regarding evaluation of EWSs: usability of early warning system; appropriateness of warnings; warning processes (whom to inform about what).*
e	Please mention any other technologies or strategies that could be used to conduct a fast and accurate routine evaluation of surveillance systems.	*I am perplexed by the use of the word 'evaluation'. To me, this means something particular and amounts to efforts undertaken to determine the 'value' of something (intervention/surveillance system) before it is finally implemented. However, I 'feel' but am not sure that you are meaning the ongoing assessment of surveillance data to determine if any leading indicators are showing a significant trend.*
f		*Call logs to healthcare.*
g	Please mention any other technologies that can deliver data with the quality attributes mentioned above.	*eHealth/digital health for surveillance can deliver such data. The reason for so many 'neutral' responses — most technological systems are only as good as their programmers! GIGO still applies. If the programmers make an error, the accuracy, completeness, granularity, standardisation and timeliness of the data may each (individually or collectively) be compromised. IF — everything is programmed perfectly, then these responses would convert to 'IoT/RFID-based systems'. eHealth/digital health systems suffer from the same potential limitations.*
h		*Tailor-made tele-measurement system; offline (non-IoT/RFID) measurement and data storage devices.*
i		*Fast (traditional) testing. Analysis of healthcare phone counselling (symptoms).*
j	Please use the space below to leave any general comments related to the ideas discussed in the preparedness phase.	*I don't feel that I can answer these questions accurately without a better understanding of the context. Is the focus only on COVID-19? Disease propagation in general? What are actual current uses of IoT/RFID in this context? What are the 'things' that are being used to collect the data? What percentage of the population has access to these 'things', and what type of data do they actually collect? RFID implies tracking movements — what has been tagged? What is possible to tag? Are there specific scenarios/vignettes that could be used to clarify what actual process is being studied?*

#	Question	Comment
k		*I shall associate 'preparedness' with the ability to 'detect'. Two comments. First. My knowledge of the spectrum of tags available is limited. From the literature, I understand it is broad, e.g.: "RFID transponders [13] can be manufactured over large scale in any shape and material, including plastics, paper, elastomers, as well as dissolvable organics compounds. The tag can be embedded into things and can be attached onto the human skin as well. Readers can be rugged and multifunction, integrable into a smartphone and even into a smartwatch-like personal device. Not least, RFID relies on standard protocols and is intrinsically low-cost." Bianco GM, Occhiuzzi C, Panunzio N, Marrocco G. A Survey on Radio Frequency Identification as a Scalable Technology to Face Pandemics. IEEE Journal of Radio Frequency Identification. 2021 Oct 5. Second: However, my concern with many of the questions and seeming basic premise is — to my knowledge, we simply do not have the IoT/RFID 'detectors' necessary, let alone with sufficient specificity and sensitivity. Additionally, physical steps are still needed to 'sample' (humans; wastewater; etc.) — it simply cannot, at this time, be done 'automatically', other than for analysis of pre-existing information (e.g., social media syndromic surveillance). The basic concept of using the (largely global) IoT infrastructure and applying (where possible) RFID technology is fine. But practical ability (suitable RFID tags; 'interoperability' with legacy systems) would seem to be getting in the way, and is not (yet) being addressed in this research.*
l		*From the questions, it is not clear whether the "evaluation of surveillance, monitoring, early warning system" as such is meant (i.e., evaluation of the system, its outcome, etc.), OR if the evaluation of data from such systems is meant.*
m	How similar/different is the pandemic preparedness phase from that of similar disasters such as biological attacks?	*Quite similar, I would say.*
n		*The question is unclear. Assume what is meant: "How similar/different is the preparedness phase for pandemics compared to that of the preparedness phase for similar disasters such as biological attacks?" In theory, essentially the same. Both are preparing for the unexpected 'release' of an unknown virulent agent. The main differences (which may not impact the preparedness phase significantly) are a) biological attacks are more likely to be focussed geographically (one town/city; one water supply, etc.), and b) biological attacks are more likely to be more sudden — a pandemic will have a location from which it emanates (equal to a 'patient zero'), which may give other locations some limited time before it hits.*
o		*Given recent pandemics (COVID, SARS, etc.), we have more information on what works and what doesn't work compared to biological attacks.*
p		*Main and potentially significant difference: a pandemic outbreak (as, e.g., the COVID-19 pandemic) is not known; there is very limited experience, which leads to unknown requirements for preparedness; "biological attacks" have been conducted, and there is a certain level of experience, related to a certain "plan-ability" for the preparedness.*
q		*Almost similar. Maybe the intensity of spreading will be higher. So, more preparation required.*
r		*There are key similarities as long as data points can be measured, collected and analysed, ideally in real time.*
s		*Depending on the biological agent. But generally, the pandemic scenario should be slower, less intense and more geographically distributed. Higher probability of warning signs.*

#	Question	Comment
t	Please mention any technical obstacles that could prevent a single IoT/RFID early warning network from targeting different diseases at the same time.	*"Technical obstacles" — probably none; practical obstacles — yes — whatever leading indicator is selected, it must be: 1. common to the different target diseases (or several leading indicators specific to the different target diseases); and 2. be capable of detection within the 'noise' of IoT/RFID inputs.*
u		*Limitations/specialisation of data analysis algorithms to specific disease(s); limitations/selection of chosen/installed IoT/RFID sensor devices.*
v		*Difference between the attributes could be difficult to recognise if the diseases are closely similar*.
w		*Internet reliability, technological readiness/adaptation in low-income settings (countries or demographic groups). Infrastructure. Cost.*

Note. Comments were derived from nine expert respondents.

Abbreviations. EWS, early warning system; COVID, Coronavirus disease of 2019; GIGO, garbage in, garbage out; IoT, Internet of Things; RFID, radio frequency identification; SARS, severe acute respiratory syndrome.

5.2.1.3 Mitigation

The mitigation section consisted of 10 Likert-scale questions and four open-ended questions. The Likert-scale component aimed to evaluate the ability of IoT/RFID technologies to support the functions of EWSs. Challenges such as cross-border transmission, whether among humans or livestock, were examined. This section also evaluated the potential to use IoT/RFID technologies to enforce reporting practices or to support wastewater and syndromic surveillance activities. All questions included in this section met the conditional consensus evaluation criteria and were considered resolved. Question 1 was the only question that garnered negative consensus. Mitigation-related questions and responses are presented in Table 0-8 below.

Table 0-8. Results for the Likert mitigation component of the first questionnaire.

#	Question	SA	A	N	D	SD	C
1	Airlines can use IoT/RFID-based syndromic surveillance systems during pandemics to monitor travellers' vital signs and movements for days before flights, which could prevent virus transmission to destination countries.	1	2	2	3	1	
2	An IoT/RFID early warning system supported by machine learning could help in detecting pandemics when symptoms of the disease overlap with symptoms of other diseases.	1	4	2	1	0	
3	If IoT/RFID technologies were used to collect and record patients' data, artificial intelligence and machine learning could be used to detect large infectious disease outbreaks in hospitals.	2	4	2	1	0	
4	IoT/RFID-based early warning systems can provide a cost-effective solution to low-income countries which have weak early warning systems.	3	3	2	1	0	
5	Identification of outbreaks among livestock in communities of subsistence farmers and nomadic herders could be achieved by equipping a sample of their livestock with IoT/RFID syndromic surveillance devices.	3	3	2	1	0	
6	IoT/RFID-based syndromic surveillance systems can help detect outbreaks caused by unknown pathogens in livestock.	2	5	2	0	0	
7	IoT/RFID-based reporting systems can facilitate and automate the collaboration between veterinary and human health systems.	3	4	2	0	0	
8	Wastewater epidemiological systems can produce more timely and accurate data by incorporating IoT technologies for sample collection and reporting.	3	5	0	1	0	
9	IoT/RFID-based syndromic surveillance systems can be deployed to monitor livestock in transit, which could lead to outbreak detection and prevention before reaching the destination country.	4	3	2	0	0	
10	IoT/RFID-based syndromic data reporting systems can improve adherence to reporting regulations in livestock farms and veterinary clinics.	6	3	0	0	0	

Notes. Nine expert participants responded. Column headers: #, question number; questions, question text; SA, number of "strongly agree" responses; A, number of "agree" responses; N, number of neutral responses; D, number of "disagree" responses; SD, number of "strongly disagree" responses; C, results of conditional consensus evaluation,

with green representing an agreement consensus, red representing a disagreement consensus. Note that, orange, which represents no consensus either way, is absent.

Abbreviations. IoT, Internet of Things; RFID, radio frequency identification.

The qualitative component of the mitigation section included four open-ended questions, which generated 15 answers and comments. The first question aimed to identify if there are possible early warning methods to detect pathogen transmission from wildlife to livestock. The question generated two comments. Comment "a" proposed stricter reporting, and comment "b" proposed classic triage, which in some ways, is also a component of reporting.

The second question aimed to collect comments on the mitigation section of the questionnaire. The question generated four comments, of which comments "e" and "f", related to question 1 in the Likert-scale mitigation component. These two comments highlighted privacy concerns when monitoring travellers' symptoms before flights. Comment "d" suggested that IoT/RFID technologies are more suitable for conventional applications.

The third open-ended question aimed to collect experts' opinions about the differences between IDOs’ vs. biological attack responses’ mitigation phases. This question generated six comments. The first comment suggested that these disaster types are similar and that syndromic surveillance systems could help detect biological attacks. Comments “h” and “j” stated that differences in geographical coverage could result in dissimilar mitigation requirements. In addition to the geographical coverage point, comment "h" raised the point that social and psychophysiological impacts differ in IDOs vs. biological attacks. Comment "i" stated that it is hard to mitigate against biological attacks. Comment "k" stated that unknown pathogens could result in different mitigation tasks.

One issue with the comments about the differences between disaster types during the mitigation phase was that some comments reflected a confusion between mitigation and the response phases.

The last qualitative question about mitigation aimed to obtain experts’ solutions to a key wastewater surveillance limitation. This limitation is that wastewater surveillance depends on testing, which means pathogen samples are required, thus reducing the potential for detecting unknown pathogens. Comments "m" and "n" suggested syndromic surveillance, using social media or direct observation, as a solution. Comment "o" suggested testing for entire families of pathogens, rather than specific strains. The expert stated that it could be possible to detect an increase in the presence of pathogens from the same family, which may lead to the detection of unknown pathogens from that family. The questions and the comments they generated are presented in Table 0-9.

Table 0-9. Questionnaire one: qualitative questions and answers on the subject of mitigation.

#	Question	Comment
a	Please mention any technologies or strategies that could aid the early detection of pathogen transmission from wildlife to livestock.	*Stricter reporting.*
b		*Classic triage, based on a minimum required set of data to detect generally abnormal conditions.*
c	Please use the space below to leave any general comments related to the ideas discussed in the mitigation phase.	*The specific example of livestock monitoring helps significantly and makes it possible to answer the questions more effectively.*
d		*"Please see my earlier 'general comments in response to the 'preparedness' section. Also, perhaps stretching into 'recovery' from 'mitigation'. wouldn't IoT/RFID technology be better applied to mundane but essential aspects such as 'monitor social distancing/home confinement/use of PPE'?*
e		*There are huge privacy concerns associated with surveillance systems for tracking travellers.*
f		*Airlines can certainly use IoT/RFID-based syndromic surveillance systems at airports (and perhaps on-board their planes), but the monitoring of vital signs and movement "for days before flights" appears unrealistic and legally doubtful (privacy protection; data security).*
g	How similar/different is the pandemic mitigation phase from that of similar disasters such as biological attacks?	*Somewhat similar. Monitoring vital signs may also be useful for detecting biological attacks.*
h		*How similar or different is the mitigation phase of a pandemic compared to that of a similar disaster such as a biological attack? Having not made this a topic of even vague personal research, I will suggest again it may be the scale and 'viciousness' of the two that differ and may impact mitigation. Biological attacks (typically) are more focussed/localised and vicious/heinous in the agents used, making those impacted 'victims' with severe and different psychophysiological and social impacts and solutions for mitigation. A pandemic is construed by the affected public as more of a 'natural' event, and the severity and spectrum of psychophysiological and social impacts and solutions may differ. Other mitigation strategies (post-exposure vaccination) may be similar.*
i		*Hard to mitigate against biological attacks since they could be very diverse.*
j		*Potentially unknown pandemic comes with unknown or unclear symptoms, making the surveillance and corresponding mitigation challenging and uncertain — potential biological attacks are fundamentally known, making the detection and mitigation more plan-able*
k		*Similar, though there is the potential for unknown versus known between a pandemic and a biological attack.*
l		*Most likely different early waring and intensity and geographical spread. Pandemic likely doesn't have unaffected areas/services.*

#	Question	Comment
m	Wastewater surveillance can be used only to monitor known pathogens. Please mention any tools or strategies that can help monitor or detect unknown emerging pathogens.	*Social media syndromic analysis — won't 'identify' but might 'detect'.*
n		*Monitor for characteristic symptoms that indicate the impact from any potential pathogen.*
o		*I guess it would be possible to assess an increase in a specific virus type, even if you don't measure the specific strain. Like 'abnormal levels of coronaviruses', even if you wouldn't have known that it was C19.*

Note. Comments were generated by nine expert participants.

Abbreviations. C19, COVID-19; IoT, Internet of Things; RFID, radio frequency identification.

5.2.1.4 Response

The response section of questionnaire one consisted of 10 Likert-scale questions and three open-ended questions. The Likert-scale component aimed to evaluate the capabilities of IoT/RFID technologies to support healthcare delivery, research efforts, privacy requirements, resource quality tracking, policymaking and infectious waste management. Questions 1, 2, 3 and 6 failed to meet the consensus conditions defined for this study. All of these questions were rephrased and included in the second-round questionnaire. The questions and responses collected are presented in Table 0-10 below.

Table 0-10. Qualitative questions and answers on the subject of response, questionnaire one.

#	Question	SA	A	N	D	SD	C
1	An IoT/RFID inventory management system in hospitals, combined with accurate patient records, can automate and improve outcomes of resource and treatment prioritisation, sparing healthcare workers the ethical dilemmas associated with this task.	1	2	3	2	1	
2	IoT/RFID devices can be used in hospitals to examine and classify patients to infected, possible and non-infected cases, and to direct them to the appropriate wards, with minimal healthcare worker involvement.	0	4	3	2	0	
3	IoT/RFID's ability to reduce the time and cost of data cleansing will speed up research and allow researchers with low budgets to compete with rich institutes and companies.	0	4	4	1	0	
4	IoT/RFID's ability to collect anonymous or to anonymise data before sharing it with receiving parties will likely reduce the impact of data privacy regulations on international coordination and cooperation.	0	5	2	2	0	
5	IoT/RFID technologies can aid in controlling vaccine quality and reducing the costs of vaccination campaigns.	0	6	2	1	0	
6	Data originating from IoT/RFID-based reporting systems is more suitable for machine learning applications than data from traditional systems.	3	1	4	1	0	
7	IoT/RFID-based surveillance systems support the timely evaluation of response activities and their outcomes.	1	7	1	0	0	
8	A well designed IoT/RFID-based surveillance system can provide granular, accurate and timely information needed to support fine-tuned interventions, such as partial or targeted lockdowns.	3	4	1	1	0	
9	IoT/RFID-based resource management combined with timely surveillance data can aid policymakers in resource allocation and prioritisation.	2	6	1	0	0	
10	Infectious waste collection and segregation can be improved and automated by using RFID chips to mark the high-risk bags.	4	5	0	0	0	

Notes. Nine expert participants responded. Column headers: #, question number; questions, question text; SA, number of "strongly agree" responses; A, number of "agree" responses; N, number of neutral responses; D, number of "disagree" responses; SD, number of "strongly disagree" responses; C, results of conditional consensus evaluation,

with green representing an agreement consensus. Note that red, representing a disagreement consensus, is absent. Orange represents no consensus either way.

Abbreviations. IoT, Internet of Things; RFID, radio frequency identification.

The open-ended component of the response section included three questions that generated 13 responses and comments. The first of those questions aimed to collect the experts' opinions about the response section. This question generated four comments. The first, comment “a”, stated that people's willingness to be tagged with RFID chips could be the main determinant of the success of potential technological applications. The second comment, “b”, was related to question 1 of the Likert-scale questions. This comment highlighted the moral and ethical issues related to resource prioritisation using artificial intelligence, and indicated the need for a study that investigates HCWs’ perspectives on this issue. Comment “c” highlighted that for the increased data collection using IoT/RFID to be useful, data analysis capabilities need to handle the large amounts of data collected. Comment "d" indicated that humans still need to be involved in IoT/RFID data collection systems to monitor them.

The second question collected experts' opinions about the differences between responding to IDOs and other disasters, such as biological attacks. This question generated four comments. Comments "e" and "h" stated that the response to those two disaster types is similar. Comment "f" echoed previous comments about the differences between scale and severity in biological attacks vs. pandemics, which may necessitate different responses. Comment "g" stated that pandemic responses could be more challenging due to unknown pathogens, which is less likely in the case of biological attacks.

