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Review Article

Digital Transformation in Rubella Surveillance: A Scoping Review of Global Practices, Challenges, and Opportunities

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Abstract

Background: The global fight against rubella and congenital rubella syndrome necessitates effective public health surveillance systems. Digital transformation in rubella surveillance has emerged as a pivotal solution to overcome challenges associated with traditional paper-based reporting methods, including inefficiencies in data collection, delays, and inaccuracies. This scoping review examines global practices, challenges, and opportunities in digital rubella surveillance. Method: A scoping review methodology was employed, guided by the Arksey and O'Malley framework and enhancements from the Joanna Briggs Institute. A systematic search was conducted across databases, including PubMed, Scopus, and the WHO Global Health Library, covering literature from 2010 to 2024. Eighteen studies meeting the inclusion criteria, focusing on digital surveillance tools and practices in rubella monitoring, were synthesised. Data were extracted and analysed thematically to identify common practices, challenges, and opportunities. *Results*: The most prominent theme was implementation challenges (50%), particularly data completeness, infrastructure limitations, privacy concerns, and training gaps. Surveillance effectiveness (38.9%) focused on diagnostic accuracy and reporting timeliness. Global practices (33.3%) highlighted mobile apps, EMRs, GIS, and DHIS2 use, with varied adoption across income settings. Opportunities (16.7%) included AI integration, age-structured data strategies, and cross-border collaborations to enhance CRS prevention and surveillance system performance. *Conclusion*: Digital transformation holds transformative potential for rubella surveillance, offering scalable and cost-effective solutions to address existing gaps. Policymakers and stakeholders must prioritise investments in digital infrastructure, training, and regulatory frameworks to optimise these systems and support rubella elimination goals.

Keywords

Digital Transformation, Rubella Surveillance, Global Practices, Challenges and Opportunities

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1. Introduction

Rubella, commonly known as German measles, is a contagious viral infection that primarily affects children and young adults. The global prevalence of rubella varies significantly, with the disease largely controlled or eliminated in regions with high vaccine coverage. Still, it remains a public health challenge in low- and middle-income countries (LMICs). [1-3] It is a vaccine-preventable disease, yet its elimination requires effective surveillance to detect cases, monitor trends, and guide vaccination strategies. Epidemiologically, rubella outbreaks often affect communities with low immunisation coverage, disproportionately impacting women of childbearing age and their unborn children. [3, 4] According to the World Health Organization (WHO), prior to widespread vaccination, major epidemics of rubella occurred every 6-9 years, resulting in substantial morbidity, particularly among pregnant women and their unborn children. [3].

The burden of rubella extends beyond the symptomatic infection to its severe complications, including congenital rubella syndrome (CRS). A togavirus of the genus Rubivirus causes the disease and is primarily transmitted through respiratory droplets. CRS is a major cause of preventable congenital disabilities, such as hearing impairment, heart defects, and developmental delays. The introduction of the rubella vaccine has drastically reduced the incidence of both rubella and CRS, yet disparities in vaccine coverage persist. [2] WHO estimates that in 2020, over 100,000 babies were born with CRS globally, underscoring the critical need for robust surveillance systems to track and mitigate rubella transmission. [3, 4].

Public health surveillance involves the continuous and systematic collection, analysis, interpretation, and dissemination of data on diseases or health-related events of significant public health concerns. This process underpins public health actions aimed at reducing morbidity and mortality while improving overall health outcomes. [5, 6] The data generated by surveillance systems serve as a foundation for immediate public health interventions, program planning and evaluation, monitoring disease trends, and developing research hypothesis's Consequently, regular assessment of these systems is essential for enhancing their efficiency and cost-effectiveness. [7] Frameworks established by global organisations guide the design and execution of these evaluations. [7].

Effective surveillance of rubella and CRS is pivotal for achieving global health goals. Surveillance facilitates early detection, timely intervention, and informed policy-making, all of which are essential for controlling outbreaks and monitoring progress towards rubella elimination. Traditionally, rubella surveillance systems have relied on manual, paper-based reporting methods. However, these systems often suffer from delays, inaccuracies, and incomplete data, limiting their effectiveness in the modern epidemiological landscape. For example, a cross-sectional study assessing South Africa's rubella surveillance system highlighted deficiencies in simplicity, positive predictive value, and timeliness, which could be mitigated through digital solutions. [2].

