Rapid Review: What are the latest innovations in public health surveillance methods?

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Please Note: An update of this review may be available. Access the most current version of this review by visiting the National Collaborating Centre for Methods and Tools COVID-19 Rapid Evidence Service at the above link.

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Executive Summary

Background

Public health surveillance includes the ongoing collection, analysis and interpretation of health-related data to inform public health decision making. As public health evolves and adapts to continuously changing population health needs, innovative strategies for population health surveillance are required to meet those needs.

The development of new technologies has driven many of the novel and innovative approaches to public health surveillance. Advances in digital technologies have contributed to novel sources of data and innovative analyses of these data. Development of molecular genomic technologies have allowed for efficient analyses of viral genomics. Application of artificial intelligence to surveillance analyses has enabled novel insights into population-level data.

Public health crises have been shown to accelerate public health innovations. For example, following the West Africa Ebola outbreak, the World Health Organization issued a call for the development of resilient, integrated public health systems, leading to the implementation of public health emergency frameworks (Kieny 2014). Increased incidence of wildfires has prompted the development of coordinated responses across jurisdictions and innovations in risk reduction (Gilliland 2022). Globally, the COVID-19 pandemic sparked many changes to public health surveillance, which were explored in a prior rapid scoping review (National Collaborating Centre for Methods and Tools 2022). These changes include widespread application of digital technologies for population health surveillance, advancements in wastewater epidemiology, and many examples of adaptations and innovations in surveillance by public health service providers.

This rapid scoping review was produced to support public health decision makers' strategic planning for public health surveillance methods, strategies and systems. This review looks beyond COVID-19 innovations and seeks to identify and summarize emerging research evidence to support evidence-informed planning for public health surveillance. This review complements the prior rapid review (National Collaborating Centre for Methods and Tools 2022).

This rapid scoping review includes evidence available up to June 8, 2023, to answer the question: **What are the latest innovations in public health surveillance methods, including novel methods, novel data sources, dissemination/communication, and approaches to surveillance?**

Key Points

- In the last five years, there has been substantial evidence published for adapted and novel strategies for public health surveillance. This review includes 767 articles describing innovations in public health surveillance methods. Many of these innovations were made within established public health surveillance practices, and the novelty lies within advancements in the methods or application to new challenges.

- In addition to articles that detail surveillance methods, there were 67 articles exploring the potential implications of surveillance innovations, from ethical, legal, security, equity and Indigenous perspectives. These articles highlight the need to carefully consider any potential harm to populations, particularly equity-seeking populations, when planning public health surveillance.
- COVID-19 surveillance dominates the literature included in this review, reflecting the global efforts to manage the pandemic. Of the 767 articles that describe innovative surveillance methods, 556 (72%) focused on surveillance of COVID-19. Of the 211 remaining articles, 144 (68%) focus on surveillance of infectious diseases, reflecting fewer innovations occurring in other public health topic areas.
- The surveillance methods included in this review are very diverse in approaches, public health topics, and contexts. Innovations reflect advancements in technologies, particularly methods that capitalize on the omnipresence of digital technologies in modern life, digital innovations in healthcare settings, advancements in the efficiency and feasibility of genomic sequencing, and expanding wastewater testing infrastructures.
- Surveillance innovations also exhibited resourcefulness and creativity, where surveillance strategies were adapted and applied to new public health topics, contexts, settings and pandemic restrictions.
- Articles for wastewater surveillance were highly prevalent in this review, accounting for nearly half of all studies in this review (363 articles, 47% of all included articles). These studies were largely dominated by wastewater testing for COVID-19 (319 articles, 88% of wastewater surveillance articles), but there were examples of wastewater testing for other infectious diseases and other public health topics. The significant investment in and application of wastewater testing infrastructure and processes for COVID-19 surveillance provides an opportunity to expand public health wastewater surveillance for other topics.
- Digital methods of surveillance, using digital data to monitor the health of populations, was also highly represented in included studies, accounting for more than one quarter of included articles (203 articles, 26% of all included articles). As populations are increasingly online, and the use of digital technologies in modern life grows, opportunities for digital public health surveillance are likely to grow.
  - Many studies relied on Big Data, large sets of data that are collected using digital technologies but not necessarily for the purpose of public health surveillance. Given the number of articles that discuss the potential harms of innovations in digital public health surveillance, there is potential for policy restrictions in how this data may be used.
  - Many studies also relied on user engagement with surveys and apps, such as daily logging of symptoms, which was likely driven by the urgency of the COVID-19 pandemic. Without a unifying, urgent need, populations may be less likely to engage in such public health surveillance efforts.
- Artificial intelligence was applied in many types of surveillance, including the analysis of genomes and hospital records, and predicting trends based on collected data.
- Applications of artificial intelligence are likely to grow as technologies develop, but as reflected in editorials included in this review, the potential impact on inequities and trust in public health must be considered.

- Articles for communication of public health surveillance data focused on digital methods, largely through the development of online dashboards to visualize data for decision making. Automation of the analysis of digital data has allowed for dashboards to be updated in near-real time.

Overview of Evidence and Knowledge Gaps

- Since this review took a scoping review approach, findings for the effectiveness of surveillance methods and the quality of included articles were not evaluated. A systematic analysis of included articles, including the extraction of outcome data, rigorous quality assessment of included articles and judgements of the certainty of evidence, is strongly recommended when considering the potential future implementation of any of the surveillance methods discussed in this report.
- As this review did not include grey literature, it is likely that there are innovations in public health surveillance that were not captured in this review. Furthermore, as public health organizations focused on the pandemic response and recovery, it is likely there has been limited capacity to report on recent innovations, meaning some surveillance innovations implemented during COVID-19 in practice may not be captured in either the published or grey literature.
- Similarly, there are likely additional grey literature sources of evidence for the implications of innovations in public health surveillance methods. Articles that provide perspectives on potential harms may exist in other forms of media, such as online blogs or news media articles, which were not captured in this review.
- Literature was heavily focused on infectious disease surveillance, particularly COVID-19. Beyond COVID-19 articles, two-thirds of articles describe innovations in infectious disease surveillance. Other public health topic areas, such as chronic diseases or population mental health are underrepresented in the literature and surveillance innovations in these areas may be lagging.
- Only one article described collaboration with Indigenous peoples to develop an approach to surveillance, and only one article discussed the potential implications of surveillance for Indigenous peoples. There were no articles that focused on the experiences of other populations who live with social and structural inequities. Particularly, articles focused on digital surveillance may overrepresent populations who access and engage with digital technologies and may be younger and have higher income. This is a major gap in the published literature, and these perspectives must be considered in developing surveillance strategies.