The third and last open-ended question in the response section of questionnaire one aimed to identify limitations to IoT/RFID surveillance systems that could affect the application of machine learning solutions in IDO management. This question generated four responses. The first of these, comment “i”, stated that humans' willingness to be tagged by RFID chips could affect machine learning applications, presumably because human willingness could affect the accuracy or the quantity of the data collected. Comments "j" and "l" highlighted data standardisation issues that could reduce the ability to use data generated by machine learning applications. Comment "j" added that legacy infrastructures could result in a situation where data do not support machine learning applications. Comment "m" argued that there is a need to be careful when drawing conclusions from data collected and used in ML applications, as mistakes could be costly. The open-ended questions and comments about the response phase are presented in Table 0-11 below.

Table 0-11. Questionnaire one: qualitative questions and answers on the subject of response.

#	Question	Comment
a	Please use the space below to leave any general comments related to the ideas discussed in the response phase.	*Again, a bit easier to respond, but everything depends on context. In particular, a lot depends on people's willingness to be 'tagged'. Without that, a lot of potential uses simply aren't going to be available.*
b		*Of particular note, in consideration of the question concerning the use of any technological solution — indeed for any decision — there is one over-riding moral principle: just because we can/could do something, does NOT mean we should. Your earlier example regarding "resource and treatment prioritisation" (sparing healthcare workers the ethical dilemmas associated with this task) gave me pause. It would be interesting to see the perspective of healthcare workers to this issue. Yes, it is very stressful (and often would not be needed if foolish people actively got vaccinated), but should it be taken 'out of their hands and given to a machine'? Very Orwellian ... rather takes the humanity out of humanity!! Never forget the legal, regulatory, ethical and moral perspectives of any research. I see consideration of the first two, but not (yet) of the latter two.*
c		*IoT/RFID can provide a huge amount of data. The critical issue is to filter and provide useful data to decision-makers to avoid information overload.*
d		*Important with a "white-box" approach: keeping the humans in the loop.*
e	How similar/different is the pandemic response phase from that of similar disasters such as biological attacks?	*Relatively similar.*
f		*As before, rephrased as: how similar/different is the response phase to a pandemic compared to that for a similar disaster such as a biological attack? I think my answer, in principle, will be the same as before — scale and severity of the events will frame and alter the response phase.*
g		*Pandemic response needs to consider the viral distribution and spread, and the specific, potentially unknown risks of unknown viruses, while the (potential) consequences and corresponding counter-actions of disasters as a biological attack are more known.*
h		*In terms of containment strategy based on data, very similar.*
i	Please mention any limitations of IoT/RFID surveillance systems that could impact data suitability for machine learning applications.	*It depends on the type of surveillance — it will be more likely that animals or physical locations could be given RFID tags than that humans would agree to wear them.*
j		*Not sure how relevant this is, but again, wondering about the 'interoperability' and 'legacy infrastructure' issues. How many decades have we been debating and attempting interoperability of e-record systems ... and made very little fundamental or practical progress?*

#	Question	Comment
k		*Limited generalisability of learning outcome from specific IoT/RFID data <=> appropriateness of collected data for specific intended ML decision support outcomes*
l		*Maybe data might need to be translated to other formats*.
m		*Important to be aware of the limitations in your (surrogate) markers that you are detecting. An overconfidence in the automated system could lead to wrong conclusions with high impact on people's privacy, public health or pandemic progression*.

Note. Nine expert respondents produced the comments appearing in this table.

Abbreviations. IoT, Internet of Things; ML, management level; RFID, radio frequency identification.

5.2.1.5 Recovery

The recovery section of questionnaire one consisted of 11 Likert-scale questions and two open-ended questions. The Likert-scale component aimed to evaluate the capabilities of IoT/RFID technologies to aid in preventing situations that could result in the resurgence of infections. This included situations when a pathogen can be reintroduced through infectious waste. The ability of IoT/RFID technologies to assist in the resumption of regular healthcare services and other socialites' functions was also examined. Questions 1, 2, 3, 4 and 5 did not meet consensus conditions and were revised and included in the second-round questionnaire. The questions and responses collected are presented in Table 0-12 below.

Table 0-12. Recovery Likert component, questionnaire one.

#	Question	SA	A	N	D	SD	C
1	Corpses of those who pass away due to a pandemic could pile up and still be infectious after the pandemic has ended; IoT/RFID can be used to safely disinfect these corpses.	0	3	3	1	2	
2	The mental health of healthcare workers can be negatively affected due to the stress of work conditions during pandemics. However, the mental healthcare system could suffer from high demand after a pandemic. IoT/RFID can help provide remote monitoring and mental health services to healthcare workers.	0	1	7	1	0	
3	Some pathogens like Ebola could result in highly infectious wastewater in tanks, containers and sewerage systems. IoT/RFID can be used to disinfect such wastewater safely.	1	3	2	1	2	
4	During the recovery phase, healthcare systems need to revert to their normal workflow; however, a resurgence in infections means the resumption of pandemic workflow. New information about the causative pathogen could also require changes to workflow. These rapid changes could result in confusion, or a high mental load on staff and patients. IoT/RFID-based applications can be used to monitor and guide healthcare workers and patients through these changes	0	3	4	2	0	
5	A shortage of critical care nursing staff could occur after a pandemic due to factors such as burnout. Non-specialised nurses can cover this shortage if IoT/RFID were used to monitor and guide their compliance to the five Rs of healthcare (right drug, right patient, right dose, right route and right time).	1	3	3	2	0	
6	Healthcare facilities and equipment could require thorough disinfection after a pandemic; IoT/RFID can be used to disinfect these objects and track the progress of disinfection.	1	4	3	0	1	
7	During the recovery phase, some medications could become scarce due to manufacturing disruptions or high demand; IoT/RFID could be used to track and allocate such medications to those who need them the most.	2	3	2	1	1	
8	Areas dedicated to confirmed cases in healthcare facilities need to be reduced or eliminated at the end	1	4	4	0	0	

#	Question	SA	A	N	D	SD	C
	of a pandemic to restore health services to pre-pandemic states. A possible resurgence, however, will require reinstating those areas quickly. IoT/RFID-based applications can be used to monitor healthcare workers' and patients' adherence to such rapid changes in layout.						
9	Cancelling non-urgent medical procedures is a way to reduce pressure on the healthcare system during a pandemic. This, however, can result in a backlog of patients needing attention after a pandemic. IoT/RFID technologies, combined with telehealth, can help in reducing this backlog through remote treatment and monitoring.	1	6	2	0	0	
10	Some response measures, such as the size of public gatherings allowed, could be lifted gradually to minimise the risk of resurgence. IoT/RFID-based monitoring systems are flexible enough to monitor adherence to such gradual easement of measures.	3	4	2	0	0	
11	RFID cards and IoT-based reader/writer devices can be used to create vaccination passports that are tamper-proof, traceable and can be checked without human involvement.	5	3	1	0	0	

Notes. Nine expert participants responded. Column headers: #, question number; questions, question text; SA, number of "strongly agree" responses; A, number of "agree" responses; N, number of neutral responses; D, number of "disagree" responses; SD, number of "strongly disagree" responses; C, results of conditional consensus evaluation, with green representing an agreement consensus. Note the absences of red, which represents a disagreement consensus. Orange represents no consensus either way.

Abbreviations. IoT, Internet of Things; RFID, radio frequency identification.

The open-ended component of the recovery section in questionnaire one included two questions that generated seven responses and comments. The first of those questions collected experts' comments about the questions included in the recovery section. This question generated five comments. Comments "a" and "d" raised a point related to the clarity of Likert questions 1, 3 and 6, which were addressed in the second questionnaire. Comment "b" stated that the acceptance rate of IoT/RFID technologies among humans makes determining the potential of using those technologies in IDO management hard. Comments "c" and "e" presented points similar to those raised by "b". These comments discussed the human factor, and the ethical and legal challenges, that could affect the application of IoT/RFID technologies in real life.

The last qualitative question aimed to identify differences between the recovery phase in IDOs and similar disasters, such as biological attacks. The first comment, "f", stated that the recovery phases are similar. Comment "g" stated that these two disaster types present different challenges. The questions and comments generated are presented in Table 0-13 below.

Table 0-13. Qualitative questions and answers on the subject of recovery.

#	Question	Comment
a	Please use the space below to leave any general comments related to the ideas discussed in the recovery phase.	*IoT/RFID can be used to disinfect ... Does this mean that it can be used to organise and/or track the disinfection, or that it, by itself, can be used to automatically disinfect?*
b		*I feel like I can more confidently specify what I think in the case of inanimate objects and the use of RFID because of the human element of acceptance of being tracked.*
c		*Many of the suggestions I had to disagree with because IoT/RFID cannot itself do what was being suggested (e.g., disinfect). Also, some of the suggestions seemed to be attempting to reduce medicine to a 'checklist' — far more to it that that ... Finally, bear in mind that while some things may technically be achievable (e.g., IoT/RFID-based vaccination passports) there are many other issues (public objection/obstruction; human rights issues; privacy protection; laws across different jurisdictions/countries/regions) that may preclude their deployment.*
d		*It is hard to see how IoT/RFID can be used to do actions (e.g., disinfect corpses). It is easier to see how this technology can be used for data collection and monitoring.*
e		*Ethical concerns need to be carefully handled.*
f	How similar/different is the pandemic recovery phase from that of similar disasters such as biological attacks?	*Probably relatively similar.*
g		*Biological attacks are potentially quite different, and understanding the different routes of transmission versus what we are currently seeing with Coronavirus.*

Notes. Nine expert participants responded.

Abbreviations. IoT, Internet of Things; RFID, radio frequency identification.

5.2.2 Results from the second questionnaire

The second questionnaire was composed based on the results and feedback received from the first questionnaire. The Likert and multichoice questions that did not pass the conditional consensus evaluation used in evaluating response from questionnaire one were revised and reintroduced in the second-round questionnaire.

Qualitative findings from questionnaire one were used to revise non-consensus-bearing questions, and, in some cases, generate new questions for round two. The questions added to round two included Likert questions that asked directly whether participants agreed with certain statements describing differences between IDO management and the management of other disasters. This was done because questionnaire one's open-ended questions resulted in repetition of some points. Expert respondents' confusion between management phases was another reason for introducing questions to questionnaire two in Likert-scale form.

In addition to Likert-scale questions examining the difference between management of IDOs and other disasters, a few open-ended questions were included in round two to collect experts' comments on those differences. Open-ended questions were introduced after the Likert-scale questions to try and used the close questions for better subject orientation. This system resulted in clearer and more focused comments than the first-round questionnaire.

A number of the qualitative comments collected in the first round raised concerns about deploying IoT/RFID to aid in IDO management. Due to this concern, a new section was added to questionnaire two to evaluate possible solutions to the limitations raised by the panellists.

5.2.2.1 Preparedness

The preparedness section of questionnaire two consisted of eight Likert-scale questions and two open-ended questions. The Likert-scale component aimed to evaluate the capabilities of IoT/RFID technologies in collecting data that can be used to evaluate IDO preparedness levels. The questions also attempted to evaluate IoT/RFID capabilities to collect data with desired quality attributes. The possibility of using IoT/RFID to aid in surge capacity building was also evaluated. A group of questions was also included to collect experts' feedback on the differences between IDO preparedness and preparedness for other disaster types. All Likert-scale questions included in this section met conditional consensus conditions. The questions and responses are presented in Table 0-14 below.

Table 0-14. Preparedness Likert component, questionnaire two.

#	Question	SA	A	N	D	SD	C
1	IoT data collection and reporting devices can be embedded in certain screening and testing equipment at healthcare facilities. This, in addition to RFID bracelet tags to identify patients, could allow auto-updating patients' information in the system, which would increase the accuracy of data and reduce the reporting burden on healthcare workers.	5	4	0	0	0	

#	Question	SA	A	N	D	SD	C
2	Accurate data collected from previous infectious disease outbreaks (IDOs) can be used to improve early warning systems and identify benchmarks for future evaluation.	4	5	0	0	0	
3	An early warning system consists of many surveillance systems that pool data together. These systems could include mosquito-density monitoring systems or syndromic surveillance systems at healthcare facilities or livestock farms, among many others. Testing the performance of an entire IoT/RIFD warning system can be automated and conducted routinely and cheaply by injecting mock data into the data collection components of the sub-systems.	2	5	2	0	0	
4	Implementing proper IoT/RFID data collection systems in a high percentage of healthcare facilities in a country can help in creating detailed datasets representing cities, suburbs or districts. This, in combination with AI, will lead to the development of specific epidemiological models for specific locations.	1	6	2	0	0	
5	Healthcare services during IDOs require increasing the number of healthcare workers, which could be challenging. IoT/RFID-based remote monitoring devices can allow medical experts from countries with low healthcare demand to monitor and treat patients from countries with high demand if the language barriers were addressed.	0	6	2	1	0	
6	Devising coordination plans for IDOs is more challenging than other disasters due to the constant changes in the geographical coverage of IDOs, which results in different networks of possible stakeholders.	0	6	1	2	0	
7	Determining the cost-effectiveness of an IDO's response plan is more challenging than other disasters due to IDOs' typically unclear scope and duration.	4	2	2	1	0	
8	The types of resources required to respond to an IDO are hard to determine in advance due to the different characteristics of the pathogens that may cause IDOs.	1	4	2	2	0	

Notes. Nine expert participants responded. Column headers: #, question number; questions, question text; SA, number of "strongly agree" responses; A, number of "agree" responses; N, number of neutral responses; D, number of "disagree" responses; SD, number of "strongly disagree" responses; C, results of conditional consensus evaluation, with green representing an agreement consensus. Note that red, representing a disagreement consensus, and orange, representing no consensus either way, are both absent.

Abbreviations. AI, artificial intelligence; IoT, Internet of Things; RFID, radio frequency identification.

Two open-ended questions were included in the preparedness section of questionnaire two to collect experts' comments on the Likert-scale questions. The first of these questions resulted in four comments. Comment "a" reiterated the need for human involvement in IoT/RFID systems and the incorporation of IoT/RFID with traditional data collection systems. Comment "b" stated that IoT/RFID data collection during IDOs can result in data representing only the circumstances of a specific IDO, and that more frequent data collection is needed. The same comment stated that remote patient monitoring can provide diagnoses and treatment assistance, but cannot be the sole basis of diagnosis/treatment. Comment "c" highlighted the moral and political challenges of IoT/RIFD applications.

The second question aimed to elicit experts' comments on the differences between preparedness for an IDO vs. preparedness for other disasters. This question generated three comments. The first of these, “e”, stated the IDOs present more challenges as the general population is more involved in the response. The same experts argued that tough trade-offs might present themselves in the case of IDO management as there is a need to balance the response with social needs and functions. Comment "f" argued that most disasters have unknown durations and resource requirements. The comment reiterated the point that the population's involvement in IDO response, and the fluctuating and unclear levels of support for some interventions, make responses to IDOs harder than other disasters. Comment "g" stated that the differences between pathogens could make preparedness for IDOs a challenging task. The round two questions and comments about preparedness are shown in Table 0-15 below.

Table 0-15. Questionnaire two: qualitative questions and answers about the subject of preparedness.

#	Question	Comment
a	Please leave any additional general comments on the preparedness section in the space below.	*Important with a white-box approach and ability to combine IoT with more manual, traditional systems.*
b		*IoT/RFID data collection facilities at healthcare facilities only collect momentary, one-time data, which might be influenced strongly by the event of an IDO, and hence would lead to limited accuracy of a model. More frequent or recurring data collection would be better; IoT/RFID-based remote monitoring can provide decision support for treatment by medical experts, but cannot be the sole basis for treatment.*
c		*Being able to physically do something does not necessarily mean that it should be done morally or can be done politically.*
d		*Infectious disease outbreaks (IDOs) should be expanded at first use. (Comment on format of the questionnaire)*
e	Please leave any additional comments on the differences between IDOs and other disasters during the preparedness phase below.	*What's more specific and challenging is the level of involvement of the rest of society, which the response system is part of. And the trade-off between containment/mitigation measures vs keeping the society open.*
f		*These were awkward questions to respond to. There are so many different and changing parameters for every disaster type — most are of uncertain duration, and scope can creep. Also, you typically do not know at the outset what or how much in terms of resources for any disaster type and throughout the disaster cycle. The first I had some empathy with — as we have seen from COVID-19, the fickle response of some segments of society make handling an IDO more difficult (refusing vaccination, wearing of masks, and social distancing, etc.).*
g		*A key variable is pathogenicity and contagion in determining resources; otherwise, other inputs would be not dissimilar between IDOs.*

Note. Nine expert participants responded.

Abbreviations. COVID-19, Coronavirus of the year 2019; IoT, Internet of Things; RFID, radio frequency identification.

5.2.2.2 *Mitigation*

The mitigation section of questionnaire two consisted of eight Likert-scale questions and two open-ended questions. The Likert-scale component aimed to evaluate IoT/RFID capability to assist in early warning, enforcement of biosafety measures and cross-border transmission detection. A group of questions were also included to collect the experts' feedback on the differences between the typical IDO's mitigation phase and that of other disasters. Questions 1 and 3 failed to meet the consensus evaluation conditions set for this Delphi study. The questions and responses are presented in Table 0-16 below.

Table 0-16. Mitigation Likert component, questionnaire two.