Digital transformation has emerged as a game-changer in disease surveillance, offering innovative tools and platforms to enhance data collection, analysis, and dissemination. Digital technologies, such as mobile health (mHealth) applications, electronic health records (EHRs), geographic information systems (GIS), and machine learning algorithms, enable real-time monitoring of rubella cases and predictive modelling of outbreaks. These advancements not only improve the efficiency and accuracy of surveillance but also strengthen global coordination in response efforts.[8] Moreover, seroprevalence data, when integrated into digital platforms, provides a clearer understanding of immunity gaps and supports effective vaccination strategies.[9-11].

The WHO has set ambitious goals for rubella elimination, targeting the eradication of rubella in at least five WHO regions by 2025. Achieving these goals requires a paradigm shift in how surveillance systems operate, leveraging digital solutions to address existing gaps and challenges [3, 4] The U.S. example of rubella elimination demonstrates the importance of a sensitive surveillance system to document and monitor disease transmission effectively.[12].

Despite significant strides in rubella control, the limitations of current surveillance systems remain a critical barrier to achieving global elimination targets. Paper-based reporting systems are often characterised by inefficiencies, such as delayed reporting and data inaccuracies, which hinder timely decision-making and resource allocation. In LMICs, where the burden of rubella is highest, these challenges are exacerbated by infrastructural constraints and limited access to technological resources. [13, 14] In contrast, global experiences, such as those highlighted by the WHO's Measles and Rubella Laboratory Network, demonstrate the value of virologic surveillance and genetic characterisation in documenting the interruption of disease transmission. [15].

Digital solutions offer a promising pathway to overcome these challenges. By integrating real-time data collection, automated alerts, and advanced analytics, digital platforms can transform rubella surveillance into a more responsive and adaptive system. However, the adoption of digital solutions is not without challenges. Issues such as technological infrastructure, data privacy concerns, and the digital divide pose significant barriers to implementation. Additionally, there is a need for evidence-based insights into the global practices and lessons learned from implementing digital surveillance systems for rubella.

This scoping review aims to fill these knowledge gaps by synthesising evidence on global practices, challenges, and opportunities in digital rubella surveillance. By identifying best practices and common pitfalls, the study seeks to inform policymakers and stakeholders of the potential of digital

transformation to enhance rubella control efforts.

1.1. Research Questions

The scoping review aims to address this overarching question:

1. What are the current digital surveillance practices used globally for rubella monitoring?
2. What are the key technical challenges encountered in the implementation of digital rubella surveillance systems?
3. What opportunities do emerging digital transformation offer in enhancing the efficiency, accuracy, and reach of rubella surveillance systems?

1.2. Research Objectives

1. To identify global digital surveillance practices for rubella, highlighting successful case studies and innovative approaches.
2. To examine the challenges faced in implementing digital solutions for rubella surveillance, including technical, operational, and socio-cultural barriers.
3. To explore the opportunities presented by digital transformation in enhancing the efficiency, accuracy, and reach of rubella surveillance systems.

2. Rationale for Digital Transformation in Rubella Surveillance

While digital transformation has significantly advanced surveillance systems across various vaccine-preventable diseases (, and historically limited investment in rubella-specific digital tools. Yet, the consequences of rubella infection, particularly congenital rubella syndrome (CRS) are devastating and irreversible. Therefore, a standalone, digitally enabled surveillance system for rubella is essential to capture subtle epidemiological signals, monitor immunity gaps, and prevent CRS cases. VPDs), the case for rubella surveillance remains comparatively underdeveloped. Unlike diseases such as measles and polio, which have received substantial international attention and resources due to their high transmissibility and eradication targets, rubella surveillance has traditionally been deprioritized, often integrated passively into broader measles surveillance systems. This integration can obscure rubella-specific trends and delay targeted interventions, especially in low-resource settings.

Measles surveillance, for example, has benefitted from robust virologic and case-based surveillance mechanisms underpinned by the Global Measles and Rubella Laboratory Network (GMRLN). This infrastructure supports high-sensitivity detection, genetic characterization, and rapid outbreak response, often aided by digital platforms that allow real-time data sharing across borders. Similarly, polio eradication programs have long employed sophisticated digital and GIS-enabled tools for acute flaccid paralysis (AFP) surveillance, environmental sampling, and microplanning of immunization campaigns, all contributing to the near-elimination of the disease globally.

In contrast, rubella surveillance has lagged due to a number of factors: the often mild or subclinical nature of the disease, its overshadowing by measles symptoms.

Digital transformation offers an opportunity to bridge this gap by enabling: Real-time, age-structured data collection critical for identifying childbearing-age women at risk, Mobile and electronic health record (EHR) integration for improving case reporting and vaccine coverage monitoring, Predictive analytics and AI models to identify outbreak risk areas and CRS burden, and Automated alerts and dashboards for program managers to intervene promptly.