Further Considerations for Innovations to Public Health Surveillance Methods: Perspectives of Public Health Epidemiologists.

- Two public health epidemiologists working in Ontario provided feedback on the findings of this review. Overall, they found the findings aligned with their perspectives on public health surveillance innovations.
- It was noted that many of the surveillance strategies or concepts captured in this review are not truly novel, but that innovations lie in advancements to methods and application of strategies to new situations. In particular, surveillance has long occurred in point-of-

care settings, but applications of artificial intelligence, robotics and predictive modelling are innovations in this field.
- The emphasis on infectious disease surveillance was also noted, with concern that while infectious disease surveillance is an important aspect of public health, it is only one part, and advancements in surveillance of other public health topic areas may be lacking.
- It was suggested that with the growing use of artificial intelligence in public health surveillance, its potential impact on the public's trust of public health must also be considered.

Methods

A description of the development of the National Collaborating Centre for Methods and Tools' Rapid Evidence Service has been published (Neil-Sztramko *et al.*, 2021). The paper provides an overview of the review process with rationale for methodological decisions. This methodology was adapted to a scoping review approach guided by methodology described by Arksey and O'Malley (Arksey & O'Malley, 2005).

Research Question

What are the latest innovations in public health surveillance, including novel methods, novel data sources, dissemination/communication, and approaches to surveillance?

Search

On June 8, 2023, the following databases were searched using key terms [novel, or innovation, innovative, monitor, population, surveillance, methods, population]:

- MEDLINE database
- Embase
- Ovid Emcare
- Global Health Database
- Web of Science

A copy of the full search strategy is available in Appendix 1.

Study Selection Criteria

English-language, peer-reviewed sources and sources published ahead-of-print before peer review were included. Grey literature was also included.

	Inclusion Criteria	Exclusion Criteria	Rationale
Population	Global, international, national, provincial, territorial, state, regional, municipal populations	Individual-level surveillance (i.e., surveillance of an individual) where data is analyzed at the level of the individual rather than population.	To inform population-level surveillance programs and systems
Concept	New, novel or adapted surveillance programs and systems for public health topics Dissemination/ communication of surveillance innovations	New/novel assays for detection of an infectious disease, e.g., sensitivity testing of a new SARS-CoV-2 rapid test	To inform planning of public health surveillance programs on a large scale
Context	All disciplines of public health		To inform comprehensive public health surveillance planning for Canada
Limits	2018-present	Grey literature	Publications prior to 2018 no longer reflect current innovations. Grey literature was excluded to facilitate rapid review timeline

Data Extraction and Summary

Data relevant to the research question, such as the target subject and method of surveillance, setting and context, and type of evidence were extracted. Results were summarized narratively to provide an overview of trends in the included literature.

The quality of included studies was not assessed as this scoping review reports on trends in studies and does not report study findings.

Citizen Engagement in the Review Process

Given the technical nature of this review topic, public health practitioners were approached to peer review this report. Two public health epidemiologists were invited to provide feedback on a draft of this review. Each provided feedback on the initial draft and approved the final report. Their comments were summarized and added to a section of the review entitled: Further Considerations for Innovations to Public Health Surveillance Methods: Perspectives of Public Health Epidemiologists.

Findings

Summary of Evidence

A total of 19 392 references were retrieved through database searching. After screening, 834 articles were included in the review, and are listed in Appendix 2. Of the 834 included articles, 767 describe innovations in public health surveillance, and 67 discuss the implications of surveillance innovations from ethical, legal, security, equity and Indigenous perspectives.

The 767 articles describing public health innovations include many different types of surveillance. The following table lists the public health surveillance methods, along with the total number of articles, single studies and syntheses, and articles focused on surveillance of COVID-19. Each of these public health surveillance methods is described in further detail later in this report.

	Total articles [n (%)]	Syntheses [n]	Single studies [n]	COVID-19 studies [n (%)]
Wastewater surveillance	363 (47)	47	316	319 (88)
Digital surveillance	203 (26)	37	166	108 (53)
Surveillance using data collected at point-of-care settings	80 (10)	5	75	48 (60)
Genomic surveillance	42 (5)	2	40	34 (81)
Adaptation of an existing surveillance system to a new subject or context	20 (3)	0	20	16 (80)
Other	59 (8)	6	53	31 (53)
Total	**767**	**97**	**670**	**556 (72)**

In addition to COVID-19, many public health topics were monitored in included articles. These public health topics are listed in the following table.

	Total articles [n]
Antimicrobial resistance	7
Health Promotion	12
Health Equity	2
Immunization	12
Health Communication	2
Mental Health and Substance Use	22
Infectious Diseases	710
Total	**767**