#	Question	SA	A	N	D	SD	C
1	IoT-based syndromic surveillance devices, such as temperature scanners, can be installed near the habitats of wildlife species that could carry high-risk pathogens. This will likely allow the identification of wide-scale outbreaks among wildlife species and will provide early warnings to authorities.	0	2	4	2	1	
2	Embedding RFID chips in personal protective equipment (PPE) used in healthcare facilities, and installing RFID readers at the gates of high-risk areas, could enforce PPE regulations in facilities, or alert workers to improper selection of PPE.	4	5	0	0	0	
3	One of the challenges of early warning systems is the lack of accurate and consistent case definitions across healthcare facilities and other agencies. IoT/RFID early warning systems can overcome this challenge if the raw syndromic and healthcare data collected were analysed on a central server, or the case definitions could be pushed to all data collection nodes from a central server as updates.	2	2	3	1	1	
4	Epidemiological research labs constitute high infectious disease outbreak (IDO) risks; using RFID chips in specimen collection tubes and other containers, instead of paper labels, can provide better specimen track-and-trace capabilities, and reduce researcher contact with potentially contaminated objects.	0	7	2	0	0	
5	Many countries have already rolled out passports with RFID chips holding individuals' identities. The vital signs of airport visitors can be acquired without direct contact using scanners and other sensors. This syndromic data could be collected from the RFID chip and stored in a database along with the traveller's identity. This could allow the identification of symptomatic passengers before they reach the transit and/or destination countries.	0	7	0	2	0	
6	Prevention of IDOs is hard as this requires monitoring large, high-risk areas, while the risk areas for other preventable disasters, such as oil spills, are smaller and more manageable.	2	3	1	2	1	
7	Prevention of IDOs is hard as pathogens can be very different, which can have a high impact on prevention efforts, while in the case of other disasters, the risks are more stable. (For example, prevention of most nuclear incidents involves the same safety protocols).	0	2	3	4	0	

#	Question	SA	A	N	D	SD	C
8	IDO prevention receives little attention compared to the attention given to the response, while prevention is the main focus for other disasters, such as nuclear incidents or oil spills.	1	4	1	3	0	

Notes. Nine expert participants responded. Column headers: #, question number; questions, question text; SA, number of "strongly agree" responses; A, number of "agree" responses; N, number of neutral responses; D, number of "disagree" responses; SD, number of "strongly disagree" responses; C, results of conditional consensus evaluation, with green representing an agreement consensus, red representing a disagreement consensus and orange representing no consensus either way.

Abbreviations. IoT, Internet of Things; RFID, radio frequency identification.

The qualitative component of the mitigation section in questionnaire two included two open-ended questions that generated four comments. The first question aimed to collect the experts' comments on the Likert-scale questions. This question resulted in two comments. The first of those, comment "a", stated that the current state of IoT/RFID technologies does not allow for accurate syndromic surveillance. The same comment also highlighted privacy and security issues with this surveillance type. The second comment addressed question 1 of the Likert-scale mitigation questions. This comment, "b", stated that monitoring wildlife could be challenging due to animal spread and movement. The problem of potential pollution resulting from attaching sensors to wildlife was also highlighted. The same comment highlighted the challenges of uniform case definitions mentioned in question 3. The expert expressed the need for uniform international case definitions and questioned the ability of technology to overcome variations introduced by human factors. This comment supported syndromic surveillance at airports using passport RFID chips, as suggested in question 5, but highlighted potential opposition to this solution due to privacy concerns.

The second open-ended question aimed to collect experts' comments on the differences between IDOs' typical mitigation phase vs. that of other disaster types. The first comment stated that the knowledge of IDO prevention methods is limited. The same expert stated that uncertainties relating to the cost-effectiveness of prevention methods reduce the attention given to IDO prevention. The second comment highlighted human actions causing IDOs and other disasters. The same comment targeted questions 6 and 7. The expert stated that preventing other disasters can be as challenging as IDO prevention. The expert cited nuclear disasters, such as Fukushima, to show that standard prevention protocols can fail in this type of disaster, too. The questions and comments generated are shown in Table 0-17 below.

Table 0-17. Questionnaire two: qualitative questions and answers about the subject of mitigation.

#	Question	Comment
a	Please leave any additional general comments on the mitigation section in the space below.	*Vital signs acquired with contactless sensors do (today) not allow a reliable identification of IDO symptoms; the automatic combination of vital signs and personal identity information creates high security/privacy protection risks.*
b		*I had great difficulty with the first question concerning zoonotic diseases. When we first moved to the Rockies, we were young and naïve; at one campground, we saw a bear wandering through the site we had been assigned. Returning to the warden and requesting another site, we were told, "That bear. He has legs, you know!" The populations can be so spread out, they migrate, and their habitat ranges from +40° to –50° Centigrade. I doubt equipment sensitive enough, accurate enough and rugged enough exists. You would end up wasting a lot of devices, and littering the environment for nominal reward. For the third question, any data analysis — whether or not centralised — would still suffer from issues of differing, inaccurate and inconsistent case definitions. One authority may respond at 'x' value, another at 'y' value, and yet another at 'z' value each according to their own case definitions. What is needed is international agreement on standard case definitions; then, the suggested approach would be of value. Technology does not resolve the human factor. For the fifth question, whilst I had to 'somewhat agree' from a technological perspective (and whilst I am unimpressed by the response of some societal groups to COVID-19), I am sure many would cry foul about such an approach 'trampling on human rights/dignity, and other legal, regulatory and ethical issues'. Too many people seem focussed on 'my rights' instead of 'my responsibilities'!!*
c	Please leave any additional comments on the differences between IDOs and other disasters during the mitigation phase below.	*In the case of new IDOs, little knowledge is available about preventive measures (e.g., how to prevent); also, the knowledge about impact costs and likelihood (=risk) are limited, and hence the 'attention' and willingness for prevention.*
d		*The argument for this series of questions might make an interesting topic for debate. ALL of our problems are man-made — we strip natural resources, we contaminate and abuse our natural environment, we spread like a cancer, ignoring the delicate balance of species, their unique contributions to the balance of nature. And we do this whilst thinking we are superior. We are not — Mother Nature rules supreme, and we keep throwing technological solutions at the problems we create, only to create another 2, 3, 5 or 10 for every one we try to solve!!! We are arrogant, and terrible stewards of our planet. Anyway — according to your logic, all disasters are preventable, since they arise from human decisions — we choose to live in flood plains, on steep slopes, in the middle of forests, on fault lines, or place nuclear power stations in vulnerable locations, or (a small proportion of us) choose to use unlawful violence or intimidation against the population. Question no. 1— "other preventable disasters, such as oil spills, are smaller and more manageable" — we may think we can handle 'small' disasters, but we really do not know what havoc we are inflicting on the eco-system even from 'small disasters'. Question 2. I had to 'somewhat agree' — for example, if COVID-19 had truly been an air-borne virus, we would have been in much deeper trouble. However, the statement about "prevention of most nuclear incidents involve the same safety protocols" — is naive; they didn't work so well in Fukushima, Chernobyl or Three Mile Island. ("Globally, there have been at least 99 (civilian and military) recorded nuclear power plant accidents from 1952 to 2009. Wikipedia"). As for the third question — cannot disagree. You would think we would have learnt from SARS, Bird Flu and the like — but we haven't.*

5.2.2.3 Response

The response section of questionnaire two consisted of eight Likert-scale questions and two open-ended questions. The Likert-scale component aimed to evaluate the capabilities of IoT/RFID technologies to support case identification, treatment prioritisation and HCW shortages and wellbeing. A group of questions were also included to collect the experts' feedback on the differences between responding to IDOs and other disasters. All the Likert questions included in the response section met the consensus measurement conditions outlined earlier. The questions and the responses are presented in Table 0-18 below.

Table 0-18. Response Likert component, questionnaire two.

#	Question	SA	A	N	D	SD	C
1	IoT sensors can be used to determine the number and temperature of people present in a room or a public transport vehicle. Based on these data, an air filtration system or negative air pressure system could be triggered to reduce infection probability.	4	3	0	2	0	
2	IoT and RFID cards can be used to monitor healthcare workers' workload and break times, data which can be used to reduce burnouts and enforce breaks when necessary.	2	3	0	3	1	
3	IoT/RFID-based hospital resource management systems, combined with accurate patient health records, can support healthcare workers in resource allocation and prioritisation due to IoT/RFID capacity to process real-time data from numerous sources at the same time.	4	3	1	1	0	
4	A desperate measure to address the high demand for healthcare workers during IDOs can be addressed by employing nurses under training to perform certain tasks such as administration of medication for certain patients. IoT/RFID technology can be used to monitor the 5 Rs rule in healthcare (right time, right dosage, right medicine, right patients, right medicine administration).	1	7	1	0	0	
5	Unlike most other disasters, the response phase of IDOs is non-linear as pathogen mutation and new waves of infection can result in returning to previous stages of the response.	3	3	3	0	0	
6	An effective response to an IDO hinges on timely and accurate epidemiological data to guide policy, while responses to other disasters are more dependent on available resources.	1	4	1	3	0	
7	The data required to respond to IDOs effectively cannot be collected in advance; this is not the case for other disasters.	0	1	2	6	0	
8	An infectious disease outbreak (IDO) that evolves into a pandemic becomes a transboundary crisis that requires a coherent international response policy, while most response mechanisms we have are at national level.	4	4	0	1	0	

Notes. Nine expert participants responded. Column headers: #, question number; questions, question text; SA, number of "strongly agree" responses; A, number of "agree" responses; N, number of neutral responses; D, number of "disagree" responses; SD, number of "strongly disagree" responses; C, results of conditional consensus evaluation,

with green representing an agreement consensus, red representing a disagreement consensus and orange, which is absent, representing no consensus either way.

Abbreviations. IoT, Internet of Things; RFID, radio frequency identification.

The qualitative component of the response section of questionnaire two included two open-ended questions, which generated four comments. The first question aimed to collect general comments from the experts on the response section. Comments “a” and “b” were related to Likert question 4. One of those comments stated that technological capabilities allow for monitoring and assisting HCWs when performing specific duties, but this solution has not been implemented so far.

The second question aimed to collect experts' views on the differences between responding to IDOs vs. disasters. This question generated two comments. The first of those stated that it is hard to have a unified global response mechanism in the case of pandemics as differences between cultures can result in resistance or failure of some response measures in some countries. The second comment explained why the expert disagreed with the statement presented by Likert-scale question 6. The expert argued that resource shortages are as challenging as data shortages when responding to IDOs. The same expert also explained that past data are essential to guide responses to other disasters, not just IDOs. The questions and the comments generated are presented in Table 0-19 below.

Table 0-19. Questionnaire two: qualitative questions and answers on the subject of response.

#	Question	Comment
a	Please leave any additional general comments on the response section in the space below.	*Use of many types of healthcare worker under training was employed in response to COVID-19, but I have not read any papers assessing how successful this was. Have you?*
b		*Technology exists currently but not deployed, and iatrogenic events are common occurrences in hospitals, where the 5Rs are not monitored.*
c	Please leave any additional comments on the differences between IDOs and other disasters during the response phase below.	*Response policies and mechanisms against a pandemic have to be legally and culturally accepted, and have to fit the social and healthcare resources; due to strong social and cultural differences on an international level, a single coherent international response policy is not possible/practical!*
d		*I could not agree to question 2. Many countries were faced with resource shortages in the wake of COVID-19 — PPE, vaccines, etc.; so, resource shortages are an issue for IPOs (IDO), too. Question 3 also caused me some discomfort — we learn 'lessons' on how to handle any future disasters from the data we accumulate from both past experiences, and from real-time monitoring. The forest fires experienced in Alberta some years ago were very dynamic given prevailing meteorological conditions, and data could not be predicted/collected in advance. This is NOT unique to IPOs (IDOs).*

Note. Nine expert participants responded.

Abbreviations. IDO, infectious disease outbreak; IoT, Internet of Things; PPE, personal protective equipment; RFID, radio frequency identification.

5.2.2.4 Recovery

The recovery section of questionnaire two consisted of nine Likert-scale questions and two open-ended questions. The Likert-scale component aimed to evaluate the capabilities of IoT/RFID to limit the resurgence of an IDO through contaminated corpses, objects and waste. The questions also aimed to evaluate the capabilities of IoT/RFID technologies to assist in the resumption of healthcare services after an IDO. A group of questions was also included to collect participating experts' feedback on the differences between the recovery phase in IDOs vs. other disasters. All questions included in the Likert component met the consensus conditions, apart from question "9". The questions and responses are presented in Table 0-20 below.

Table 0-20. Recovery Likert component, questionnaire two.

#	Question	SA	A	N	D	SD	C
1	Diseases such as Ebola prompted healthcare authorities in some countries to issue special regulations on how to handle corpses at healthcare facilities. These regulations required minimising contact with the corpse and spraying it with disinfectant before placing it in a special body bag. RFID chips holding information about the cause of death attached to the deceased, combined with an IoT-equipped spraying chamber, can be used to spray the corpse and update the data on the bracelet accordingly.	0	7	2	0	0	
2	Handling the corpses of IDO fatalities could include laying them in special body bags and attaching paperwork to record information related to the deceased. Using RFID chips embedded in the body bag to record the deceased's data instead of paper-based methods will likely reduce the transmission risk when reading, recording and updating the data.	1	6	1	1	0	
3	RFID chips could be attached to certain hospital equipment. Those chips can record equipment usage history, data which can be used to trigger IoT-aided robots to disinfect the equipment when necessary, and update equipment data to reflect this.	3	4	2	0	0	
4	Some infectious diseases can result in highly infectious bodily fluids accumulating at healthcare facilities. Some of these fluids can be too risky to be disposed of in the main wastewater system, or to be transported to other areas. IoT-based sensors can be used to trigger a disinfection mechanism using UV, chemicals or heat, and disposal of those fluids can then occur when it is deemed safe.	1	4	2	2	0	
5	During the recovery phase, the numbers of healthcare workers could be low due to deaths or burnouts. The use of IoT/RFID remote treatment and monitoring systems can allow healthcare workers from healthcare facilities with low demand to perform their duties remotely at multiple other healthcare facilities connected to the system without the need to travel.	1	4	3	1	0	
6	Inadequate IDO recovery policies, such as improper infectious waste disposal, could result in lapsing back	2	5	2	0	0	

#	Question	SA	A	N	D	SD	C
	to the response phase, which is unlikely to be the case with other types of disasters.						Green
7	Determining an accurate point in time to start the recovery phase is more challenging when managing IDOs than when managing other disasters as it is hard to determine that the disease has been eliminated.	3	3	2	1	0	Green
8	The duration of the response phase can lead to a fragile IDO recovery phase as the chance for pathogen mutation increases with time, while this is not the case with other disasters.	3	4	2	0	0	Green
9	Data accuracy and timeliness can determine the success of the recovery phase, while it is unlikely to be as detrimental in other disasters.	0	2	4	3	0	Orange

Notes. Nine expert participants responded. Column headers: #, question number; questions, question text; SA, number of "strongly agree" responses; A, number of "agree" responses; N, number of neutral responses; D, number of "disagree" responses; SD, number of "strongly disagree" responses; C, results of conditional consensus evaluation, with green representing an agreement consensus. Red, which represents a disagreement consensus, is absent. Orange represents no consensus either way.

Abbreviations. IDO, infectious disease outbreak; IoT, Internet of Things; RFID, radio frequency identification; UV, ultra-violet.

The qualitative component of the recovery section in questionnaire two included two open-ended questions that generated six comments. The first of those questions generated three comments targeting the recovery section in general. The first comment argued that the uncertainties inherent in IDOs make dependence on technologies too risky. The second comment stated that available sensors do not allow for measuring contamination levels, which could reduce the effectiveness of those technologies in disinfection tasks. The expert argued that these technologies could assist in diagnosis and surveillance, but not in treatment provision. Comment "c" stated that IoT/RFID sensors could be used to identify contaminated samples, but could not trigger a satisfactory disinfection mechanism, which is related to Likert question 4.

The second open-ended question aimed to collect experts' opinions on the differences between the recovery phase in IDOs and other disasters. This question generated three comments. The first of those, comment "c", stated that responding to a specific pathogen strain can be more definitive to other disasters. It is possible that the expert meant that immunisation against one strain of a virus could be considered a definitive success in the case of IDOs, while in the case of other disasters, there is no guarantee that the same event will occur again under the same circumstances. The second comment stated that data accuracy and timeliness are important during the recovery phase of other disaster types. The last comment stated that the comparison of IDOs vs. other disasters is invalid as "other disasters" differ significantly from each other. The questions and their answers are presented in Table 0-21 below.

Table 0-21. Questionnaire two: qualitative questions and answers about the subject of recovery.