Novelty of This Review

This scoping review is novel in its exclusive and targeted focus on digital health interventions specific to rubella and CRS surveillance, which has been underrepresented in the broader digital infectious disease surveillance literature. While prior reviews and studies have often integrated rubella within broader measles surveillance systems or generalized vaccine-preventable disease frameworks, this review distinctly isolates rubella surveillance as a standalone priority. It is the first to synthesise global evidence (from 2010-2024) on the adoption, challenges, and opportunities of digital tools, such as mobile health applications, GIS, EMRs, and AI, in rubella surveillance specifically, across both high- and low-resource settings.

Unlike existing literature that focuses predominantly on diseases with high global elimination visibility (e.g., measles, polio, COVID-19), this review highlights the unique epidemiological profile and surveillance needs of rubella, particularly in LMICs where CRS remains a major public health burden. By doing so, the review fills a critical gap by:

1. Differentiating rubella from measles in surveillance system design,
2. Identifying underexplored rubella-specific digital practices, and
3. Highlighting novel opportunities such as AI integration and age-structured data modeling tailored to CRS prevention.

3. Methodology

3.1. Study Design

This scoping review is conducted following the Arksey and O'Malley framework. [16], which provides a systematic approach to mapping existing literature and identifying gaps in the research field. The framework consists of five key stages: (1) identifying the research question, (2) identifying relevant studies, (3) study selection, (4) data charting, and (5) collating, summarising, and reporting results. The methodology also follows enhancements from Levac et al. [17] and the Joanna

Briggs Institute (JBI) manual for scoping reviews. [18] This framework ensures a comprehensive exploration of digital transformation in Rubella surveillance globally, capturing practices, challenges, and opportunities.

3.2. Eligibility Criteria

3.2.1. Inclusion Criteria

Studies that explore the application of digital tools such as electronic health records (EHRs), artificial intelligence (AI), geographic information systems (GIS), mobile health applications (mHealth), and other digital solutions in Rubella surveillance are considered eligible. Studies discuss the implementation and outcomes of Rubella surveillance programs initiated by global organisations such as the World Health Organization (WHO), Centers for Disease Control and Prevention (CDC), and national health systems are included.

Language: Studies published in English or other relevant languages that can be translated and analysed.

Publication Type: Peer-reviewed articles and grey literature, including government reports, policy briefs, and organisational documents related to Rubella surveillance from 2010 to 2024. The decision to restrict the review to studies published between 2010 and 2024 was informed by the specific focus of this review on the digital transformation of rubella surveillance systems. Digital health technologies, including EHRs, MHealth applications, GIS, cloud computing, and AI, began to see widespread application and integration into public health systems from around 2010 onward. Prior to 2010, most rubella surveillance systems were largely paper-based or relied on rudimentary electronic reporting platforms, which fall outside the scope of this review.

3.2.2. Exclusion Criteria

Studies that do not address digital technologies specifically in the context of Rubella surveillance and opinion pieces, commentaries, editorials, or theoretical discussions that do not provide empirical data or practical insights are excluded.

3.3. Data Source and Search Strategy

A comprehensive search is conducted across multiple electronic databases, including PubMed, Scopus, Web of Science, Google Scholar, and the WHO Global Health Library. Grey literature is sourced from relevant institutional websites such as the WHO, CDC, and national health ministries. The search strategy uses a combination of Medical Subject Headings (MeSH) and free-text keywords such as "Digital transformation," "Rubella surveillance," "eHealth," "mHealth," "GIS in surveillance," and "disease monitoring." Boolean operators (AND, OR) are applied to refine search results and ensure relevance.

3.4. Study Selection Process

Titles and abstracts of the identified studies are screened for relevance and eligibility. Articles that pass the initial screening are reviewed in full. Discrepancies in the inclusion decision are resolved. A PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews) flow diagram is used to document the selection process, showing the number of records identified, screened, and included in the final review.

3.5. Data Extraction and Synthesis

A data extraction form is developed to capture key information from selected studies, including publication details, study objectives, digital technologies utilised, surveillance outcomes, challenges faced, and opportunities identified. The data are synthesised using a thematic analysis approach to identify common themes and patterns across different contexts.

3.6. Data Analysis

A descriptive analytical approach will be applied to map the findings of the included studies. The data synthesis will involve both quantitative summaries (e.g., frequency of specific intervention types) and qualitative thematic analysis (to identify common themes and patterns across studies). The findings of this scoping reviews will be reported following the PRISMA-ScR guidelines. A flowchart will be used to display the study selection process, and the results will be presented both narratively and in tables, summarising key findings.