The following Sankey diagram illustrates the number of included articles that describe different surveillance methods for each public health topic.
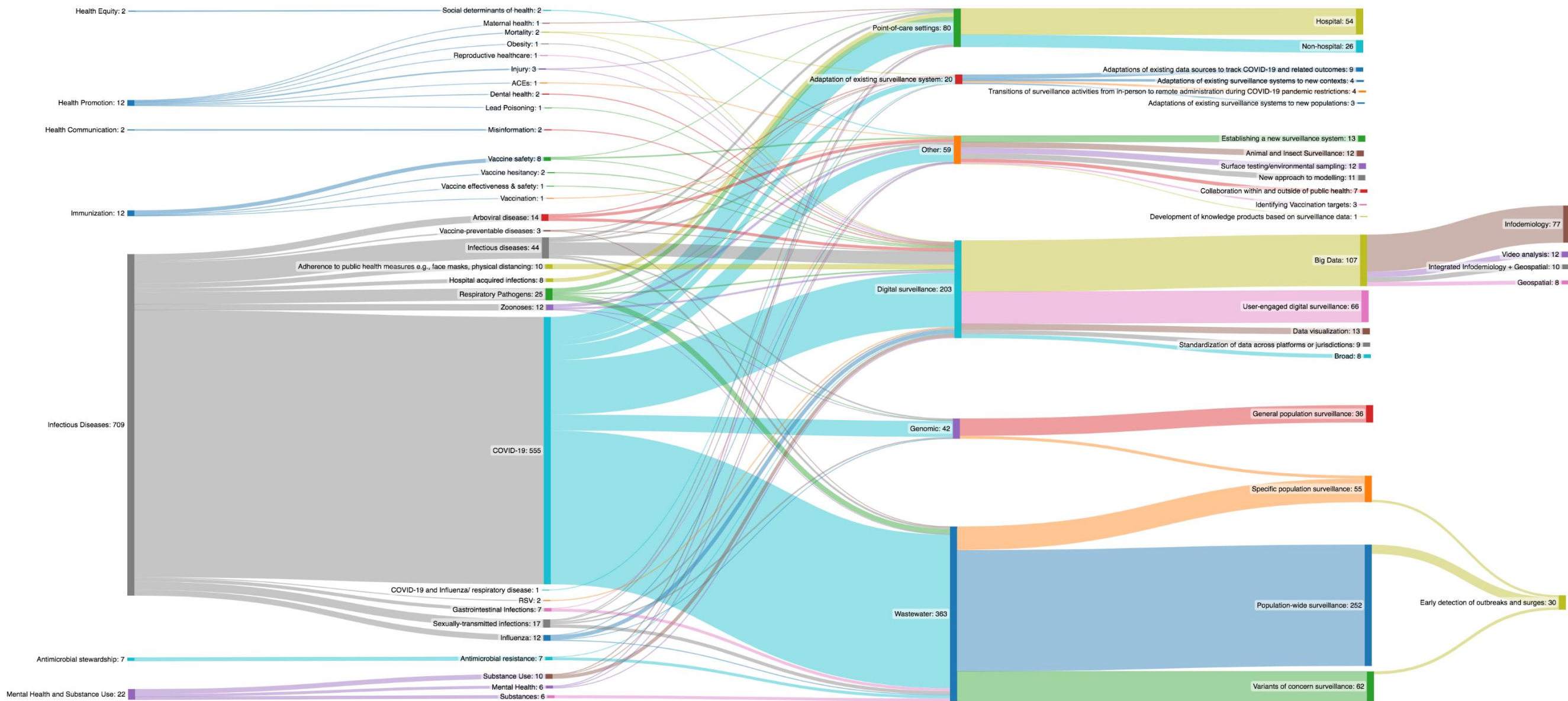
In the following sections, each of the included surveillance types is explored in more detail, followed by a summary of articles that discuss the implications of public health surveillance innovations.

Adaptations to existing surveillance

There are 20 articles that describe the adaptation of an existing surveillance system to a new subject or context. There were no syntheses, and two papers were described as qualitative case studies. The remaining 18 papers were largely descriptive in nature; therefore, a study design was not reported.

Of these 20 reports, 16 (80%) describe adaptations in response to the COVID-19 pandemic, and four describe adaptations to new contexts. Reports included descriptions of:

1. Adaptations of existing data sources to track COVID-19 and related outcomes (nine studies)
2. Transitions of surveillance activities from in-person to remote administration during COVID-19 pandemic restrictions (four studies)
3. Adaptations of surveillance systems to new populations (three studies)
4. Adaptations of existing surveillance systems to new contexts (four studies)

Adaptations of existing data sources to track COVID-19 and related outcomes

Nine studies describe the adaption of existing data sources to track the spread of COVID-19 and related outcomes. Of these nine reports, six describe the adaptation of an existing integrated population surveillance system for influenza or other infections to surveillance of COVID-19 (Bagaria 2022, Silverman 2020, Rigoine de Fougerolles 2022, Rizzo 2022, Vega-Alonso 2023, Fahim 2023). Furthermore, two studies used existing data networks for maternal, fetal and neonatal health to track the impact of COVID-19 in pregnant women (McClymont 2021, Tong 2023), and one additional study described the leveraging of school absenteeism data to track and predict the spread of COVID-19 (Lai 2021).

Transitions of surveillance activities from in-person to remote administration during COVID-19 pandemic restrictions

Other surveillance adaptations in response to the COVID-19 pandemic include the transition of surveillance activities from in-person to remote administration which was described in four reports. For example, two studies described the use of videoconferencing software for HIV screening (Holt 2023, Rivera 2022). Another study described conducting public health assessments of potential Creutzfeld-Jakob cases using phone or videoconferencing software (Watson 2021). Finally, a study based in Malaysia described a system for conducting verbal post-mortem assessments with caregivers of the deceased over the phone to determine the cause of death (Nasaruddin 2022).

Adaptations of surveillance systems to new populations

Three studies describe how COVID-19 data was integrated with existing surveillance systems for people experiencing houselessness or displaced people. Of these three studies, two describe data management for people experiencing houselessness in England (Capelastegui 2023) and Los Angeles, California, USA (Jones 2022). The third study describes monitoring of COVID-19 in refugee centres along the Thailand-Myanmar border (Knust 2022).

Independent of the COVID-19 pandemic, three studies describe the adaptation of existing surveillance systems to a new context. A US-based study described changes to the Animal and Plant Health Inspection Service and National Notifiable Disease Surveillance System to monitor vector-borne diseases in the context of climate change (Halabi 2020). Similarly, a study in Colombia described modifications to a vector-surveillance system during the COVID-19 pandemic (Rojo Ospina 2023). Another study based in Africa described national surveillance systems for neglected tropical diseases following the WHO's declaration of a post-eradication era (Hatherell 2021). Finally, a study based in Borno State, Nigeria described adaptations to polio surveillance in the context of armed conflict or restricted access to populations (Wiesen 2022).

Healthcare and related settings

There are 80 included articles that describe public health surveillance using data collected from point-of-care settings, such as a hospital, pharmacy, long-term care facility, etc. Innovations include using novel data collection settings to conduct population-level surveillance, using point-of-care data to monitor the spread of COVID-19, and the development and testing of new methods for analyzing electronic medical records.

Of the 80 included articles, 48 (60%) describe efforts to monitor the spread of COVID-19. Reports included descriptions of surveillance using data from:

1. Hospitals (54 articles)
2. Non-hospital points of care, such as emergency medical services, pharmacies, telehealth services, etc. (26 articles)

Hospital settings

There were 54 articles describing the use of data from hospitals. There were four syntheses, including a systematic review that compared the effectiveness of various early warning systems for emerging infectious diseases using hospital and public health records (Meckawy 2022). The remaining three syntheses were non-systematic literature reviews providing overviews of how healthcare-related data has been applied to infectious disease surveillance (Amusa 2023, Zahoor 2022, Pham 2020). Of the 50 single studies and reports, most monitored COVID-19 (n=28) or influenza and other infectious diseases (n=10). These reports estimated community rates of transmission and predicted outbreaks based on hospital data. Several reports explored using artificial intelligence to conduct these analyses, using data on hospital usage (Merlo 2023), case counts in hospitals (Raut 2022) or visit notes (Shapiro 2022, Tsui 2018, Weng 2020, Willis 2021, Gamage 2023, Cohen 2021). One report developed an automated robot to conduct laboratory testing of patient samples (Arnott 2021). In addition, seven reports explored using artificial intelligence to monitor electronic medical records for other infectious diseases, including chlamydia (Trolard 2020) and hospital-acquired infections (Lukasewicz 2022, Verberk 2022, Noaman 2018, Tarai 2019, Wynn 2023, Villamarin-Bello 2019). Other topics of hospital-based surveillance included dementia incidence (Jones 2023), injuries (Magnus 2020) and self harm (Fortune 2022).