#	Question	Comment
a	Please leave any additional general comments on the recovery section in the space below.	*A pandemic will likely surpass stockpile and preparedness calculations, so depending too much on a high-tech solution introduce risk.*
b		*There are no IoT sensors today that can (directly) measure a viral infection, and hence, decide about need for disinfection etc.; IoT/RFID sensors cannot treat (neither locally nor remotely), but can provide decision support for diagnosis, treatment, etc.; certain routine surveillance and consultations can be done remotely with the support of IoT/RFID.*
c		*Q. 3 — somewhat 'futuristic' in concept! Possible, but I question how probable. Q 4 — I could not really respond to — the question seemed to imply to me that specimens could not be safely disposed of locally (lack of appropriate facilities?), and could not be safely transported elsewhere — a stalemate situation. IoT-based sensors could certainly be used to identify such samples, but are not going to magically "trigger a [satisfactory] disinfection mechanism".*
d	Please leave any additional comments on the differences between IDOs and other disasters during the recovery phase below.	*A successful response to an IDO is quite definitive (at least for a specific strain), but a new mass casualty bus crash can happen straight after the one you just managed, regardless of your 'success'.* .
e		*Data accuracy and timeliness are generally important to determine the success of the recovery phase (e.g., local water levels in case of wide-area flooding, radiation levels in case of nuclear disaster, etc.).*
f		*You regroup all 'other' disasters together and ask us to compare with IDOs. Disasters vary hugely and cannot be grouped together like this.*

5.2.2.5 Challenges

The challenges section was added to the questionnaire in response to comments left by the panellists during the first round of the Delphi study. Because the comments from questionnaire one highlighted limitations and challenges in deploying IoT/RFID technologies to support IDO management efforts, this section was added to collect experts' feedback on solutions suggested for the limitations they highlighted in questionnaire one. The section contained eight questions, all of which met the conditional consensus criteria, apart from question "c". The questions and responses are presented in Table 0-22 below.

Table 0-22 IoT/RFID implementation challenges identified by the panel.

#	Question	SA	A	N	D	SD	C
1	It was reported that early containment of COVID-19 was possible only before the case count surpassed 40 [237]. This number is unlikely to be statistically significant, which would make detection of an outbreak at this stage challenging. The chance for early detection of an outbreak could be increased by increasing the density of the data collection nodes to cover every private practice, clinic and hospital division, and by analysing the data as close as possible	0	7	1	1	0	

#	Question	SA	A	N	D	SD	C
	to the collection node so that low case counts are statistically significant.						
2	Low- and middle-income countries could be lacking in the communication infrastructure needed to utilise IoT/RFID reporting systems. An infrastructure composed of drones with communication range extenders, or drones that can fly to areas where there is communication coverage, and then transmit the data collected, could provide a temporary solution to such cases.	0	6	1	2	0	
3	Privacy concerns related to surveillance and healthcare data could be elevated by implementing a data system similar to that of online banking. The user's data can be stored in a "data bank", where the user creates his/her account and connects the data collecting sensors to it. Users can review their data online and transfer certain records if they wish.	0	4	2	3	0	
4	The systems described above can be improved further by using patient smartphones' near frequency communication (NFC)capabilities as a key to identify and unlock the account when visiting healthcare facilities, which can allow reading and updating the data, just like banking payment systems. NFC is a technology considered to be a subset of RIFD. Most mobile phones are NFC-capable. NFC allows reading and writing to other NFC-capable devices, but its working distance is limited to 10 cm.	0	5	3	1	0	
5	IoT/RFID-based data collection and reporting systems can be made more transparent as the system's functions and processes can be audited by outside parties.	1	7	1	0	0	
6	It is hard to implement an IoT/RFID system for an entire country or city at once. Systems can be rolled out in stages by either adding interfaces to older systems to communicate with the new ones, or by adding a component to the new system that can interpret the data from the old systems.	3	6	0	0	0	
7	Determining an accurate point in time to start the recovery phase is more challenging when managing IDOs than when managing other disasters as it is hard to determine that the disease has been eliminated.	3	3	2	1	0	
7	IoT/RFID-based early warning systems are still in their early stages. A discussion between academics, manufacturers and other stockholders at this stage could help in standardising data produced by those systems. This will likely increase the availability of epidemiological data suitable for machine learning applications.	4	5	0	0	0	
8	One of the limitations of epidemiological models is that most are developed based on data from developed countries, which results in biased models. Proper implementation of IoT/RFID-based data collection and reporting systems is likely to address the lack of expertise in developing countries as some of the data could be collected without human intervention.	2	4	2	0	1	

Notes. Nine expert participants responded. Column headers: #, question number; questions, question text; SA, number of "strongly agree" responses; A, number of "agree" responses; N, number of neutral responses; D, number of "disagree" responses; SD, number of "strongly disagree" responses; C, results of conditional consensus evaluation,

with green representing an agreement consensus and orange representing no consensus either way. Note that red, which represents a disagreement consensus, is absent.

Abbreviations. IoT, Internet of Things; RFID, radio frequency identification.

CHAPTER 6 DISCUSSION

6.1 INTRODUCTION

This chapter presents and interprets the research results, and then, discusses their implications. The chapter also offers recommendations based on the findings. An overview of this research is then presented in light of the research objectives. The main objective of this chapter is to summarise and explain the research findings. This thesis objective is outlined in section 0, and the research questions are restated. Section 0 highlights the findings in relation to the research questions. The conclusion is then presented in section 0. Limitations of this research are presented in section 0, and finally, section 0 suggests possible future work.

6.2 RESEARCH OVERVIEW

Humanity has suffered from death and disruptions caused by epidemics and pandemics throughout history. The frequency of these events has increased in recent years due to human actions and other environmental factors. Furthermore, modern technologies, such as air travel, have increased and accelerated lethal pathogens' ability to spread. The constant and evolving risk of disease requires a re-examination of the challenges and tools available to prevent pandemic events, or at least, to reduce the damage they cause. The rapidity and scale of recent IDOs, coupled with the need for a fast response, highlight the need for adequate preparedness. COVID-19 exposed the poor preparedness levels of most countries and international organisations, and their poor preparedness, in turn, highlights a glaring need to re-examine challenges to preparedness and to develop new tools to overcome these challenges.

HCSs are critical resources needed to save lives and alleviate the impacts of IDOs on society. The potential for long IDOs exposes HCSs to numerous risks, including resource and HCW shortages, among many others. These huge risks, and the cruciality of the world's HCSs to IDO management, highlight the need for a close examination of the challenges faced by this sector and the identification of possible solutions to alleviate the problems experienced during the COVID-19 pandemic. The sheer scale of IDOs makes them a public health matter, which necessitates adequate policymaking. However, IDOs are ill-defined and highly dynamic problems riddled with uncertainties, posing significant policymaking challenges. Solutions to navigate those uncertainties are required to aid policymakers in their tasks and to improve IDO management outcomes. Based on recent pandemic events, this study set out to answer four main questions. These were:

- What are the challenges faced in the IDO management process?
- How can IoT/RFID facilitate and improve preparedness for IDOs?
- How can IoT/RFID facilitate healthcare responses during IDOs?
- How can IoT/RFID aid decision-makers in devising effective IDOs management policies?

6.3 ADDRESSING THE RESEARCH QUESTIONS

This section aims to discuss the thesis findings in relation to each of the four research questions mooted in Section 6.2.

6.3.1 Question 1: What are the challenges faced in the IDO management process?

The results of the first SLR included in this thesis support the view that IDO management challenges can be divided into two main categories. The first encompasses the IDOs management barriers discussed in Section 3.2.2. Barriers arise due to the special nature of IDOs, which are highly dynamic events with unpredictable coverage, duration and management needs. There are four barriers likely to be encountered during all management phases that hinder the identification, quantification, implementation and evaluation of resources, systems and processes: (1) knowledge-related, (2) organisational, (3) political and (4) ethical barriers.

Some knowledge-related barriers arise due to uncertainties inherent in IDOs, which are magnified by interactions between pathogens, hosts and the environment. These barriers make data collection and forecasting tasks challenging. Knowledge-related barriers complicate everything to do with an IDO. Their dynamic nature leads to difficulties in determining the scope, duration and coverage. Scope here refers to the domain dealing with the pathogen, whether veterinarian or human health systems. Dynamic unknowns make determining which organisations will be involved in different management phases problematic, thereby affecting preparedness implementation, which results in conflicting response plans. These barriers can also make evaluation of outcomes challenging.

The duration and coverage of IDOs showcase existing political barriers that reduce the ability to manage this type of disaster. Delayed returns on investments in preparedness reduce political will and population support for being prepared, which affects IDO management when a pandemic happens. Conflicting political views and orientations within a country also lead to inconsistent responses between regions and states, thus reducing progress made by a proactive region or organisation.

IDOs also present ethical dilemmas that slow or paralyse the decision-making process. Ethical challenges arise due to contrasting convictions and beliefs, or the nature of the process being conducted, such as treatment prioritisation. Policymakers need to identify or modify IDO management measures to pivot appropriately and navigate ethical barriers to increase the odds for good outcomes. Unfortunately, ethical barriers turn the process of identifying and quantifying the actions needed into a conundrum.

Ethical barriers interact and are influenced and magnified by other barriers, too. For example, alleviating knowledge barriers renders the scope of an IDO clearer and reduces the effects of organisational barriers by making the identification of organisations and stakeholders required to manage a particular pathogen easier. Overcoming knowledge barriers also paves the way to determining the cost–benefit ratios of various preparedness measures, giving politicians a better way to justify spending. Finally, addressing knowledge barriers means navigating ethical barriers may be easier as the knowledge gained assists in determining suitable trade-offs between different choices. Figure 0-1 illustrates the four barriers and their effects on IDO management tasks.

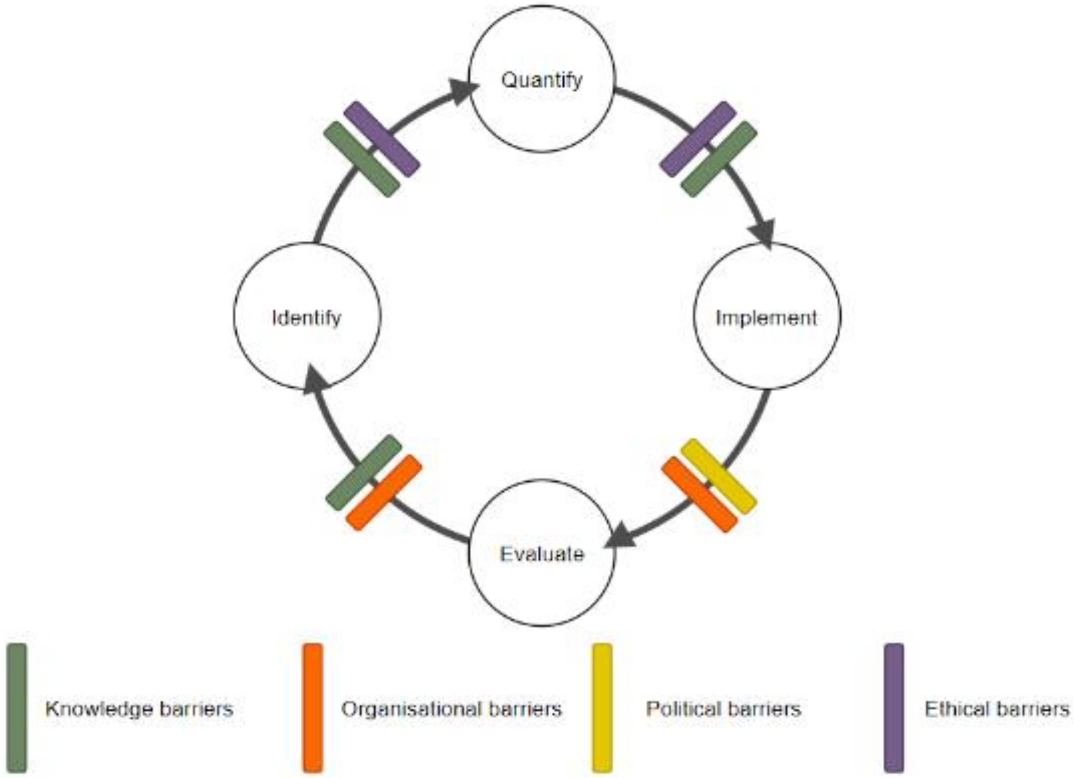

Figure 0-1 The effects of management barriers on preparedness efforts

Note. Figure 0-1 is the author's original work.

Inherent limitations in certain tools and the quality of resources supplied to manage an IDO can also magnify management barriers. The majority of these limitations relate to data collection, sharing and analysis (see Section 3.2.2.3, "Data-related challenges", for a detailed discussion), which highlights the high standard of data quality attributes needed to successfully manage an IDO.

Other challenges faced during IDOs were also presented using a novel framework, the PMC (see Section 3.2.3, "Phase challenges", for more detail). The PMC was devised based on the gaps in the IDO management process as identified in the literature. This framework consists of seven phases: (1) preparedness, (2) resilience building, (3) spark prevention, (4) spark fending, (5) response, (6) de-escalation and (7) recovery.

6.3.2 Question 2: How can IoT/RFID facilitate and improve IDO preparedness?

Research question two aimed to identify IoT/RFID applications to improve preparedness. In order to identify possible applications of these technologies, there is a need to collate challenges the constrain preparedness. The process of preparedness requires certain inputs and tools, which are classified as:

- suitable historical data,
- current surveillance data,
- models and forecasting tools,
- population vulnerability assessment tools,
- IDO risk assessment tools, and
- preparedness assessment methods.

These were discussed in detail in Section 3.3.3.1, “Preparedness”.

These tools’ limitations result in preparedness challenges, which hamper preparedness tasks, such as implementing and evaluating surveillance and EWSs. Implementation limits are tied to cost and usability. Clearly, such systems need to be flexible enough to detect different diseases, and to support different sensitivity levels as required. Evaluating and improving preparedness tools are difficult tasks that impact preparedness levels worldwide. Yet without them, the ability to detect and identify infections in certain settings reduces preparedness to near zero. An example scenarios is the detection of an EID, which is complicated by symptom overlaps with endemic diseases. The limited ability to detect diseases that can potentially infect humans emerging in wildlife and livestock in non-commercial settings is another challenge that besets preparedness practitioners.

One surveillance method that could make the detection of EIDs and IDOs easier is a robust reporting system. The difficulties in detection necessitate cooperation between veterinary and human health domains, so a standard reporting system could induce cooperation and address the current lack of resources, the nil data standardisation and the limited adherence to existing reporting protocols demonstrated by farmers and veterinarians.

The findings of the Delphi study (see Chapter 5) indicate that IoT/RFID would be effective in overcoming many of the challenges encountered during the preparedness phase. Furthermore, these technologies may provide tools and inputs needed for cost-effective preparedness efforts. For example, IoT and RFID technologies support the collection of data with the quality attributes suitable for IDO management, which is confirmed by [52]. Attributes key to successful management are: timeliness, accuracy, completeness, standardisation, balance and granularity. The ability of IoT/RFID to provide data with the required quality attributes is confirmed by previous studies [53-58].

In addition, IoT/RFID technologies can be employed to create flexible surveillance and EWSs that guide preparedness efforts and support all subsequent phases of IDO management [462]. This is possible because the data collection and analysis layers of these systems can be separated. Furthermore, IoT/RFID can target different diseases by using different detection and identification algorithms. This argument is supported by [157], who stated that some of the digital tools used to track and trace COVID-19 patients could be used for the same jobs in the case of malaria. Algorithms can be updated regularly by a central authority using standardised case definitions. The data collected can also detect EIDs via any unusual patterns appearing in the data.

The Delphi study (Chapter 5) results also showed that IoT/RFID can be used to prevent the importation of livestock suffering from infectious diseases, thus bolstering prevention efforts. Using IoT/RFID to collect syndromic livestock data while animals are in transit to other countries makes this application possible. These technologies can also be used to monitor livestock in non-commercial settings by equipping a sample of the animals with syndromic surveillance equipment. Furthermore, equipping a sample of livestock in nomadic communities with IoT/RFID tools can help people monitor IDOs in livestock over larger areas.

IoT/RFID technologies and PoC testing (as discussed in section 3.2.2.3.5 Testing) can be further refined to improve and automate water-based epidemiology. Existing PoC tests can be automated and connected to IoT devices, which means wastewater and fresh waterways can be continuously monitored. This form of surveillance is a potentially valuable source of epidemiological data as it can be used to cover vast areas, and the wildlife inhabiting those areas. IoT/RFID can also facilitate integration and cooperation between the veterinary and human health systems, which is possible under the umbrella of the OH approach (discussed in Section 3.3.3.3, “Spark prevention”), a suggestion supported by [609]. This would be possible through the automation and standardisation of data. Furthermore, IoT/RFID makes adherence to reporting regulations by busy people (farmers and veterinarians) easy by automating the reporting process.

Finally, Chapter 5’s Delphi results indicate that testing and evaluating IoT/RFID-based surveillance and EWSs can be automated and routinely conducted. This could be done by injecting data into various sensors and data collection nodes. Such tests are suitable for evaluating both data collection and analysis layers, and they allow for fine-tuning system sensitivity and specificity.

6.3.3 Question 3: How can IoT/RFID facilitate HCS responses to IDOs?

Research question three aimed to identify applications of IoT/RFID in HCS responses to IDOs. This goal required identifying the challenges faced by HCSs, which can be traced to resources, processes and systems needed to mount a response (for more detail, see Section 3.3.3.5, “Response”). These challenges include shortages of resources needed for healthcare provision during an IDO, e.g., manufactured medical equipment such as PPE and ventilators, and non-manufactured supplies, such as blood, bed space and human resources. Shortages of HCWs are also a major challenge — caused by deaths, infections and severe emotional and mental stress — that HCSs face during IDOs. Mental and emotional stress have their roots in ethical dilemmas arising from the need to prioritise and ration healthcare, or they derive from extreme workloads, fear of infection and constant practice and protocol changes. Furthermore, high workloads impact HCW reporting accuracy and exacerbate knowledge and data challenges.