3.7. Ethical Considerations

Since this scoping review involves secondary data analysis of publicly available research, no formal ethical approval is required. However, all studies are handled according to standard ethical guidelines for conducting literature reviews, ensuring that data is reported accurately and objectively.

3.8. Critical Appraisal of Included Studies

A critical appraisal of the methodological quality of the 18 included studies was conducted using adapted criteria from the Critical Appraisal Skills Programme (CASP) checklists for systematic reviews, qualitative studies, and diagnostic evaluations. Each study was appraised based on its clarity of aims, appropriateness of methodology, data collection and analysis rigor, relevance to rubella digital surveillance, and potential for bias. The appraisal revealed that the majority of studies (14/18) clearly articulated their research questions and employed suitable designs such as systematic reviews, diagnostic evaluations, or ecological analyses. However, methodological limitations were noted in several areas. For example, only 8 studies explicitly described ethical considera-

tions or stakeholder involvement, and 6 lacked comprehensive descriptions of sampling or data collection tools, potentially impacting transparency and reproducibility. Additionally, some studies, particularly those from LMICs, faced limitations in data completeness and infrastructure, which may have influenced findings on surveillance performance. Despite these limitations, most studies provided sufficiently rigorous evidence relevant to the review's objectives, particularly regarding implementation challenges, system effectiveness, and digital innovation opportunities. The appraisal helped contextualize the findings, affirming that while the studies vary in methodological quality, they collectively offer a credible evidence base for understanding global practices in digital rubella surveillance.

4. Results

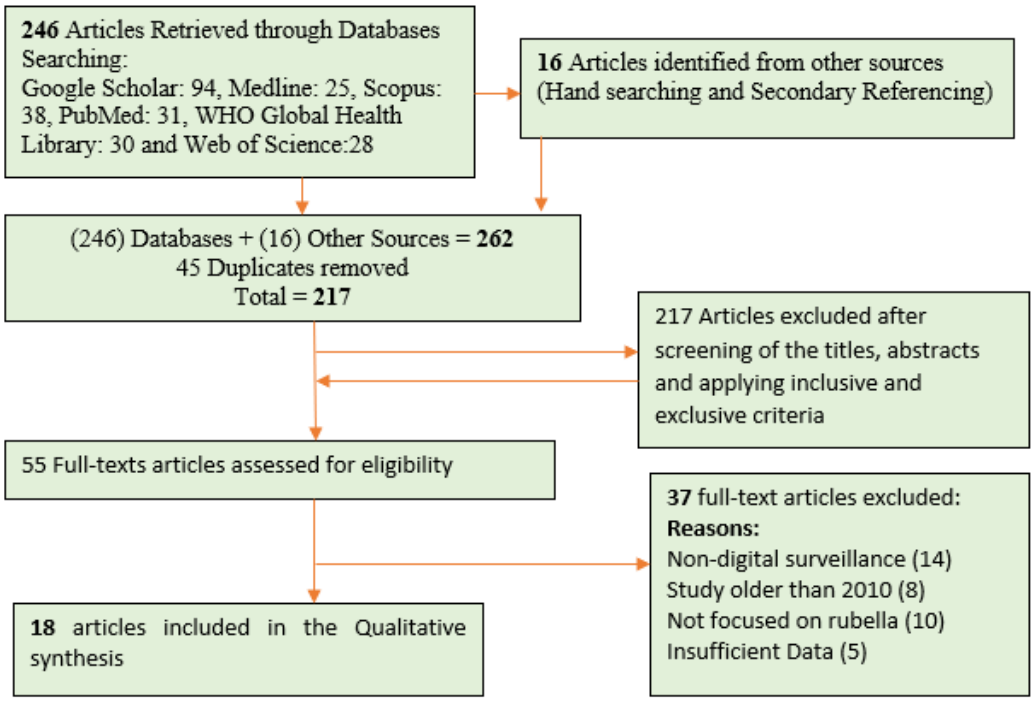

Figure 1. *PRISMA Flow Chart of Selected Articles for Scoping Review.*

Figure 1 represents the PRISMA flow chart of the selected articles for this review. Records identified through database searching across PubMed, Scopus, Google Scholar, Medline, Web of Science, and WHO Global Health Library totalled 246 articles. An additional 16 records were identified through other sources. Two hundred and seventeen (217) unique articles were screened based on titles and abstracts after removing 45 duplicates. One hundred and sixty-two (162) records were excluded as they did not meet the inclusion criteria. Then, 55 full-text articles were assessed for eligibility, and 37 full-text articles were excluded for various reasons: Non-digital surveillance (14 articles), study older than 2010 (8 articles), ten (10) articles not focused on rubella and insufficient Data (5 articles). Finally, 18 studies were included in the qualitative synthesis.