Non-hospital points-of-care

The remaining 26 articles explored the use of data from non-hospital healthcare settings. These include one synthesis, a scoping review of telehealth data to inform COVID-19

surveillance (Almasi 2021). Of the 26 single studies, two studies explored using data from fever clinics to track COVID-19 in the USA (Shih 2022) and in China (Lai 2020). Three studies describe the use of data from long-term care facilities for COVID-19 surveillance (Gravningen 2022, Stemler 2022, Garcia Gomez 2022). Five reports used data from emergency medical services, including call volumes as well as call logs and service records to estimate population-level burdens. Emergency medical service data was used to track COVID-19 (Brennan 2023, Janagama 2022), influenza (Reich 2019), suicides and overdoses (Thorndike 2023) and gamma-hydroxybutyrate (GHB) use (Ogeil 2023). Two reports conducted in LMICs used data from telehealth service providers to estimate population levels of COVID-19 (Boaventura 2023, Seck 2022). A study in Florida, USA, explored automated reporting and notification of sexually transmitted infections (Danforth 2022). Two reports used data from poison control hotlines in the USA to monitor adverse reactions to COVID-19 vaccines (Diak 2023) and adverse reactions to COVID-19 treatments (Tadfor 2023). Two reports used data collected at pharmacies, including a report in Tanzania that monitored confirmed and suspected COVID-19 cases (Mohamed 2023) and an Australian report that analyzed influenza vaccine safety data from pharmacists administering the vaccine (Salter 2021). Samples from blood donors were used for COVID-19 serosurveillance in two studies (O'Brien 2022, Harker 2023). Finally, six reports used data based on death records, including a study of maternal deaths in India (Kansal 2018), suicide deaths in Utah, USA (Liu 2020) and COVID-19 deaths in the USA (Coburn 2022), France (Fouillet 2022), Brazil (Guimaraes 2023) and South Africa (Ebonwu 2022).

Genomic surveillance

A total of 42 articles described surveillance of the evolving genomes of infectious diseases. Novel applications of genomic surveillance included sample collection in specific settings, such as airports, as well as genomic surveillance of novel pathogens, such as SARS-CoV-2, the virus that causes COVID-19, and mpox. Several studies report novel applications of artificial intelligence to analyse genomic data.

Of the 42 included articles, 34 (81%) describe genomic surveillance of SARS-CoV-2. Articles include descriptions of genomic analyses using samples collected from:

1. Specific settings, such as hospitals and airports (six articles)
2. General population (36 articles)

Specific settings

Six reports describe data collection from specific settings. This included analysis of COVID-19 samples collected from air travellers (Bart 2023, Wegrzyn 2022), hospital patients (Berggreen 2023, Smith 2023) and US military facilities (Morton 2022), and Hepatitis A samples from hospital patients (Hu 2021).

General population

The remaining 36 articles focused on samples collected more broadly from the general population. These include two syntheses, both were non-systematic literature reviews, focused on global genomic surveillance of emerging pathogens (Shaw 2018) and COVID-19 (Robishaw 2021). Of the 34 single studies and reports, one was conducted using municipal data, seven at the regional level, 14 at the national level, two internationally, and 10 using global datasets of genomic data.

Furthermore, of the 34 studies that analysed samples from the general population, 27 analysed COVID-19 samples to monitor for the entry of new variants into an area, or for the detection of new variants. The remaining seven studies analysed genomes for influenza, HIV, mpox, rabies, streptococcal pneumonia and non-malarial fever.

Five studies applied artificial intelligence to conduct genomic analyses, all for COVID-19 samples (Bhat 2021, Gonzalez-Isunza 2022, Nagpal 2022, Yvan 2022, Zhao 2023).

Wastewater

Wastewater surveillance tests wastewater for pathogens or substances and can be used to determine a population's exposure to pathogens or consumption of substances. Data for substance use was used inform both population-level surveillance of substance use as well as prevalence of mental health conditions. Wastewater surveillance was heavily featured in included articles, with 47 included syntheses and 316 single studies and reports focused on wastewater.

Most articles focused on wastewater surveillance of SARS-CoV-2. Forty-five (96%) of included syntheses and 272 (87%) of included single studies focused on wastewater surveillance of SARS-CoV-2.

There are four general applications of wastewater surveillance (Manuel 2022). The articles included in this review were classified according to the following four applications:

1. Population-wide surveillance (233 articles)
2. Specific population surveillance (44 articles)
3. Variants of concern surveillance (56 articles)
4. Early detection of outbreaks and surges (30 articles)

Population-wide surveillance

The most basic application of wastewater surveillance is to sample and test wastewater collected at municipal or regional wastewater treatment sites to monitor either pathogens or substances. Pathogen and substance levels detected through wastewater are often compared to and complement levels determined through other means of testing. General population surveillance was the most prevalent application amongst included studies, with 37 syntheses and 196 single studies, accounting for 64% of all wastewater surveillance articles.

Of the 37 syntheses, there were four systematic reviews. Two systematic reviews evaluated wastewater surveillance of SARS-CoV-2 (Anand 2022, Shah 2022), another evaluated wastewater surveillance of SARS-CoV-2 in African countries (Dzinamarira 2022), and another focused on procedures and modelling of wastewater data for SARS-CoV-2 surveillance (Ciannella 2023). One scoping review of studies of wastewater surveillance of SARS-CoV-2 was also included (Bonanno Ferraro 2022). Additionally, 32 non-systematic literature reviews were included. Three of these focused on surveillance topics other than SARS-CoV-2, including antimicrobial resistance (Cuetero-Martinez 2022), mpox (Atoui 2023), and human arboviral diseases (Lee 2022). The remaining 29 non-systematic literature reviews explored wastewater surveillance of SARS-CoV-2, mostly in terms of case examples and feasibility. One review was specific to Canada (Joung 2022). Another review focused specifically on the effects of vaccination on virus detection in wastewater samples (Armas 2023).