The Delphi study described in Chapter 5 suggests that IoT/RFID can be used to address the effects of IDOs on HCSs to improve the provision of healthcare during an outbreak. These technologies may be useful in:

- protecting HCWs,
- prioritising treatment,
- improving reporting,
- reducing and redistributing workloads, and
- increasing the capacity of HCSs during IDOs.

The protection of HCWs from infections is crucial to any response efforts because shortages in human resources are impossible to address quickly. This protection could be achieved by employing IoT/RFID in combination with robotics and ultraviolet light disinfection technology to organise the disinfection of spaces and equipment inside HCFs. These technologies are also beneficial in monitoring and adjusting airflows in confined HCF spaces to reduce infections. The possibility of employing IoT/RFID in these domains is supported by [528] [461, 472]. Furthermore, RFID tags could be attached to PPE, and with the help of RFID readers, infection prevention measures and protocols could be enforced in HCFs. Readers could be installed at the gates of isolation areas, too, and access could be adjusted to allow only HCWs who have donned the appropriate PPE to enter higher-risk areas.

IoT/RFID technologies may eliminate the need for paperwork in high-risk HCF areas, such as laboratories. RFID tags that can be read and updated without touching anything could be implanted in specimen tubes, an application supported by [378]. In addition, RFID tags could be used to identify certain laboratory technicians capable of dealing with which high-risk samples at specific workstations and wearing specified PPE. IoT/RFID may also make the enforcement of safe disposal and disinfection of bodily fluids and sample collection equipment less of a chore.

Corpse management is another possible application of IoT/RFID that could reduce workloads and infections in HCFs. Handling high numbers of corpses was a challenge during the COVID-19 pandemic, which resulted in bodies being dumped in rivers in countries such as India [610]. Targeted use of IoT/RFID can help automate corpse disinfection and preparation, and these technologies are capable of accelerating documentation and administrative processes required when processing human corpses.

The high workloads in HCSs can also be reduced, transferred or distributed by employing IoT/RFID technologies: remote monitoring and treatment can allow HCWs from other regions, or even other countries, to help manage infectious cases remotely in high-demand areas. Furthermore, IoT/RFID can be used to deploy HCWs in training during high-demand periods, and to monitor their performance to reduce medical misadventure caused by errors. Monitoring the mental health and stress levels of HCWs, which can be used to assign appropriate workloads and breaktimes, is also achievable with IoT/RFID technologies.

Countering underreporting and sloppy data collection in HCFs, which may result from high workloads, may also become easier with IoT/RFID applications. Because mental health breakdowns are often a product of tough decisions that may need to be made, e.g., triage and treatment prioritisation when resources are scarce, IoT/RFID can be used to support HCWs in those tasks and increase transparency. This argument was supported by [513, 515, 571].

6.3.4 Question 4: How can IoT/RFID aid decision-makers in devising effective IDO management policies?

The fourth and final research question aimed to identify the application of IoT/RFID to make policy decision aimed at devising effective IDO management regimes (for a detailed discussion, see Section 3.3.3.5.3). Some of the main challenges faced by policymakers include identifying and evaluating suitable rules interventions to curb epidemic/pandemic spread. Identifying, implementing and evaluating interventions is complicated due to data-related challenges.

Policymakers also face significant hurdles when allocating resources in the face of acute shortages. Inappropriate allocation of resources may result in resource wastage, or public panic and unrest. Furthermore, policymakers also need to balance differing, or competing, needs and concerns of citizens and stakeholders when allocating resources or devising response measures. Examples are privacy considerations and economic impacts on businesses and households.

Delphi study results (Chapter 5) also suggest that IoT/RFID data collection capabilities could function as policymaking aids to collect the knowledge needed for implementing preparedness and response efforts. This argument is supported by [390]. The findings indicate that these technologies can provide timely surveillance data that supports the evaluation of response interventions. This is indirectly supported by [496], who used RFID technology to judge the effectiveness of response interventions used to counter respiratory infections in schools. Such application of IoT/RFID will greatly enhance the effectiveness of IDO policies; however, some of challenges, such as identifying outcomes of specific interventions (as discussed in Section 3.3.3.5.3.1 NPIs.), are not so easy to solve. IoT/RFID technologies also facilitate the collection of data needed and monitor targeted interventions, e.g., lockdowns, and monitoring could lead to actions that reduce economic impacts. These findings are supported by [506]. Furthermore, IoT/RFID can be used to monitor targeted interventions under different conditions, e.g., interventions tailored to certain geographical areas, at certain times of the day, or for certain population groups.

Delphi study findings indicated that IoT/RFID technologies can be employed to regulate the de-escalation of response measures in a gradual and organised manner to reduce the probability of new waves of infection. For example, physical distancing measures could be lifted in certain areas, while still being enforced in high-risk locations. Resource allocation tasks to counter shortages that may arise during IDOs, achieved by real-time tracking of inventory and resource consumption in different regions and HCFs, can also be achieved, finding supported by [59, 470] [428, 514].

Applying modern IoT/RFID technologies to collect data from multiple sources over long periods can also help address the statistical significance problem described in Section 3.2.2.3.4 Surveillance systems, which could facilitate the early detection of IDOs. Early detection supports fine-tuned, appropriate policymaking as it give policymakers the power to initiate response measures early. These findings are supported by [462]. Delphi study results also indicated that IoT/RFID is useful in alleviating privacy concerns at all levels, thus easing the navigation of thorny ethical dilemmas often encountered in the response phase. Data collection that does not identify individuals, and processes that anonymise the data after collection, are supported by IoT/RFID. Furthermore, privacy concerns can also be alleviated via system audits conducted by independent parties to ensure privacy regulations are followed.

In addition, IoT/RFID can be used to encourage individuals and organisation to adhere to infectious waste management policies. Multiple RFID tags attached to rubbish bags could be provided with PoC test kits. These tags could be activated and updated based on PoC test results. The ability to read RFID tags (using compatible readers) without opening rubbish bags can help waste collection companies to identify bags they collect from houses where pathogen-positive cases reside. These same tags can be used to ensure the appropriate destruction of infectious waste by the companies in charge. Last but not least, cutting-edge IoT/RFID technologies, when embedded in vaccine passports, can also be employed to monitor vaccination campaign progress. Passport-embedded technology automates the checking of vaccination status before an individual enters a high-risk location, findings supported by [516].

6.4 CONCLUSION

IoT and RFID technologies can be employed to overcome and navigate many challenges faced when managing IDOs. These technologies can be used to provide support for preparedness efforts, thus enhancing the entire IDO management process. These technologies can also support healthcare provision during IDOs by reducing infections in HCWs and patients, improving treatment prioritisation and maximising the benefits of the resources available. Furthermore, IoT/RFID can support policymakers throughout all IDO management phases.

IoT/RFID technologies can potentially be used by practitioners to navigate some of the management barriers specific to IDOs. IDOs are considered to be wicked problems — they are highly dynamic and are plagued by significant knowledge gaps. These knowledge gaps and uncertainties are further magnified by the IDO's potential for wide geographical coverage and long durations. Because such disasters are becoming more frequent, and global connectivity is "a given", whether in terms of travel or trade, the use of IoT/RFID will become a necessity if we are to reduce pathogen spread risk and the negative impacts of pandemics. The COVID-19 pandemic is living and ongoing proof of the need to enhance IDO management practices in every possible way.

6.5 LIMITATIONS

The first SLR, presented in chapter 3, suffered from several limitations. The first of these is the lack of standard rules and protocols for this type of SLR discussed in section. Grouping challenges under different themes can be done in many different ways, and there are no scientific methods available for evaluating a grouping scheme's suitability as discussed in section **Error! Reference source not found.**. Another constraint faced when conducting an SLR is the potential for a causal relationship between challenges identified by the reviewer. "Causal relationship" implies that some challenges can be of greater importance as they influence multiple others. Due to the time limitations imposed on this research, no attempts were made to identify causal links or to rank challenges. Furthermore, the current SLR targeted only scientific papers collected from the databases mentioned in Section 3.1.2, "Data collection and filtration". International organisational reports from the UN and the WHO have not been collected or reviewed.

The second SLR, presented in chapter 4, aimed to collect and present IoT/RFID technological applications to IDO management. However, in the current work, none of the suggested applications for IoT/RFID was critically evaluated to determine their effectiveness on targeted tasks. The literature was simply surveyed to find out what applications were suggested by other scholars. Furthermore, the second SLR did not examine applications of IoT/RFID in fields related to IDO management challenges the author identified. Rather, because of time constraints, the review was limited in scope to IoT/RFID applications directly associated with IDOs. Examples of related fields might include IoT/RFID applications in the fields of livestock and animal husbandry. In addition, the second SLR targeted only scientific papers collected from databases described in Section 4.1.2 Data collection and filtration. Other potential sources discussing IoT/RFID applications and innovations, such as manufacturers' webpages or news articles, were not collected or reviewed.

The Chapter 5 Delphi study (an evaluation of the suggested applications) showed how its limitations related mainly to the panel of experts. The expert panel recruited for this study did not represent all types of stakeholders involved in IDO management. For example, no HCWs or infectious waste management professionals were recruited to evaluate applications of IoT/RFID in their domains. Furthermore, all of the experts recruited for this study come from high-income and developed countries, which may reduce the transferability of the findings to developing countries. Another issue is that seven out of the nine experts recruited for this study come from academic fields, which means feedback from the practical side of IDO management was limited.

6.6 RECOMMENDATIONS AND FUTURE RESEARCH

IDO preparedness investment returns are delayed, which reduces the political will to support adequate preparedness measures. One way to navigate this issue is to direct research efforts towards finding and evaluating possible systems, which offer both immediate and delayed results, that aid in healthcare provision under normal circumstances, and increase preparedness levels. As bold initiatives tailor-made for IDOs, IoT/RFID technologies provide a unique opportunity to improve cooperation, and to reduce organisational needs and costs. The results of both SLRs showed that a great number of IoT/RFID systems were suggested by scholars to improve IDO management. The challenge, however, is that most of those systems target only a small number of the difficulties, and in isolation from other challenges. In this regard, we recommend researching system integration to address challenges faced in whole domains. Research should also be directed towards designing cheap and practical surveillance systems that can connect veterinary, human health and environmental surveillance systems to improve early detection and with the ability to apply a OH approach (see sections 3.3.3.3.2 One Health and 3.2.2.3.4 Surveillance systems). Such systems would greatly support spark prevention, fending and response efforts.

The de-escalation/restoration phase is one of the most challenging. Research should be directed towards finding safe de-escalation methods using appropriate techniques. For example, is it better to lift a lockdown by allowing only one house member to leave isolation and head to work or tend to household shopping needs, and then, gradually increase the number? Or is it better to lift a lockdown gradually by allowing people to go out at certain times, and then expand the time slots? Or is it better to lift lockdowns fully, but keep barriers between suburbs to contain outbreaks by reimposing lockdowns only in the suburbs experiencing resurgence? After determining the most suitable methods for safe de-escalation, fit-for-purpose technological solutions need to be investigated to support such measures.

Another area where IoT can assist in is the universal testing campaigns discussed in section 3.2.2.3.5 Testing In a recent study, [247] suggest polymer chain reaction tests as a tool to achieve universal testing. The method proposed involves mixing several samples from different individuals and using a single PoC test to reduce cost. This method can be applied to entire households when an IoT-capable PoC test is mailed out to each household. The testing campaign can be timed so that an entire country is tested at the same time. Furthermore, in combination with technologies such as AI facial recognition, smartphones can be used to verify that all individuals in a household have been tested. Such methods should be investigated further to help in organising universal testing during future IDOs.

By using IoT/RFID applications suggested in the literature, in addition to those suggested in this thesis, a smart hospital system can be proposed. This system could be purpose-built for IDOs as well as normal conditions. Such a system could use RFID tags to identify HCWs. In combination with access control points, these tags can be used to enforce ward segregation and isolation rules in HCFs. Furthermore, using those tags along with tagged PPE can facilitate the monitoring of HCWs' PPE usage to identify those who change PPE without a clear need, or those who do not change PPE when required. RFID tags on PPE can also help track PPE usage in real time, which could help with policymakers' resource allocation efforts.

RFID tags on PPE can also be used to check its proper selection before an HCW enters a high-risk area. The tags can also help HCWs follow the correct donning and duffing sequences to reduce cross-contamination in HCFs. Furthermore, tagged PPE may assist HCWs to follow the appropriate disposal guidelines for PPE to reduce infectious waste. The ability of RFID to connect specific PPE items with specific HCWs will also allow the testing of used items, such as facemasks, to ascertain HCWs' infectiousness without their direct involvement.

Implementing the IoT in such systems can be costly as a high number of components may need replacement and/or updates. Therefore, research should be directed towards devising low-cost IoT/RFID readers and nodes that can be connected to old, legacy medical equipment to register and relay data.

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Appendix A: Changes to SLR 1 search string

Database	Search string used	Reason of change
PubMed	("disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR epidemic* OR pandemic* OR outbreak* OR "communicable disease" OR "communicable diseases") AND (management* OR control* OR challenge*)	The * acts as a wild card when searching PubMed. It was added to include the variations of the search words with different suffixes
Google scholar First string	("Disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR epidemic OR epidemics OR pandemic OR pandemics OR outbreak OR outbreaks OR "communicable disease" OR "communicable diseases" AND Management)	The default search string was broken down into three sub-strings because google scholar max length of search string is 256 characters [130]. The search string was changed to match the usages of google operators. For example, the symbol * in google is used to represent a whole word X in search phrase. So instead, it was removed and nouns that could show up in plural form were added in a plural form. Parentheses do not affect the order or operation in Google scholar, so they were removed
Google scholar second string	"Disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR epidemic OR epidemics OR pandemic OR pandemics OR outbreak OR outbreaks OR "communicable disease" OR "communicable diseases" AND control	Same as above
Google scholar third string	"Disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR epidemic OR epidemics OR pandemic OR pandemics OR outbreak OR outbreaks OR "communicable disease" OR "communicable diseases" AND challenge	Same as above
IEEE explorer	("Disaster medicine"	Default search string

	OR "disaster healthcare" OR "healthcare disaster" OR epidemic* OR pandemic* OR outbreak* OR "communicable disease" OR "communicable diseases") AND (management* OR control* OR challenge*)	
PLOS	("Disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR epidemic* OR pandemic* OR outbreak* OR "communicable disease" OR "communicable diseases") AND (management* OR control* OR challenge*)	Default search string
Science direct	("Disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR epidemic OR pandemic OR outbreak) AND (management OR control OR challenge)	The database does not support wildcards so the * operator was removed. [130] The phrases "communicable disease" and "communicable diseases" were removed due to the high number of irrelevant results returned. The irrelevant results included many articles addressing non-communicable diseases.

Appendix B: Changes to SLR 2 search string

Database	Search string used	Reason of change
PubMed	(disaster OR "disaster management" OR "disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR epidemic* OR pandemic* OR outbreak* OR "infectious disease" OR "infectious diseases" OR "communicable disease" OR "communicable diseases") AND (IoT OR "internet of things" OR RFID OR "radio frequency identification")	The * acts as a wild card when searching PubMed. It was added to include the variations of the search words with different suffixes
Google scholar First string	disaster OR "disaster management" OR "disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR epidemic OR epidemics OR pandemic OR pandemics IoT	The default search string was broken down into three sub-strings because google scholar max length of search string is 256 characters [130]. The search string was changed to match the usages of google operators. For example, the symbol * in google is used to represent a whole word X in search phrase. So instead, it was removed and nouns that could show up in plural form were added in a plural form. Parentheses do not affect the order or operation in Google scholar so they were removed The problem with google search engine (including google scholar) is that the parentheses do not affect the order of operation and that the OR operator has precedence over the AND operator (The and operator is not supported by google but it does perform what is known as soft and, in which spaces between single words, or the spaces between phrases grouped by the quotation mark, are treated as an AND)
Google scholar second string	outbreak OR outbreaks OR "infectious disease"	Same as above

	OR "infectious diseases" OR "communicable disease" OR "communicable diseases" IoT	
Google scholar forth string	disaster OR "disaster management" OR "disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR epidemic OR epidemics OR pandemic OR pandemics "Internet of things"	Same as above
Google scholar fifth string	disaster OR "disaster management" OR "disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR epidemic OR epidemics OR pandemic OR pandemics "Internet of things"	
Google scholar sixth string	disaster OR "disaster management" OR "disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR epidemic OR epidemics OR pandemic OR pandemics RFID	

Google scholar seventh string	outbreak OR outbreaks OR "infectious disease" OR "infectious diseases" OR "communicable disease" OR "communicable diseases" "radio frequency identification"	
Google scholar eighth string	Disaster OR "disaster management" OR "disaster medicine" OR "disaster healthcare" OR "healthcare disaster" OR epidemic OR epidemics OR pandemic OR pandemics "radio frequency identification"	
Google scholar ninth string	outbreak OR outbreaks OR "infectious disease" OR "infectious diseases" OR "communicable disease" OR "communicable diseases" RFID	
IEEE explorer	Default search string	
PLOS	Default search string	
Science direct first string	(disaster OR "disaster management" OR "disaster medicine" OR "disaster healthcare") AND (IoT OR "internet of things" OR RFID OR "radio frequency identification"	The database does not support wildcards so the * operator was removed. [130] The database can process search strings that includes up to eight Boolean terms
Science direct second string	("healthcare disaster" OR epidemic OR pandemic OR outbreak) AND (IoT OR "internet of things" OR RFID OR "radio frequency identification")	Same as above
Science direct third string	("infectious disease" OR "infectious diseases" OR "communicable disease" OR	Same as above

	"communicable diseases") AND (IoT OR "internet of things" OR RFID OR "radio frequency identification”)	

Appendix C: Ethics approval letter 1

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

23 September 2021

Samaneh Madanian
Faculty of Design and Creative Technologies

Dear Samaneh

Re Ethics Application: **21/337 The role of Internet of Things and Radio Frequency Identification technologies in managing pandemics and infectious diseases outbreaks.**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 23 September 2024.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.
8. AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: Mohammad.nazayer@gmail.com; david.parry@murdoch.edu.au

Appendix D: Ethics approval letter 2

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

30 November 2021

Samaneh Madanian
Faculty of Design and Creative Technologies

Dear Samaneh

Re: Ethics Application: **21/337 The role of Internet of Things and Radio Frequency Identification technologies in managing pandemics and infectious diseases outbreaks.**

Thank you for your application for an amendment to your ethics application.