Of the 196 single studies of population-wide surveillance, four evaluated wastewater surveillance of antimicrobial resistance (Harrington 2022, Steenbeek 2022, Acosta 2023, Prieto

Riquelme 2022), six focused on detection of substances, including illicit drugs, tobacco, alcohol and pharmacologic drugs (Lee 2023, Cruz-Cruz 2019, Esteves-Danta 2022, Psichoudak 2022, Massano 2022, Bade 2023), 23 evaluated wastewater surveillance of pathogens other than SARS-CoV-2, including ten of respiratory pathogens such as respiratory syncytial virus (RSV) and influenza, five of mpox (Sharkey 2022, Mejia 2022, Wolfe 2022a, Wolfe 2022b, Girón-Guzmán 2022), five of gastrointestinal pathogens such as norovirus and enterovirus (Ibrahim 2023, Kim 2023, Tedcastle 2022, Ammerman 2023, Erster 2022), and one study each of adenovirus (Martin 2023), Candida auris (Rossi 2023), and pathogens in general (Faraway 2022). The remaining 163 single studies evaluated wastewater surveillance of SARS-CoV-2. Of these, 115 monitored wastewater levels of SARS-CoV-2 at the city or municipal level, 30 at the regional, state or provincial level, and 18 at the national level or more broadly. Of the 163 studies of COVID-19 wastewater surveillance, 44 (17%) were conducted in low- or middle-income countries.

Specific population surveillance

Surveillance of specific populations is conducted similarly to general population surveillance, but wastewater samples are collected from specific sources, such as hospitals, campuses or worksites. In this review, there is one synthesis and 43 single studies of wastewater surveillance at specific sites.

The only synthesis of studies of wastewater surveillance at specific sites is a non-systematic literature review of SARS-CoV-2 monitoring in medical and industrial wastewater (Yang 2023).

Of the 43 single studies, five evaluated surveillance of topics other than SARS-CoV-2. These included a report of antimicrobial resistance in hospital wastewater (Wang 2022), as well as influenza at a university or college campus (Wolfe 2022). Three studies tested wastewater collected at airports to detect if pathogens were imported with incoming travellers, including mpox (La Rosa 2022), polio (Krzysztoszek 2022), and viromes in general (Hjelmso 2019).

The remaining 38 reports evaluated wastewater surveillance of SARS-CoV-2. Three reports used samples from airports or commercial airplanes (Nkambule 2023, Farkas 2023, Ahmed 2023). Two reports used samples from ships, including a study of US Coast Guard vessels (Hall 2022) and a US naval aircraft carrier (Boni 2022). Three reports used hospital wastewater samples (Acosta 2022, Ou 2023, Acosta 2021) while another used samples from both a hospital and long-term care facility (Gallardo-Escarate 2021). There were two reports of samples collected at correctional facilities (Saber 2023, Klevens 2023). Two reports collected samples from large worksites, including a national government lab in India (Malik 2023) and a hydroelectric plant in Brazil (Cabral 2022). Finally, the remaining 25 reports were based on samples collected on university or college campuses.

Variants of concern surveillance

In addition to quantifying the amount of genetic material of pathogens of interest in wastewater samples, it is possible to sequence the genetic material to detect known or potentially new variants. This can be done with samples from the general population or specific populations. In this review, there were three syntheses and 53 single studies of variants of concern surveillance.

The three included syntheses include one systematic review (Tiwari 2023) and two non-systematic literature reviews (Shrestha 2021, Anshika 2022). All three focused on detecting variants of SARS-CoV-2 in the general population.

There were 53 single studies. Three of these studies detected variants of pathogens other than SARS-CoV-2, including norovirus (Mabasa 2018) and two studies of influenza variants (Mercier 2022, Vo 2023). Of the 50 studies of SARS-CoV-2 variants, 47 monitored the general population. Of these 47 studies, 33 collected samples at the city or municipal level, six collected samples at the regional, state or provincial level, and eight at the national level. Of the three studies of specific populations, one detected variants of concern from airplane wastewater samples (Ahmed 2022) and two from university or college campus wastewater (Sweetapple 2022, Sellers 2022).

Early detection of outbreaks and surges

Finally, wastewater surveillance can be used to detect pathogens prior to the reporting of cases in the population. These early warning systems can be used population-wide or for specific populations. Some early warning systems were for the early detection of emerging variants of concern. In this review, there were six syntheses and 24 single studies of the early detection of SARS-CoV-2.

The six included syntheses were all non-systematic literature reviews of population-wide early warning systems for SARS-CoV-2.

Of the 24 included single studies, 13 were conducted across the general population. Ten studies were at the city or municipal level while three studies were conducted at the regional, state or provincial level. Five studies used samples from specific populations, including airplanes (Li 2023), hospital (Hong 2020), two schools (Fielding-Miller 2021, Rajput 2023) and a university or college campus (Karthikeyan 2021).

The remaining six single studies explored the early detection of SARS-CoV-2 variants of concern. One used airport wastewater samples (Morfino 2023), while five used samples from the general population (Sapoval 2023, Rajput 2023, Peng 2022, Wilhelm 2022, Vo 2022).

Digital surveillance

Digital surveillance refers to the use of digital technologies for the surveillance of population health. Digital data can be collected through mobile phone apps, websites and the "Internet of Things", which are devices with sensors and software that allow networking and sharing of data. These devices include a wide array of items such as smartwatches, heart monitors, banking machines, point-of-sale systems, and many machines in industrial, manufacturing and agricultural settings.

Approximately half of all included digital surveillance articles focused on monitoring of COVID-19 transmission (n=108, 53%). Thirty articles were set in LMICs (18%). All but eight of the 203 articles can be categorized into four general categories of digital surveillance with one, Big Data, further categorized into four sub-categories:

1. Big Data (107 articles)
    a. Infodemiology (77 articles)
    b. Geospatial (8 articles)
    c. Integration of infodemiology and geospatial data (10 articles)
    d. Video analysis (12 articles)
2. User-engaged digital surveillance (66 articles)
3. Standardization of data across platforms or jurisdictions (9 articles)
4. Data visualization (13 articles)

In addition to articles that fall into the four categories above, there were eight articles, including seven non-systematic literature reviews and one cross-sectional study, on digital technologies. These articles all had a broad focus, exploring more than one of the categories above. Five reviews provided overviews of case examples of digital surveillance for COVID-19 (Alwashmi 2020, Neal 2022, Smith 2020, Jia 2023), with one focused on artificial intelligence applications to digital surveillance for public health (Ahmed 2021). Two literature reviews explored digital surveillance for infectious diseases in general (Maati 2021, Rahman 2022). The cross-sectional study conducted a survey of digital surveillance methods for COVID-19 in European countries (Unim 2022).

Big Data

Big Data are large data sets generated using digital technologies. Data are not submitted by users for the purpose of analysis, but rather the data is captured using websites and networked devices.

Infodemiology

Infodemiology refers to the analysis of data entered by users, e.g., search engine search terms, social media posts, news media. Data are often analyzed for content to identify trends across populations.

Fifty-one (48%) of the included articles on infodemiology were focused on monitoring COVID-19, while the remaining articles looked at other infectious diseases or other public health topics.

There were 11 syntheses on infodemiology for public health surveillance of various public health topics. This included four systematic reviews. One of these systematic reviews evaluated monitoring of COVID-19 transmission, using data from search terms entered into search engines (Ma 2022). The other three systematic reviews evaluated the monitoring of infectious diseases in general, using data from search engine search terms and social media posts (Barros 2020, Pilipiec 2023), or Wikipedia articles (Santangelo 2022). There were two scoping reviews that explored the use of search engine search terms and social media posts to monitor substance use (Keller 2023) and cannabis use specifically (Hallinan 2022). There were also five non-systematic literature reviews that provided overviews of using search engine search terms or social media posts to monitor COVID-19 transmission (Zhang 2022, Garett 2022, Michailidis 2022) or infectious diseases generally (Roberts 2019, Jiao 2023).

Of the 66 single studies, 38 (49%) focused on COVID-19. Of the COVID-19-focused studies, 12 studies monitored COVID-19 transmission using search terms entered in Google or other search engines, 20 used social media posts, of which 15 focused on Twitter. Two studies analysed instant messages sent through WeChat, an instant message service in China (Wang 2020a, Wang 2020b). Two studies analysed posts from public health organizations, such as the Centers for Disease Control and Prevention (Kolak 2021) or European Centre for Disease Control and Prevention (Barone 2020). Finally, two studies analysed news media (Fenton 2022, Ahamad 2020).

Of the remaining studies, a total of 16 monitored other infectious diseases using infodemiology and are summarized here. Two studies monitored arboviral diseases, including dengue using Google search terms (Husnayain 2020), and mosquito-borne illnesses in general using social media and news media (Jain 2018). One study evaluated the transmission of swine flu using news media (Tizzani 2021). There were two studies

that monitored HIV through search engine search terms (Nan 2018) and social media (van Heerden 2020). Six studies monitored respiratory infections using Google search terms, including four that focused on influenza (Clemente 2019, Liu 2022, Cai 2021, Santangelo 2021) and two that focused on RSV (Wang 2023, Ricco 2022). Google search terms were also used to monitor hand, foot and mouth disease (Qian 2022), measles (Samaras 2021), and mpox (Bhagavathula 2022). Infectious diseases in general were monitored using Twitter posts (Elgazzar 2021) and Google search terms (Manso 2022).

Other public health topics were monitored through infodemiology, as described in 12 studies. This includes five studies that analyzed Twitter posts and other social media to monitor substance use (Yan 2022, Tran 2019, Tringale 2021, Lokala 2022) and mental health (Syaputra 2022). Another study explored Google search terms related to reproductive services, specifically abortion (Guendelman 2022). Two studies monitored Google search terms related to dental heath issues during the COVID-19 pandemic (Sycinska-Dziarnowska 2020, Rizzato 2021). Social media were also analyzed for the spread of misinformation (Chiou 2022, Schillinger 2020) and to evaluate confidence in vaccines (Alam 2022, Ahmed 2023).

Geospatial

Another type of Big Data featured in included studies was geospatial data. This is geographically linked data often captured by cell phones and analyzed to track the movement of populations and evaluate the potential spread of infectious diseases.

There were eight articles that evaluated geospatial data, of which six (75%) focused on monitoring COVID-19 transmission.

There were three included syntheses. Two syntheses explored the use of cell phone geospatial data, including one systematic review that focused on COVID-19 (Wang 2022). The two other syntheses were non-systematic literature reviews that discussed COVID-19 surveillance (Kostkova 2021), and infectious disease surveillance more broadly (Buckee 2018).

Of the five included single studies, four monitored COVID-19 using cell phone geospatial data (Amit 2020, Martin 2020), the Geographic Information System (Rupali 2022) or rideshare service data (Safranek 2022). Another study explored infectious diseases in general using cell phone geospatial data and credit card transaction records in South Korea (Kim 2023).

Integration of infodemiology and geospatial data

There were ten articles, mostly syntheses, that explored data across the above two subcategories of Big Data. One systematic review evaluated how geospatial data has been linked to social media data to monitor infectious diseases (Jing 2023). Two scoping reviews (Donelle 2023, Francombe 2022) and five non-systematic reviews captured examples of Big Data used to monitor the COVID-19 pandemic (Shen 2022) or infectious diseases (Parmar 2022, Riswantini 2022, Acosta 2022, Maulana Sirojjudin 2021).

There were also two single studies. One study in India connected data entered by users into apps with geospatial data to track COVID-19 (Ummer 2021). The other study applied artificial intelligence to Google mobility data and Google search term data to predict COVID-19 outbreaks in the UK (Ward 2022).

Video analysis

Finally, Big Data also included video captured by closed-circuit television security surveillance, often analysed for adherence to public health measures, such as face mask wearing and physical distancing.

The only synthesis of video analysis was a non-systematic literature review of video analysis for adherence to mask wearing and physical distancing (Zitouni 2020).

There were 11 single studies in total. Nine single studies analysed videos for mask wearing and physical distancing, of which two used videos captured by transit system security cameras (Cao 2022, Kundu 2022), and seven used unspecified video datasets. Another study used facial recognition software to conduct contact tracing (Wang 2022). Finally, one study explored the use of videos to detect obesity in youth populations (Tang 2021).

User-engaged digital surveillance

User-engaged digital surveillance differs from Big Data in that the data is submitted by users specifically for the purpose of surveillance. Data can be collected through apps and online surveys. Users can also install apps that run independently, or wear devices that independently collect health data.

Of the 66 articles that describe user-engaged digital surveillance, 42 (62%) focused on COVID-19.

There were five syntheses in this category. One systematic review evaluated the use of wearable devices to monitor stress and estimate prevalence of mental health issues within the population (Morales 2022). A scoping review explored the use of wearable devices for the early detection of COVID-19 (Cheong 2022). Another scoping review explored apps and online surveys for monitoring vaccine safety in Canada (Psihogios 2022). Two non-systematic literature reviews discussed apps for monitoring COVID-19 spread (Shaban 2021, Marzan-Rodriguez 2020).