The 2nd round (questionnaire) for the Delhi Study has been approved.

Standard Conditions of Approval.

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard.
8. AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted. When the research is undertaken outside New Zealand, you need to meet all ethical, legal, and locality obligations or requirements for those jurisdictions.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: Mohammad.nazayer@gmail.com; david.parry@murdoch.edu.au

Appendix E: Information sheet

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Participant Information Sheet

Date Information Sheet Produced:

25/08/2021

Project Title

The role of Internet of Things (IoT) and Radio Frequency Identification (RFID) technologies in managing pandemics and infectious diseases outbreaks.

An Invitation

My name is Mohammad Nazayer, a master's student at Auckland University of Technology in New Zealand. I am conducting a Delphi study as a part of my master's thesis. Your participation in this study is optional, and you may withdraw from this study at any time.

What is the purpose of this research?

The main aim of this research is to identify the challenges faced when managing epidemic disasters and to evaluate applications of the internet of things and radio frequency identification technologies in solving these challenges. This research will help me complete my master's degree and its findings may be used for academic publications and presentations.

How was I identified and why am I being invited to participate in this research?

Expert opinions are needed at this stage of this research to evaluate the potential application of the internet of things and radio frequency identification in pandemic management. The recruitment process for this research started with the identification of potential participants via a webpage containing the names of Committee members of the 2020 Program of Information Systems for Crisis Response and Management community (ISCRAM). A search for publicly available email addresses was then conducted and your email address was one of those found. The requirements to take part in this research are the ability to communicate in English, and at least five years of experience of academic research or practice in the fields of disaster management, disaster medicine, disaster e-health or crisis management,

How do I agree to participate in this research?

Attached to this email is a consent form. To indicate your willingness to participate in this project you are kindly invited to copy the text from the form and paste it in a reply to this email or sending it to thc3795@autuni.ac.nz after adding your name the date at the end of the email.

Your participation in this research is voluntary (it is your choice) and whether or not you choose to participate will neither advantage nor disadvantage you. You are able to withdraw from the study at any time. If you choose to withdraw from the study, then you will be offered the choice between having any data that is identifiable as belonging to you removed or allowing it to continue to be used. However, once the findings have been produced, removal of your data may not be possible.

What will happen in this research?

You are kindly invited to contribute to this project by evaluating specific applications of the technologies mentioned earlier through an electronic questionnaire. A link to the questionnaire will be emailed to all participants once the preparation stage is completed. It will include several questions to be answered using the Likert scale along with open-ended questions and it will take approximately 15 to 20 minutes of your time. You are also invited to comment on any of the questions and scenarios included in the questionnaire. The project will include two or three questionnaires with two weeks between each of them. The feedback received at the end of each round will be incorporated into the next one in an attempt to reach consent between the panel members.

What are the discomforts and risks?

To the best of my knowledge, this project has no discomforts or risks associated with it. You will be commenting on issues related to your work or research field. Your identity will not be disclosed to any other participants or third parties.

What are the benefits?

Participants in this research will be able to validate, revise and share their knowledge by exchanging ideas with other members of the panel. Participants could identify new applications of the technologies mentioned and new directions of research. This project also aims to identify solutions to challenges faced when collecting and sharing data for research. This research also aims to identify areas that have been addressed by the scientific community and thus reduce duplicate research.

The wider community could benefit through possible improvements to the tools involved in pandemic management and the new possible applications and research directions. Vulnerable communities could benefit from this research as it aims to find applications of the technologies mentioned to identify their needs and guide policies targeting them. Health providers could also identify ways to improve planning and response to pandemics.

Finally, this research will help me fulfil the requirements for a master's degree, improve my research skills and guide possible future research projects I may conduct.

How will my privacy be protected?

The privacy of participants is very important to me and the Auckland University of Technology. Your responses and identity will not be revealed to any third parties. None of the other participants recruited for this project will be able to access any information that can lead to the disclosure of your identity. The feedback provided to other participants after each of the three questionnaires and the final findings which will be included in my thesis will not include any data that could lead to the disclosure of your identity.

What are the costs of participating in this research?

Each of the three questionnaires included in this research will require between 15 to 20 minutes to be completed with two weeks between each questionnaire.

What opportunity do I have to consider this invitation?

It would be a great help if you could respond to this email within two weeks.

Will I receive feedback on the results of this research?

A summary of results will be sent to the participants once the project is completed and you will be able to access the thesis online.

What do I do if I have concerns about this research?

Any concerns regarding the nature of this project should be notified in the first instance to the Project Supervisor Dr Samaneh (Sam) Madanian, Email Address: sam.madanian@aut.ac.nz, Phone number: +64-9-921-9999 ext. 6539.

Concerns regarding the conduct of the research should be notified to the Executive Secretary of AUTEC, ethics@aut.ac.nz, (+649) 921 9999 ext 6038.

Whom do I contact for further information about this research?

Please keep this Information Sheet and a copy of the Consent Form for your future reference. You are also able to contact the research team as follows:

Researcher Contact Details:

Mohammad Nazayer

Master's student

School of Engineering, Computer and Mathematical Sciences

AUT University, Auckland, New Zealand

Email address: thc3795@autuni.ac.nz

Project Supervisor Contact Details:

Dr Samaneh (Sam) Madanian

School of Engineering, Computer and Mathematical Sciences

AUT University, Auckland, New Zealand

Email Address: sam.madanian@aut.ac.nz,

Phone number: +64-9-921-9999 ext. 6539.

Approved by the Auckland University of Technology Ethics Committee on 23/ 09/2021, AUTEC Reference number 21/337.

Appendix F: Consent form

Consent Form

Project title: ***The role of Internet of Things and Radio Frequency Identification technologies in managing pandemics and infectious diseases outbreaks.***

Project Supervisor: ***Dr Samaneh (Sam) Madanian***

Researcher: ***Mohammad Nazayer***

- I have read and understood the information provided about this research project in the Information Sheet dated 25/08/2021.
- I have had an opportunity to ask questions and to have them answered
- I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without being disadvantaged in any way.
- I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible.
- I agree to take part in this research.
- I understand that this is a Delphi study and that involves between 2 to 3 questionnaires.
- I agree to be contacted again to participate in the future questionnaires mentioned above.
- I wish to receive a summary of the research findings (please indicate with yes or no): ………………………….

Participant's name: ………………………………………………………………………………………………………

Date: ………………………………………

Appendix G: Delphi questionnaire 1

Applications of IoT/RFID in pandemic management - deployed

Start of Block:

The role of Internet of Things (IoT) and Radio Frequency Identification (RFID) technologies in managing pandemics and infectious diseases outbreaks.

Delphi study – questionnaire 1
Estimated time: 20 minutes

Dear panellist,

Thank you for taking part in this project. This study is a part of a master's thesis investigating the role of IoT/RFID in pandemic management. The main goals of this research is to identify current applications of IoT/RFID in pandemic management, find out gaps in the research covering this area, and determining possible new applications of those technologies in all stages of disaster management. These phases are preparedness, mitigation, response and recovery. The definitions of those phases can be found on the next section of the survey.

This subject is multi-disciplinary, and your input as an expert in your field is crucial to bridge the gap between those different disciplines and obtain knowledge applicable to real-world scenarios. This study involves 2 – 3 questionnaires and this is the first round of those. At the end of each round, the feedback collected from panellists will be used to refine the next questionnaire. Subsequent rounds will include a summary of the previous questionnaire results, these are sent to the panellists in an attempt to bridge the gaps between them and reach consent.
This questionnaire will take approximately 20 minutes to complete and it mainly consists of closed-ended questions with a few open-ended ones. Comments are more than welcome and you can use the space at the end of each phase section to do so. English is my second language and I am still taking the first steps in my research journey, so please if my phrasing of a question was not clear or if I failed to define any concepts, or if my approach was unsuitable, I will be grateful if you could please let me know in the comment sections. Definitions of cornerstone concepts can be found on the following page.

You can move forward or backwards to different sections of the survey using the respective buttons. **You do not have to finish the entire survey in one go, you can stop any time and your progress will be saved.** To come back to your survey simply click on the access link you used the first time but once you end the survey you cannot go back or redo it.

Finally, I would like to assure you that the confidentiality of your identity and the data you provide will be guarded and preserved. Other panellists will not have access to your data or identity and the final published report will not contain any data that could lead to the disclosure of your identity. As a reminder, you can withdraw from this study at any stage and you can request the deletion of your data before the findings are published.

Thank you for your time,
Mohammad Nazayer

End of Block:

Start of Block:

Definitions

Radio Frequency Identification (RFID): A method used for tagging items to identify them, where each item or class of items are assigned unique identifiers. These tags emit radio signals which can be read by special receivers. Some tags are writable only once, which means they are only readable henceforward. The second type of tags is re-writable so the data on those can be read and also updated (Weinstein, 2005).

Internet of Things (IoT): This refers to a network of physical and virtual heterogeneous objects equipped with wireless communication capabilities, programmable components, and logical processing abilities. These objects can communicate and interact with each other. The flow of the data collected by these devices can be coordinated and specific events based on the data can be triggered. This results in devices able to monitor real-world events and react based on them (Firdhous, Sudantha, & Karunaratne).

IoT/RFID-based systems: These are systems that use IoT/RFID devices to collect and report data. **Traditional systems**: These are systems that rely on active human guidance and interaction to collect and report data. These systems cannot operate without human direct involvement.

Reporting: Reporting involves relaying data and/or the results of data aggregation and analysis to higher levels of decision-making.

Surveillance: Surveillance is the continuous collection and reporting of data that could lead to the prediction, detection or identification of pandemics or infected cases. Surveillance systems consist of data collection nodes, reporting systems, and data analysis methods.

Early warning systems: Early warning systems consist of multiple surveillance systems combined with other data sources- such as demographic information- and analysis capabilities to analyze data coming from those different sources. **Syndromic data reporting systems**: These are systems that collect vital signs and other human or livestock health indicators. Syndromic surveillance systems in this study refer to a collection of IoT/RFID devices and sensors that collect this data and report it electronically without human intervention.

Wastewater epidemiological systems: These are systems that monitor and test sewage and wastewater for specific pathogens. Most of the current systems depend on human sample collection, reporting and testing. Pandemic management is usually presented using framework consisting of four phases, These phases are: **Preparedness**: This phase involves resource planning, evaluating, and improving different systems needed in all other stages of pandemic management. **Mitigation**: This phase covers pandemic prevention and the reduction of its impact. Mitigation can be achieved by increasing the probability of early detection and reducing the probability of virus transmission. **Response**: This phase involves actions and measures taken during a wide-scale outbreak to reduce the impact, stop the spread of a pandemic, and eventually containing it. **Recovery**: This phase refers to actions and measures taken after a wide-scale outbreak to return society to pre-pandemic conditions and restore interrupted services.

Firdhous, M. F. M., Sudantha, B. H., & Karunaratne, P. M. (2017). IoT enabled proactive indoor air quality monitoring system for sustainable health management.

Weinstein, R. (2005). RFID: a technical overview and its application to the enterprise. IT Professional, 7(3), 27-33. doi:10.1109/mitp.2005.69

End of Block:

Start of Block:

Demographic information

Please enter your name or your initials below.

____

Education level

- ☐ Doctorate
- ☐ Master's
- ☐ MBA
- ☐ Bachelor's
- ☐ Other (Please specify below)

____

Occupation

- ☐ Academia
- ☐ Research
- ☐ Consulting
- ☐ Government
- ☐ Healthcare
- ☐ Healthcare IT
- ☐ Disaster medicine
- ☐ Disaster management
- ☐ Other (Please specify below)

____

Total years of experience in fields related to this research subject

- ○ 0 - 5
- ○ 6 - 10
- ○ 11 - 15
- ○ 16 - 20
- ○ 21 - 30
- ○ More than 30

End of Block:

Start of Block:

Preparedness → Data collection
* The ability to prevent and manage pandemics depend directly on the quality and availability of data.

Pandemic management requires data with certain attributes. Please indicate whether IoT-RFID-based data collection systems or the traditional data collection systems are more capable of delivering data with the following quality attributes.

	IoT/RFID- based systems	Neutral	Traditional systems
Accuracy	○	○	○
Balanced (unbiased)	○	○	○
Completeness	○	○	○
Granularity	○	○	○
Standardisation	○	○	○
Timeliness	○	○	○

Please mention any other technologies that can deliver data with the quality attributes mentioned above.

____

Page Break

Preparedness → Systems monitoring and evaluation

* Reporting and surveillance systems can directly influence the response speed. Currently, there are no international benchmarks or indicators that can be used to evaluate those systems which results in states using subjective measures.

The evaluation and monitoring of IoT/RFID-based surveillance systems can be automated and conducted routinely.
* Surveillance is the continuous collection and reporting of data that could lead to the prediction, detection or identification of pandemics or infected cases. Surveillance systems consist of data collection nodes, reporting systems, and data analysis methods.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

IoT/RFID-based early warning systems are easier to evaluate and monitor than those using traditional data collection methods.
* Early warning systems consist of multiple surveillance systems combined with other data

sources, and analysis capabilities to analyze data coming from those different sources.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

Deducing benchmarks and indicators to evaluate early warning systems is more likely to be achieved using data collected by IoT/RFID early warning systems than data collected using traditional systems.
* Traditional data collection systems are those relying on active human guidance and interaction to collect and report data.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

Please mention any other technologies or strategies that could be used to conduct fast and accurate routine evaluation of surveillance systems.

____

Please mention any data required for defining early warning systems benchmarks and indicators which cannot be collected using IoT/RFID systems.

____

Page Break

Preparedness → Systems attributes

* Pandemics are unpredictable and they have frequently originated in low-income countries. This implies that systems used in pandemic management phases need to be flexible and cost-effective.

IoT and RFID based early warning systems are more flexible than traditional early warning systems.
* A flexible early warning system means it is capable to adapt quickly to changing surveillance requirements. These changes could be the targeted disease, symptoms, population groups, involved organizations, locations and so on.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

IoT/RFID-based early warning systems can provide a cost-effective solution to low-income countries which have weak early warning systems.
* A cost-effective system is one that is cheap to install, maintain, and adjust.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

Please mention any technical obstacles that could prevent a single IoT/RFID early warning network from targeting different diseases at the same time.

____

Please mention any other cost-effective solutions to address the lack of early warning systems in low-income countries, or any negative aspects of IoT/RFID based early warning systems.

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How similar/different is the pandemic preparedness phase from that of similar disasters such as biological attacks?

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Please use the space below to leave any general comments related to the ideas discussed in the preparedness phase.

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End of Block:

Start of Block:

Mitigation→ Increasing detection probability
* Mitigation in pandemic management refers to the prevention and reduction of possible losses. Prevention could be achieved by increasing the probability of pandemic detection.

Please indicate your level of agreement with the following statements.

IoT/RFID-based reporting systems can facilitate and automate the collaboration between veterinary and human health systems.
* Livestock disease can cause pandemics if transmitted to humans. A cooperation between

veterinary and human health systems can result in the early detection or prevention of a pandemic.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

IoT/RFID-based Syndromic data reporting systems can improve adherence to reporting regulations in livestock farms and veterinary clinics.
* IoT/RFID-based Syndromic data reporting systems collect vital signs and other indicators of human beings or livestock health state. These systems could be automated to aggregate, analyze, and report the data to decision makers.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Wastewater epidemiological systems can produce more timely and accurate data by incorporating IoT technologies for sample collection and reporting.

* Wastewater epidemiological systems monitor and test sewage and wastewater for specific pathogens. Most of those systems depend on human sample collection and testing.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Identification of outbreaks among livestock in communities of subsistence farmers and nomadic herders could be achieved by equipping a sample of their livestock with IoT/RFID syndromic surveillance devices.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

IoT/RFID-based syndromic surveillance systems can help detect outbreaks caused by unknown pathogens in livestock.