Of the 61 included single studies in this category, 38 focused on COVID-19 (62%). Fifteen of these studies collected data using mobile apps, 15 collected data using an online survey, and five used both mobile apps and online surveys. One study collected data using a telephone system that allowed individuals to leave a recorded message describing their symptoms (Gruene 2022), one study developed an app that analyzed cough sounds in the environment (Iqbal 2020), and another study explored artificial intelligence analysis of data from wearable devices (Mazzanti 2022). Of the 38 total studies focused on COVID-19, three were conducted with data collected form specific populations. This included a survey of hospital employees to predict community spread (Horng 2020), a survey of sporting event attendees (Hohmuth 2022), and a combined app and survey for a university campus (Aidid 2022). The remaining 35 studies were conducted amongst the general population: four captured data from residents of a city, seven studies were conducted at the regional, state or provincial level, 17 captured data nationally, two studies were international and five did not specify their populations.

In addition to COVID-19, 20 studies explored user-engaged surveillance for other infectious diseases. Three studies focused on monitoring influenza, using data collected through text messaging (Stewart 2019), a mobile app (Cawley 2021) or an online survey (Lee 2021), while another study gathered information regarding respiratory illness in general via text message (Stockwell 2022). Two studies developed a mobile phone-based app that analyzed cough sounds in the environment (Gabaldon 2021, Gabaldon-Figueiroa 2022). Seven

studies explored data for infectious diseases in general, collected though a website (DeJonge 2019), an online survey (Schultheiss 2023), mobile apps (El-Khatib 2018, Arias-Carrasco 2020, Cevasco 2023, Mukhi 2018), or text message submission (Byrne 2022). Three studies used apps or websites to collect data to monitor arboviral diseases, including Zika virus in Jamaica (Ruiz-Burga 2022), malaria in Tanzania (Mkali 2023), tick-borne disease in New York state (Hart 2022). Another study developed a mobile phone based acoustic sensor app to detect mosquitoes in the environment (Mukundarajan 2018). Three studies invited community members to submit data via apps, surveys or telephone helplines to monitor rabies in Indonesia (Subrata 2022), Malawi (Mastala 2023), and India (Vanak 2022).

Data to inform monitoring of other public health topics was also evaluated. One study collected online survey data regarding tobacco use in youth (Mazzilli 2022). Two studies monitored vaccine safety through data captured by an online survey (Van Hunsel 2022) or both a mobile app and online survey (Bota 2023).

Standardization of data across platforms/jurisdictions

This category of digital surveillance involves the coordination of data collection or analysis across different settings to allow for broader oversight across jurisdictions. Public health jurisdictions may collect and analyze data for the same subject using different methods, which can hinder the synthesis of data across jurisdictions.

One systematic review investigated the use of artificial intelligence for standardization of health data (Isgut 2022).

There were eight single studies that explored data standardization. Four studies focused on COVID-19 data. Of these, one study explored automated standardization of COVID-19 data in Ireland (Arnott 2021). Two studies focused on standardizing data collected in the Delhi region of India (Hasan 2023) and in the USA (Khan 2023). One study applied artificial intelligence to gather and analyse disparate health data (Bhatia 2022).

One study explored the synthesis of data regarding infectious diseases on a global scale (Badker 2020).

Several studies describe the coordination of data for other public health topics, including vaccine effectiveness in Japan (Fukuda 2023), lead poisoning in children in Arizona, USA (Asburry 2019), and mortality causes in Ghana and Peru (Cobos Munoz 2022).

Data visualization

There were also studies that explored the visualization of digital surveillance data to facilitate decision making in public health. Most of these studies explored different tools to automate data visualization, such as online dashboards.

There were 13 articles that focused on data visualization, of which four (36%) focused on data visualization for COVID-19 data.

One included synthesis explored the application of artificial intelligence to public health datasets to detect emerging infectious diseases (MacIntyre 2023).

Twelve single studies describe the development of data dashboards. Many focused on infectious diseases, including six for COVID-19 data (Mersini 2022, Krusina 2020, Tkatek 2020, Gardner 2022, Ngai 2022, Smida 2020), and one each for influenza (Shan 2022), Staphylococcus aureus (Wozniak 2020), acute febrile illness (Volkman 2020). Data visualization topics also included antimicrobial resistance (Simoes 2018), injuries (Waller 2022), and vaccine safety (Kenigsberg 2022).

Other types of surveillance

In addition to the categories of novel public health surveillance discussed so far, there were articles that did not fit in any of the above categories. Of these, 31 (53%) focused on COVID-19. These include studies of novel methods for testing, such as testing environment samples or new approaches to testing animals and insects for diseases. Studies also included approaches to monitoring population immunity and identifying targets for immunization. There were also studies that described the development of new systems for surveillance. These systems were novel in their collaborations within or outside public health, the topics they monitored or the context in which they were applied. Several studies describe the development and testing of novel approaches to modelling public health surveillance data. Finally, a study evaluated the impact of surveillance data knowledge products developed for decision makers.

Environment testing

There were 12 articles that describe testing the built environment for SARS-CoV-2. These include two syntheses, both non-systematic literature reviews of surface sampling for SARS-CoV-2 (Yao 2021, Abdeldayem 2022). Additionally, there were three single studies focused on surface sampling, including in schools (Fielding-Miller 2021), long-term care facilities (Fralick 2022), and food retail settings (Rafieepoor 2022).

Six other studies explored testing air samples for SARS-CoV-2. Of these, one study evaluated aerosols collected in hospitals (Tan 2022), one study collected samples in schools (Fernandez 2022), three studies sampled indoor settings in general (Gehrke 2021, Horve 2021, Pivato 2022), and one study evaluated air samples collected outdoors (Tao 2022).

Finally, a study evaluated the use of discarded facial tissues in a childcare setting for the monitoring of SARS-CoV-2 (Lagathu 2023).

Zoonosis testing

In total, there were 12 articles that describe novel approaches to testing for zoonoses. These include studies that developed and tested new traps for the analysis of mosquitoes for arboviruses. Other studies describe new approaches to sampling either populations or environments at risk for arboviruses.

Of the 12 articles, there was one synthesis. This synthesis was a systematic review of strategies for the elimination of filariasis in Africa (Kelly-Hope 2018).

Four studies describe the development of new mosquito traps that enable for testing of mosquito samples for potential arboviruses. These include studies of mosquito traps to monitor Leishmaniasis in a wildlife park in Australia (Panahi 2020), malaria in Western Kenya (Degefa 2019) and arboviruses in Eastern Colombia (Montenegro 2020). Another study developed a novel optical sensor that can be coupled with mosquito traps, and using artificial intelligence, determine the genus and sex classification of trapped mosquitos to inform the potential spread of arboviruses (Gonzalez-Perez 2022).

In addition to new traps for arboviral surveillance, three studies describe new approaches to sample populations and environments for arboviral surveillance. One study describes grid-based surveillance of malaria in mobile and migrant populations along the Myanmar border of China (Lu 2022). Another study evaluated a grid-based approach to setting up traps to sample mosquitoes for arboviruses in Shanghai, China (Chen 2021). Finally, a study conducted in the Amazon rainforest described the development of a malaria trigram, a visualization tool to improve monitoring of malaria (de Morais 2021).

Two studies describe trapping and testing of animals. A study conducted in Vienna, Austria describes an approach to trapping and testing city rats to identify emerging zoonotic viruses (Camp 2022), and a study conducted at a wildlife rehabilitation centre in Chile tested animals for COVID-19 (Mena 2023).

Finally, two studies describe using artificial intelligence to predict the likelihood of zoonotic outbreaks based on collected data. These included a study predicting avian influenza outbreaks (Walsh 2019) and cryptosporidiosis (Berke 2020).

Identification of immunization target populations

Three studies described the identification of populations to target with immunization efforts. These include two studies that explored population immunity to SARS-CoV2, through the establishment of a biobank of blood samples in Canada (Saginur 2023) or by adapting serosurveillance procedures to differentiate between infection-derived or vaccine-derived immunity (Duarte 2022).

The third included study described a modelling approach to determine priority populations for cholera immunization in Africa, using immunization rates and incidence rates of cholera (Xu 2022).

Collaboration within public health or with new partners

Seven studies focused on collaborative efforts of public health, either within the field of public health or with new partners outside public health. These include a study that describes the establishment of a network of surveillance experts around the globe who can be rapidly deployed in emergent situations (Schultheiss 2023), and a cross-sectional study of general practitioners available to contribute to sentinel surveillance (Meci 2022).

Another included study described the principles and operational considerations, including data stewardship and governance, for creating an overdose surveillance system among First Nations Peoples in Canada (Saginur 2023).

Three studies described a collaboration between public health and a school system to develop a school-based surveillance system for COVID-19 (Hyder 2021, Rayack 2023, Merckx 2022).

Finally, a study described a collaboration with police for real-time surveillance of suicide (Marzano 2023).

Establishing a new surveillance approach

A total of thirteen articles describe the development of a new approach to surveillance, either for new surveillance topics or in a new context.

Among the thirteen articles, five focus on infectious diseases. These include a systematic review of syndromic surveillance at mass gatherings (Spector 2022). Three single studies describe the establishment of surveillance systems for infectious diseases, including COVID-19 nationally in France (Figoni 2023) and Canada (McGill 2023), and emerging respiratory diseases in China (Ma 2023). The fifth article is a single study that describes a new approach to surveillance focusing on testing for COVID-19 in unaccompanied foreign minors in refugee centres in Italy (Tambuzzi 2022).

Four articles describe the establishment of surveillance infrastructures for other public health topics. These include adverse childhood events (Anderson 2022), social determinants of health (Borrell 2023, Relova 2022), and mental health (Thom 2023).

Finally, four articles describe surveillance systems for vaccines. Three of these articles focus on vaccine safety, including a non-systematic literature review (Piche-Renaud 2022), and studies from Australia (Laemmle-Ruff 2022) and Malaysia (Rahman 2022). The last article focused on vaccination rates in Ontario, Canada (Hobbs 2023).

New approaches to modelling

There were 11 articles that discuss new methods for modelling infectious disease data to predict outbreaks and case surges. Of these, one is a systematic review of space-time clustering techniques of infectious diseases data (Lan 2023). One explores forecasting influenza using artificial intelligence (Wang 2023). The remaining nine studies explore modelling approaches for COVID-19 data.

Development of knowledge products based on surveillance data

One study explored the impact of surveillance knowledge products. This study evaluated knowledge products developed for decision makers on public health decisions during the COVID-19 pandemic in Texas, USA (Chapman 2023).

Articles discussing implications of public health surveillance

In addition to articles that describe innovations in public health surveillance, there were many that explored these innovations from ethical, security, legal, equity perspectives, or from the perspectives of Indigenous peoples. Most of these articles focus on increased surveillance in response to the COVID-19 pandemic, but four were published prior to the pandemic and focus on surveillance for emerging infectious diseases (Degeling 2019, Eckmanns 2019, Shaw 2018, Roberts 2019)

There are a total of 67 articles in this category. Of these 67 articles, 12 are syntheses, all non-systematic literature reviews. There are also 29 single studies. Of the single studies, there are eight qualitative studies, twelve cross-sectional, and nine studies that don't report a study design. These 29 studies explore opinions on the implications of public health surveillance. There was also one article described by authors as an Indigenous critique (Williams 2022). The remaining 25 articles were editorials published in peer-reviewed journals.

Included articles explored innovations in public health surveillance from different perspectives. These different perspectives and the number of articles for each are listed below. Since many articles discussed more than one perspective, the number of articles listed here totals greater than 67.

1. Ethical (33 articles)
2. Legal (14 articles)
3. Security (31 articles)
4. Equity (14 articles)
5. Indigenous (one article)

Ethical perspectives

A total of 33 articles discuss innovations in public health surveillance from an ethical perspective. These articles explore human rights to privacy in relation to surveillance activities. Three of the articles focus on emerging infectious disease surveillance and were published prior to the COVID-19 pandemic (Degeling 2019, Eckmanns 2019, Shaw 2018). The remaining 30 focus on changes to public health surveillance during the COVID-19 pandemic.

Legal perspective

There were 14 articles that discuss legal aspects of innovations in public health surveillance. These articles discuss individuals' legal rights to privacy in relation to public health surveillance. Two of these articles were published prior to the COVID-19 pandemic and discuss surveillance for emerging infectious diseases (Degeling 2019, Eckmanns 2019).

Security perspective

Thirty-one articles provide perspectives on data security risks for public health surveillance. These articles focus on the risks of breaches of sensitive health information. One of these articles was published prior to the COVID-19 pandemic and discussed surveillance for emerging infectious diseases (Roberts 2019).

Equity perspective

Fourteen articles discuss the public health surveillance innovations from an equity perspective. These articles explore the disproportionate risks and harms to equity-deserving populations. These articles all focus on COVID-19 surveillance.

Indigenous perspective

There was one article that shared an Indigenous perspective on innovations in public health surveillance in the USA (Hendl 2022). This article focused on the risk of harms that COVID-19 contact tracing apps impose on Native American populations. Specifically, authors note that the use of contact tracing apps may lead to further oppression of Native American communities.

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