* A spike in the number of people or animals exhibiting a group of symptoms not associated with a particular disease, could reveal an outbreak caused by an unknown pathogen.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

If IoT/RFID technologies were used to collect and record patients data, artificial intelligence and machine learning can be used to detect large infectious disease outbreaks in hospitals.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

An IoT/RFID early warning system supported by machine learning could help in detecting pandemics when symptoms of the disease overlap with symptoms of other diseases.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Please mention any technologies or strategies that could aid the early detection of pathogen transmission from wildlife to livestock early.

____

JS

Wastewater surveillance can be used only to monitor known pathogens. Please mentions any tools or strategies that can help monitor or detect unknown emerging pathogens.

____

Page Break

Mitigation→ Reducing transmission probability.

* Prevention could be achieved by reducing the probability of transmission.

IoT/RFID-based syndromic surveillance systems can be deployed to monitor livestock in transit which could lead outbreak detection and prevention before reaching the destination country.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

Airlines can use IoT/RFID-based syndromic surveillance systems during pandemics to monitor travelers vital signs and movement for days before flights, which could prevent virus transmission to destination countries.

○ Strongly disagree

○ Somewhat disagree

○ Neither agree nor disagree

○ Somewhat agree

○ Strongly agree

How similar/different is the pandemic mitigation phase from that of similar disasters such as biological attacks?

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Please use the space below to leave any general comments related to the ideas discussed in the mitigation phase.

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End of Block:

Start of Block:

Response→ Decision making

* The fast-changing nature of pandemics is one of the main challenges facing decision-makers. The optimal response policies can change very quickly depending on various factors such as number of cases, the vulnerable groups, and virus mutation.

IoT/RFID-based resources management combined with timely surveillance data can aid policy-makers in resource allocation and prioritisation.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

A well designed IoT/RFID-based surveillance system can provide granular, accurate, and timely information needed to support fine-tuned interventions, such as partial or targeted lockdowns.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

IoT/RFID-based surveillance systems support the timely evaluation of response activities and their outcomes.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

Page Break

Response→ Healthcare optimization

* Overloaded healthcare systems and shortage of resource are major challenges during the pandemic response phase. Workflow optimization, and process automation can help conserve resources, improve performance, and reduce infections and mental health issues among healthcare workers.

Please rate your level of agreement with the following statements:

IoT/RFID devices can be used in hospitals to examine and classify patients to infected, possible and non-infected cases, and to direct them to the appropriate wards, with minimal healthcare workers involvement.
* Patients health could be evaluated using IoT/RFID sensors that reads vital signs. These sensors can be placed in pathways and an access control policy based on symptoms could be put in place to guide patients to appropriate wards.

○ Strongly disagree

○ Somewhat disagree

○ Neither agree nor disagree

○ Somewhat agree

○ Strongly agree

JS

An IoT/RFID inventory management system in hospitals combined with accurate patient records can automate and improve outcomes of resource and treatment prioritisation, sparing healthcare workers the ethical dilemmas associated with this task.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

JS

IoT/RFID technologies can aid in controlling vaccine quality and reducing costs of vaccination campaigns.
* IoT/RFID can be used to monitor temperatures of vaccines during storage and distribution. These technologies can be also used to automated resource allocation, and other processes usually conducted by humans during campaigns, such as recording and reporting of campaign data

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Page Break

Response→ Waste management

* Waste collection during pandemic times is a challenging task. Some of the challenges arise due to the changing locations of infected households or quarantine centers, and the need to process waste produced by such locations separately

Please rate your level of agreement with the following statements:

Infectious waste collection and segregation can be improved and automated by using RFID chips to mark the high-risk bags.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

Page Break

Response→ Research

* In some cases, pandemic containment depends on the speed and the quality of research produced. Data silos, privacy regulation, data quality and availability are some of of the issues that could slow research.

Please rate your level of agreement with the following statements:

IoT/RFID’s ability to collect anonymous or anonymise data before sharing it with receiving parties will likely reduce the impact of data privacy regulations on international coordination and cooperation.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

JS

IoT/RFID ability to reduce the time and cost of data cleansing will speed up research and allow researchers with low budgets to compete with rich institutes and companies.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Data originating from IoT/RFID-based reporting systems is more suitable for machine learning applications than data from traditional systems.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Please mention any limitations of IoT/RFID surveillance systems that could impact data suitability for machine learning applications.

How similar/different is the pandemic response phase from that of similar disasters such as biological attacks?

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JS

Please use the space below to leave any general comments related to the ideas discussed in the response phase.

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End of Block:

Start of Block:

Recovery→ Healthcare services

* After a pandemic, changes made to healthcare systems need to reverted as fast as possible yet those systems need to be ready for another resurgent of infections.

Please rate your level of agreement with the following statements:

Areas dedicated for confirmed cases in healthcare facilities need to be reduced or eliminated at the end of a pandemic to restore health services to pre-pandemic states. A possible resurgent, however, will require reinstating those areas quickly. IoT/RFID-based can be used to monitor healthcare workers and patients adherence to those fast changes in layout.

* The solution could be a dynamic access control policy that uses RFID cards and IoT scanners on certain access points.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

During the recovery phase, healthcare systems needs to revert to their normal workflow, however, a resurgent in infections means the resumption of pandemic workflow. New information about the causing pathogen could also required changes to workflow. These fast changes could result in confusion or high mental load on the staff and patients. IoT/RFID-based can be used to monitor and guide healthcare workers and patients through those changes.
* The solution could be a dynamic access control policy, which could be automated and

enforced using RFID cards and IoT scanners installed on certain entrances and pathways.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Cancelling of non-urgent medical procedures is a way to reduce pressure on healthcare system during a pandemic. This however can result in a backlog of patients that needs addressing after a pandemic. IoT/RFID technologies combined with telehealth can help in reducing this backlog through remote treatment and monitoring.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Mental health of healthcare workers can be negatively affected due to the stress of work conditions during pandemics. However, mental health care system could suffer from the high demand after a pandemic. IoT/RFID can help provide remote monitoring and mental health services to healthcare workers.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

A shortage of critical units nursing staff could occur after a pandemic due to factors such as burnout. Non-specialized nurses can cover this shortage if IoT/RFID were used monitor and guide their compliance to the 5 Rs of healthcare (Right drug, right patient, right dose, right route, and right time).

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

During the recovery phase some medications could become scarce due to manufacturing disruption or high demand, IoT/RFID could be used to track and allocate such medications to those who need them the most.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Page Break

Recovery→ Prevention of resurgent

* Eradication of pandemics is a challenging task that requires monitoring and neutralising every possible route of transmission.

Please rate your level of agreement with the following statements:

RFID cards and IoT-based reader/writer devices can be used to create vaccination passports which are tamper-proof, traceable and can be checked without human involvement.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Some pathogens like Ebola, could result in highly infectious wastewater in tanks, containers and sewerage systems. IoT/RFID can be used to disinfect such wastewater safely.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Corpses of those who passed away due to a pandemic could pile up and still be infectious after the pandemic has ended, IoT/RFID can be used to safely disinfect these corpses.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Healthcare facilities and equipment could require a thorough disinfected after a pandemic, IoT/RFID can be used to disinfect these objects and track the progress of disinfection.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Some response measures such as the size of public gathering allowed could be lifted gradually to minimize the risk of resurgent. IoT/RFID based monitoring systems are flexible enough to monitor adherence to such gradual easement of measures.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

How similar/different is the pandemic recovery phase from that of similar disasters such as biological attacks?

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Please use the space below to leave any general comments related to the ideas discussed in the recovery phase.

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End of Block:

Appendix H: Delphi questionnaire 2

Round2-Deployed

Start of Block: Landings

The role of IoT and RFID technologies in managing pandemics and Infectious Diseases Outbreaks (IDOs)

Delphi study – questionnaire 2

Estimated time: 18 minutes

Dear panelist,

I appreciate the time and effort you put in by completing the first questionnaire. The purpose of the first questionnaire was to collect your opinions on possible applications of IoT/RFID technologies in Infectious Diseases Outbreaks (IDOs) management. It also aimed at identifying areas that could be investigated further or possible challenges that could arise when implementing those applications. Consent was reached on most of the questions included in the first questionnaire based on a threshold of 51% majority. Questions with the lowest level of consent were updated based on comments provided by the panelists. Other questions were rephrased based on the feedback received. The feedback received also highlighted areas that could be investigated further. The majority of questions included in this round are closed questions, however, there are text boxes for your comments. Any comments or suggestions related to any aspects of this questionnaire, approach or terminology are highly appreciated.

Definitions:

Radio Frequency Identification (RFID): A method used for tagging items to identify them, where each item or class of items are assigned unique identifiers. These tags emit radio signals which can be read by special receivers. Some tags are writable only once, which means they are only readable henceforward. The second type of tags is re-writable so the data on those can be read and also updated *(Weinstein, 2005).*

Near Field Communication (NFC): This is a technology considered as a subset of RIFD.

Most mobile phones these data are NFC-capable. NFC allows reading and writing to other NFC capable devices and its working distance is limited to 10 cm (Trivedi, K. , 2006).

Internet of Things (IoT): This refers to a network of physical and virtual heterogeneous objects equipped with wireless communication capabilities, programmable components, and logical processing abilities. These objects can communicate and interact with each other. The flow of the data collected by these devices can be coordinated and specific events based on the data can be triggered. This results in devices able to monitor real-world events and react based on them *(Firdhous, Sudantha, & Karunaratne)*.

IoT/RFID-based systems: These are systems that use IoT/RFID devices to collect and report data. Traditional systems: These are systems that rely on active human guidance and interaction to collect and report data. These systems cannot operate without human direct involvement.

Reporting: Reporting involves relaying data and/or the results of data aggregation and analysis to higher levels of decision-making.

Surveillance: Surveillance is the continuous collection and reporting of data that could lead to the prediction, detection or identification of pandemics or infected cases. Surveillance systems consist of data collection nodes, reporting systems, and data analysis methods.

Early warning systems: Early warning systems consist of multiple surveillance systems combined with other data sources- such as demographic information- and analysis capabilities to analyse data coming from those different sources.

Syndromic data reporting systems: These are systems that collect vital signs and other human or livestock health indicators. Syndromic surveillance systems in this study refer to a collection of IoT/RFID devices and sensors that collect this data and report it electronically without human intervention.

Pandemic management is usually presented using a framework consisting of four phases, These phases are: **Preparedness**: This phase involves resource planning, evaluating, and improving different systems needed in all other stages of pandemic management. **Mitigation**: This phase covers pandemic prevention and the reduction of its impact. Mitigation can be achieved by increasing the probability of early detection and reducing the probability of virus transmission. **Response**: This phase involves actions and measures taken during a wide-scale outbreak to reduce the impact, stop the spread of a pandemic, and eventually contain it.

Recovery: This phase refers to actions and measures taken after a wide-scale outbreak to return society to pre-pandemic conditions and restore interrupted services.

Firdhous, M. F. M., Sudantha, B. H., & Karunaratne, P. M. (2017). IoT enabled proactive indoor air quality monitoring system for sustainable health management.

Weinstein, R. (2005). RFID: a technical overview and its application to the enterprise. IT Professional, 7(3), 27-33. doi:10.1109/mitp.2005.69

End of Block: Landings

Start of Block: Preparedness

Please enter your name or initials below

____

Please indicate your level of agreement with the following statements

---

IoT data collection and reporting devices can be embedded in certain screening and testing equipment at healthcare facilities. This, in addition to RFID bracelet tags to identify patients, could allow auto-updating patients' information in the system which will increase the accuracy of data and reduce the reporting burden on healthcare workers.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Accurate data collected from previous Infectious Disease Outbreaks (IDOs) can be used to improve early warning systems and identify benchmarks for future evaluation.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

An early warning system consists of many surveillance systems that pool data together. These systems could include mosquito-density monitoring systems or syndromic surveillance systems at healthcare facilities or livestock farms among many others. Testing the performance of an entire IoT/RIFD warning system can be automated and conducted routinely and cheaply by injecting mock data in the data collection components of the sub-systems.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Implementing proper IoT/RFID data collection systems in a high percentage of healthcare facilities in a country can help in creating detailed data sets representing cities, suburbs, or districts. This in combination with AI will lead to the development of specific epidemiological models for specific locations.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Healthcare services during IDOs require increasing the numbers of healthcare workers which could be challenging. IoT/RFID- based remote monitoring devices can allow medical experts from countries with low healthcare demand to monitor and treat patients from countries with high demand if the language barriers were addressed.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Please leave any additional general comments on the preparedness section in the space below.

____

Considering the following scenarios and your responses to the first round of questions, to what extend preparedness for IDOs is more challenging than that of other disasters?

Devising coordination plans for IDOs is more challenging than other disasters due to the constant changes in the geographical coverage of IDOs which results in different networks of possible stakeholders.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

Determining the cost-effectiveness of an IDO's response plan is harder and more challenging than other disasters due to the IDO's unclear scope and duration.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

The types of resources required to respond to an IDO are hard to determine in advance due to the different characteristics of the pathogens that may cause IDOs.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

Please leave any additional comments on the differences between IDOs and other disasters during the preparedness phase below.

____

End of Block: Preparedness

Start of Block: Mitigation

Page Break

Please indicate your level of agreement with the following statements

IoT-based syndromic surveillance devices, such as temperature scanners, can be installed near the habitat of wildlife species that could carry high-risk pathogens. This will likely allow identifying wide-scale outbreaks among the species and providing early warning to authorities.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

Embedding RFID chips in Protective Personal Equipment (PPE) used in healthcare facilities and installing RFID readers at the gates of high-risk areas, could enforce PPE regulations in facilities or alert the worker to improper selection of PPE.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

One of the challenges of early warning systems is the lack of accurate and consistent case definitions across healthcare facilities and other agencies. IoT/RFID early warning system can overcome this challenge if the raw syndromic and healthcare data collected was analyzed on a central server, or the case definitions could be pushed to all data collection nodes from a central server as updates.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

Epidemiological research labs constitute high Infectious Disease Outbreaks (IDOs) risk, using RFID chips in specimen collection tubes and other containers instead of paper labels can provide better specimen track and trace capabilities and reduce researcher contact with potentially contaminated objects.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

Many countries have already rolled out passports with RFID chips holding individuals identities. Vital signs of airport visitors can be acquired without direct contact using scanners and other sensors. The syndromic data could be collected and stored in a database along with the traveler's identity from the RFID chip. This could allow identifying symptomatic passengers before reaching the transit or destination countries.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Please leave any additional general comments on the mitigation section in the space below.

____

IDOs is a preventable disaster. Preventable disasters are mostly those which result from human decisions. Examples of these include terrorism, nuclear and environmental disasters. The prevention of IDOs is more challenging due to the following issues:

Prevention of IDOs is hard as this requires monitoring large high-risk areas, while the risk areas for other preventable disasters, such as oil spills, are smaller and more manageable.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Prevention of IDOs is hard as pathogens can be very different which can have a high impact on the prevention efforts while in the case of other disasters the risks are more stable. (For example, prevention of most nuclear incidents involve the same safety protocols).

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

IDOs prevention receives little attention compared to the attention given to the response while prevention is the main focus for other disasters such as nuclear incidents or oil spills

○ Strongly disagree

○ Somewhat disagree

○ Neither agree nor disagree

○ Somewhat agree

○ Strongly agree

Please leave any additional comments on the differences between IDOs and other disasters during the mitigation phase below.

____

End of Block: Mitigation

Start of Block: Response

Please indicate your level of agreement with the following statements

---

IoT sensors can be used to determine the number and temperature of people present in a room or a public transport vehicle. Based on this data an air filtration system or negative air pressure systems could be triggered to reduce infection probability.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

IoT and RFID cards can be used to monitor healthcare workers workload and break times which can be used to reduce burnouts and enforce breaks when necessary.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

IoT/RFID-based hospital resource management system combined with accurate patient health records can support healthcare workers in resource allocation and prioritization due to its capacity to process real-time data from numerous sources at the same time.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

A desperate measure to address the high demand for healthcare workers during IDOs can be addressed by employing nurses under training to perform certain tasks such as administration of medication for certain patients. IoT/RFID technology can be used to monitor the 5Rs rules in healthcare (right time, right dosage, right medicine, right patients, right medicine administration).

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Please leave any additional general comments on the response section in the space below.

____

Response to IDOs is more challenging than that of other disasters due to the following:

Unlike most other disasters, the response phase to IDOs is non-linear as pathogen mutation and new waves of infection can result in returning to previous stages of the response.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

An effective response to an IDO hinges on timely and accurate epidemiological data to guide policy, while the response to other disasters is more dependent on available resources.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

The data required to respond to IDOs effectively cannot be collectedin advance, while this is not the case for other disasters.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

An Infectious Disease Outbreak (IDO) that evolves to a pandemic becomes a transboundary crisis that requires a coherent international response policy, while most response mechanisms we have are national level.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Please leave any additional comments on the differences between IDOs and other disasters during the response phase below.

____

End of Block: Response

Start of Block: Recovery

Page Break

Please indicate your level of agreement with the following statements

Diseases such as Ebola prompted healthcare authorities in some countries to issue special regulations on how to handle corpses at healthcare facilities. These regulations require minimizing contact with the corps and spraying it with disinfectant before placing it in a special body bag. RFID chip holding information about the cause of death attached to the deceased combined with IoT equipped spraying chamber can be used to spray the corps and update the data on the bracelet accordingly.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

Handling the corpses of an IDO's fatalities could include laying them in special body bags and attaching paperwork to record information related to the deceased. Using RFID chips embedded in the body bag to record the deceased data instead of paper-based methods will likely reduce the transmission risk when reading, recording updating the data.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

RIFD chips could be attached to certain hospital equipment. Those chips can record the equipment usage history which can be used to trigger IoT aided robots to disinfect the equipment when necessary and update its data to reflect this.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Some infectious diseases can result in highly infectious bodily fluids collected at healthcare facilities. Some of these fluids can be too risky to be disposed of in the main wastewater system or to be transported to other areas. IoT-based sensors can be used to trigger a disinfection mechanism using UV, chemicals or heat, and dispose of those fluids when it is deemed safe.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

During the recovery phase, the numbers of healthcare workers could be low due to deaths or burnouts. The use of IoT/RFID remote treatment and monitoring systems can allow healthcare workers from healthcare facilities with low demand to perform their duties remotely at multiple other healthcare facilities connected to the system without the need to travel.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Please leave any additional general comments on the recovery section in the space below.

____

Recovery from IDOs is more challenging than that of other disasters due to the following:

Inadequate IDOs recovery policies, such as improper infectious waste disposal, could result in lapsing back to the response phase while this is unlikely to be the case while recovering from other disasters.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Determining an accurate point in time to start the recovery phase is more challenging when managing IDOs than when managing other disasters as it is hard to determine that the disease has been eliminated.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

The duration of the response phase can lead to a fragile IDO recovery phase as the chance for pathogen mutation increases with time, while this is not the case with other disasters.

- ○ Strongly disagree
- ○ Somewhat disagree
- ○ Neither agree nor disagree
- ○ Somewhat agree
- ○ Strongly agree

Data accuracy and timeliness can determine the success of the recovery phase, while it is unlikely to be as detrimental in other disasters.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Please leave any additional comments on the differences between IDOs and other disasters during the recovery phase below.

____

End of Block: Recovery

Start of Block: Challenges IoT

The questions below are follow up questions related to some of the IoT/RFID challenges raised by the panelists.
Please indicate your level of agreement with the following statements

---

It was reported that early containment of COVID-19 was possible only before the case count surpassed forty *(Hellewell et al., 2020)*. This number is unlikely to be statistically significant which would make detection of an outbreak at this stage challenging. The chance for early detection of an outbreak could be increased by increasing the density of the data collection nodes to cover every private practice, clinic, hospital division and analyzing the data as close as possible to the collection node so that low case counts are statistically significant.

Hellewell, J., Abbott, S., Gimma, A., Bosse, N. I., Jarvis, C. I., Russell, T. W., . . . Sun, F.

(2020). Feasibility of controlling COVID-19 outbreaks by isolation of cases and contacts. The Lancet Global Health, 8(4), e488-e496.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Low and middle-income countries could be lacking the communication infrastructure needed to utilize IoT/RFID reporting systems. An infrastructure composed of drones with communication range extenders, or drones that can fly to areas where there is communication coverage then transmit the data collected, could provide a temporary solution to such cases.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

Privacy concerns related to surveillance and healthcare data could be elevated by implementing a data system similar to that of online banking. The user's data can be stored in a "data bank".

Where the user creates his/her account and connects the data collecting sensors to it. Users can review their data online and transfer certain records if they wish to.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

The systems described above can be improved further by using a patients smartphone Near Frequency Communication capabilities (NFC), as a key to identify and unlock the account when visiting healthcare facilities to allow reading and updating the data just like banking payment systems.

Near Field Communication (NFC): This is a technology considered as a subset of RIFD. Most mobile phones these data are NFC-capable. NFC allows reading and writing to other NFC capable devices and its working distance is limited to 10 cm

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

IoT/RFID-based data collection and reporting systems can be made more transparent as the functions and processes of the system can be audited by outside parties.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

It is hard to implement an IoT/RFID system for an entire country or city at once. Those systems can be rolled out in stages by either adding interfaces to the older systems to communicate with the new ones or adding a component to the new system that can interpret the data from the old systems.

- ◯ Strongly disagree
- ◯ Somewhat disagree
- ◯ Neither agree nor disagree
- ◯ Somewhat agree
- ◯ Strongly agree

IoT/RFID-based early warning systems are still in their early stages. A discussion between academics, manufacturers, and other stockholders at this stage could help in standardizing data produced by those systems. This will likely increase the availability of epidemiological data suitable for machine learning applications.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

X→

One of the limitations of epidemiological models is that most are developed based on data from developed countries which results in biased models. Proper implementation of IoT/RFID-based data collection and reporting systems, is likely to address the lack of expertise in developing countries as some of the data could be collected without human intervention.

- Strongly disagree
- Somewhat disagree
- Neither agree nor disagree
- Somewhat agree
- Strongly agree

End of Block: Challenges IoT

Appendix I: Delphi evaluation code (round 1)

```
import java.util.*;
import java.lang.*;
import java.io.*;


class Question{

    String questionString;
    int SA;
    int A;
    int N;
    int D;
    int SD;

    Question(String questionString, int SA, int A, int N, int D, int
SD){

        this.SD= SD;
        this.D= D;
        this.N = N;
        this.SA = SA;
        this.A = A;
        this.questionString = questionString;
    }

    void result(){
        String s = "Error";
        if ((N>SA+A)&(N>SD+D)){
            s = "Neutral responses are the majority";
        }else if(
            ((A+SA)>(D+SD))&
            ((A+SA) < (N+D+SD))
            ){
            s = "Neutral results skewed the answer";
        }else if((A+SA) == (D+SD)){
            s = "result is tied";
        }
        else{
            s = " Answered";
        }
        System.out.println(questionString + ": " + s );
    }
}

class Codechef
{
    public static void main (String[] args) throws java.lang.Exception
    {
        Question Preparedness_a = new Question
("Preparedness_a",0,4,3,2,0);
        Question Preparedness_b = new Question(
"Preparedness_b",1,4,3,1,0);
        Question Preparedness_c = new Question
("Preparedness_c",2,4,2,0,1);
        Question Preparedness_d = new Question
("Preparedness_d",4,5,0,0,0);

        Question Mitigation_a = new Question
("Mitigation_a",1,2,2,3,1);
```

```
        Question Mitigation_b = new Question
("Mitigation_b",1,4,3,1,0);
        Question Mitigation_c = new Question
("Mitigation_c",2,4,2,1,0);
        Question Mitigation_d = new Question
("Mitigation_d",3,3,2,1,0);
        Question Mitigation_e = new Question
("Mitigation_e",3,3,2,1,0);
        Question Mitigation_f = new Question
("Mitigation_f",2,5,2,0,0);
        Question Mitigation_g = new Question
("Mitigation_g",3,4,2,0,0);
        Question Mitigation_h = new Question
("Mitigation_h",3,5,0,1,0);
        Question Mitigation_j = new Question
("Mitigation_j",4,3,2,0,0);
        Question Mitigation_k = new Question
("Mitigation_k",6,3,0,0,0);

        Question Response_a = new Question ("response_a",1,2,3,2,1);
        Question Response_b = new Question ("response_b",0,4,3,2,0);
        Question Response_c = new Question ("response_c",0,4,4,1,0);
        Question Response_d = new Question ("response_d",0,5,2,2,0);
        Question Response_e = new Question ("response_e",0,6,2,1,0);
        Question Response_f = new Question ("response_f",3,1,4,1,0);
        Question Response_g = new Question ("response_g",1,7,1,0,0);
        Question Response_h = new Question ("response_h",3,4,1,1,0);
        Question Response_j = new Question ("response_j",2,6,1,0,0);
        Question Response_k = new Question ("response_k",5,4,0,0,0);

        Question Recovery_a= new Question ("Recovery_a",0,3,3,1,2);
        Question Recovery_b= new Question ("Recovery_b",0,1,7,1,0);
        Question Recovery_c= new Question ("Recovery_c",1,3,2,1,2);
        Question Recovery_d= new Question ("Recovery_d",0,3,4,2,0);
        Question Recovery_e= new Question ("Recovery_e",1,3,3,2,0);
        Question Recovery_f= new Question ("Recovery_f",1,4,3,0,1);
        Question Recovery_g= new Question ("Recovery_g",2,3,2,1,1);
        Question Recovery_h= new Question ("Recovery_h",1,4,4,0,0);
        Question Recovery_j= new Question ("Recovery_j",1,6,2,0,0);
        Question Recovery_k= new Question ("Recovery_k",3,4,2,0,0);
        Question Recovery_l= new Question ("Recovery_l",5,3,1,0,0);

        System.out.println("first round results are:");
        System.out.println("******************");
        Preparedness_a.result();
        Preparedness_b.result();
        Preparedness_c.result();
        Preparedness_d.result();
        System.out.println("******************");
        Mitigation_a.result();
        Mitigation_b.result();
        Mitigation_c.result();
        Mitigation_d.result();
        Mitigation_e.result();
        Mitigation_f.result();
        Mitigation_g.result();
        Mitigation_h.result();
        Mitigation_j.result();
        Mitigation_k.result();
        System.out.println("******************");
        Response_a.result();
        Response_b.result();
        Response_c.result();
```

```
        Response_d.result();
        Response_e.result();
        Response_f.result();
        Response_g.result();
        Response_h.result();
        Response_j.result();
        Response_k.result();
        System.out.println("******************");
        Recovery_a.result();
        Recovery_b.result();
        Recovery_c.result();
        Recovery_d.result();
        Recovery_e.result();
        Recovery_f.result();
        Recovery_g.result();
        Recovery_h.result();
        Recovery_j.result();
        Recovery_k.result();
        Recovery_l.result();

    }
}
```

Appendix J: Delphi evaluation code (round 2)

```
import java.util.*;
import java.lang.*;
import java.io.*;


class Question{

    String questionString;
    int SA;
    int A;
    int N;
    int D;
    int SD;

    Question(String questionString, int SA, int A, int N, int D, int
SD){

        this.SD= SD;
        this.D= D;
        this.N = N;
        this.SA = SA;
        this.A = A;
        this.questionString = questionString;
    }

    void result(){
        String s = "Error";
        if ((N>SA+A)&(N>SD+D)){
            s = "Neutral responses are the majority";
        }else if(
            ((A+SA)>(D+SD))&
            ((A+SA) < (N+D+SD))
            ){
            s = "Neutral results skewed the answer";
        }else if((A+SA) == (D+SD)){
            s = "result is tied";
        }
        else{
            s = " Answered";
        }
        System.out.println(questionString + ": " + s );
    }
}

class Codechef
{
    public static void main (String[] args) throws java.lang.Exception
    {
        Question Preparedness_a = new Question
("Preparedness_a",5,4,0,0,0);
        Question Preparedness_b = new Question(
"Preparedness_b",4,5,0,0,0);
        Question Preparedness_c = new Question
("Preparedness_c",2,5,2,0,0);
        Question Preparedness_d = new Question
("Preparedness_d",1,6,2,0,0);
        Question Preparedness_e = new Question
("Preparedness_e",0,6,2,1,0);
        Question Preparedness_f = new Question(
"Preparedness_f",0,6,1,2,0);
```

```
        Question Preparedness_g = new Question
("Preparedness_g",4,2,2,1,0);
        Question Preparedness_h = new Question
("Preparedness_h",1,4,2,2,0);

        Question Mitigation_a = new Question
("Mitigation_a",0,2,4,2,1);
        Question Mitigation_b = new Question
("Mitigation_b",4,5,0,0,0);
        Question Mitigation_c = new Question
("Mitigation_c",2,2,3,1,1);
        Question Mitigation_d = new Question
("Mitigation_d",0,7,2,0,0);
        Question Mitigation_e = new Question
("Mitigation_e",0,7,0,2,0);
        Question Mitigation_f = new Question
("Mitigation_f",2,3,1,2,1);
        Question Mitigation_g = new Question
("Mitigation_g",0,2,3,4,0);
        Question Mitigation_h = new Question
("Mitigation_h",1,4,1,3,0);


        Question Response_a = new Question ("response_a",4,3,0,2,0);
        Question Response_b = new Question ("response_b",2,3,0,3,1);
        Question Response_c = new Question ("response_c",4,3,1,1,0);
        Question Response_d = new Question ("response_d",1,7,1,0,0);
        Question Response_e = new Question ("response_e",3,3,3,0,0);
        Question Response_f = new Question ("response_f",1,4,1,3,0);
        Question Response_g = new Question ("response_g",0,1,2,6,0);
        Question Response_h = new Question ("response_h",4,4,0,1,0);


        Question Recovery_a= new Question ("Recovery_a",0,7,2,0,0);
        Question Recovery_b= new Question ("Recovery_b",1,6,1,1,0);
        Question Recovery_c= new Question ("Recovery_c",3,4,2,0,0);
        Question Recovery_d= new Question ("Recovery_d",1,4,2,2,0);
        Question Recovery_e= new Question ("Recovery_e",1,4,3,1,0);
        Question Recovery_f= new Question ("Recovery_f",2,5,2,0,0);
        Question Recovery_g= new Question ("Recovery_g",3,3,2,1,0);
        Question Recovery_h= new Question ("Recovery_h",3,4,2,0,0);
        Question Recovery_i= new Question ("Recovery_i",0,2,4,3,0);


        System.out.println("first round results are:");
        System.out.println("******************");


        Preparedness_a.result();
        Preparedness_b.result();
        Preparedness_c.result();
        Preparedness_d.result();
        Preparedness_e.result();
        Preparedness_f.result();
        Preparedness_g.result();
        Preparedness_h.result();



        System.out.println("******************");
        Mitigation_a.result();
        Mitigation_b.result();
        Mitigation_c.result();
```

```
        Mitigation_d.result();
        Mitigation_e.result();
        Mitigation_f.result();
        Mitigation_g.result();
        Mitigation_h.result();

        System.out.println("*******************");
        Response_a.result();
        Response_b.result();
        Response_c.result();
        Response_d.result();
        Response_e.result();
        Response_f.result();
        Response_g.result();
        Response_h.result();

        System.out.println("*******************");
        Recovery_a.result();
        Recovery_b.result();
        Recovery_c.result();
        Recovery_d.result();
        Recovery_e.result();
        Recovery_f.result();
        Recovery_g.result();
        Recovery_h.result();
        Recovery_i.result();

    }
}
```

Appendix K: Delphi evaluation code results (round 1)

first round results are:

****

1. Preparedness_a: Neutral results skewed the answer
2. Preparedness_b: Answered
3. Preparedness_c: Answered
4. Preparedness_d: Answered

****

1. Mitigation_a: Answered
2. Mitigation_b: Answered
3. Mitigation_c: Answered
4. Mitigation_d: Answered
5. Mitigation_e: Answered
6. Mitigation_f: Answered
7. Mitigation_g: Answered
8. Mitigation_h: Answered
9. Mitigation_j: Answered
10. Mitigation_k: Answered

****

1. response_a: result is tied
2. response_b: Neutral results skewed the answer
3. response_c: Neutral results skewed the answer
4. response_d: Answered
5. response_e: Answered
6. response_f: Neutral results skewed the answer
7. response_g: Answered
8. response_h: Answered
9. response_j: Answered
10. response_k: Answered

****

1. Recovery_a: result is tied
2. Recovery_b: Neutral responses are the majority
3. Recovery_c: Neutral results skewed the answer
4. Recovery_d: Neutral responses are the majority
5. Recovery_e: Neutral results skewed the answer
6. Recovery_f: Answered
7. Recovery_g: Answered
8. Recovery_h: Answered
9. Recovery_j: Answered
10. Recovery_k: Answered
11. Recovery_l: Answered

Appendix L: Delphi evaluation code results (round 2)

Second round results are:

****

1. Preparedness_a: Answered
2. Preparedness_b: Answered
3. Preparedness_c: Answered
4. Preparedness_d: Answered
5. Preparedness_e: Answered
6. Preparedness_f: Answered
7. Preparedness_g: Answered
8. Preparedness_h: Answered

****

1. Mitigation_a: Neutral responses are the majority
2. Mitigation_b: Answered
3. Mitigation_c: Neutral results skewed the answer
4. Mitigation_d: Answered
5. Mitigation_e: Answered
6. Mitigation_f: Answered
7. Mitigation_g: Answered
8. Mitigation_h: Answered

****

1. response_a: Answered
2. response_b: Answered
3. response_c: Answered
4. response_d: Answered
5. response_e: Answered
6. response_f: Answered
7. response_g: Answered
8. response_h: Answered

****

1. Recovery_a: Answered
2. Recovery_b: Answered
3. Recovery_c: Answered
4. Recovery_d: Answered
5. Recovery_e: Answered
6. Recovery_f: Answered
7. Recovery_g: Answered
8. Recovery_h: Answered
9. Recovery_i: Neutral responses are the majority

****

1. Challenge_a: Answered
2. Challenge_b: Answered
3. Challenge_c: Neutral results skewed the answer
4. Challenge_d: Answered
5. Challenge_e: Answered
6. Challenge_f: Answered
7. Challenge_g: Answered

8. Challenge_h: Answered