4.1. Study Characteristics

Table 1 shows the characteristics of the included studies for this scoping review. The analysis of the 18 included studies reveals important insights into the sources and thematic focus of the literature reviewed. All the studies (100%) were sourced from journal articles published over the 15 years (2010-2024). The most frequently discussed theme was challenges in digital rubella surveillance, which was covered in 9 out of the 18 studies (50%). The theme of surveillance effectiveness appeared in 7 studies (38.9%), global digital surveillance practices were highlighted in 6 studies (33.3%), in contrast, opportunities for improvement were addressed in only three studies (16.7%).

Table 1. *Characteristics of included studies (n=18).*

Reported variables	Frequency (n=19)	Percent (%)
Literature sources		

Reported variables	Frequency (n=19)	Percent (%)
Journal Articles (2010 - 2024)	20	100.0
Themes		
Global Digital Surveillance Practices	6	33.3
Surveillance Effectiveness	7	38.9
Challenges in Digital Rubella Surveillance	9	50.0
Opportunities for Improvement	3	16.7

4.2. Thematic Summary of Findings

A total of 18 studies met the inclusion criteria for this scoping review. Quantitative synthesis of the themes emerging from these studies is as follows:

1. Challenges in Digital Rubella Surveillance were the most frequently reported theme, addressed in 9 out of 18 studies (50.0%). Key challenges included:
(1) Data accuracy and completeness issues - 5 studies (27.8%)
(2) Technological infrastructure limitations - 3 studies (16.7%)
(3) Privacy and data security concerns - 2 studies (11.1%)
(4) Capacity-building and training gaps - 2 studies (11.1%)
2. Surveillance Effectiveness was examined in 7 studies (38.9%), covering:
(1) Diagnostic tool sensitivity and specificity - 3 studies (16.7%)
(2) Timeliness and completeness of reporting - 3 studies (16.7%)
(3) Performance variability in surveillance systems - 1 study (5.6%)
3. Global Digital Surveillance Practices were highlighted in 6 studies (33.3%), including:
(1) Use of mobile apps, EMRs, GIS, DHIS2, or cloud-based systems - 6 studies (33.3%)
(2) Real-time data collection and campaign planning - 2 studies (11.1%)
4. Opportunities for Improvement were noted in 3 studies (16.7%), with focus on:
(1) AI and machine learning integration - 1 study (5.6%)
(2) Strengthening routine immunisation and cross-border collaborations - 1 study (5.6%)
(3) Adoption of age-structured surveillance models - 1 study (5.6%)

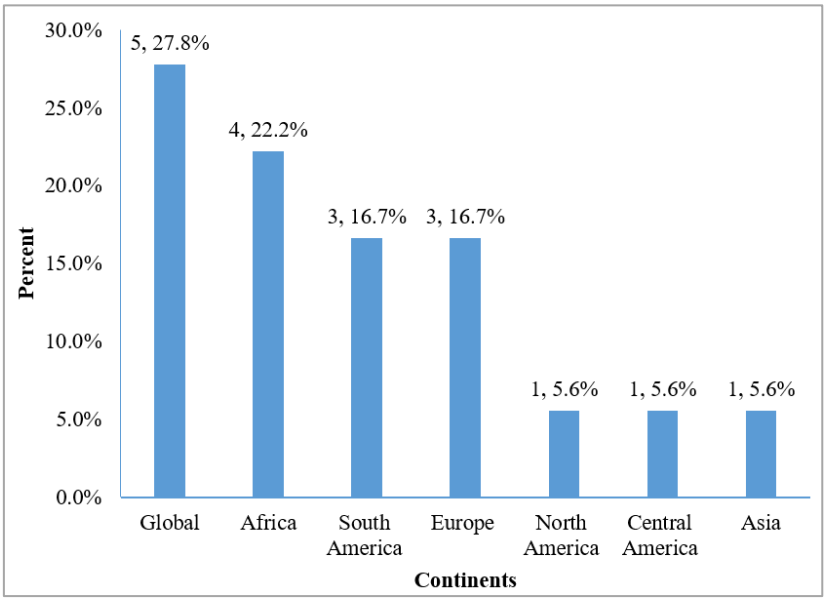

Figure 2. *Distribution of the Included Studies Across Continents.*

Figure 2 shows the distribution of the included studies across continents. The included studies are distributed across various continents, with Global studies accounting for 5 (27.8%) of the total and Africa 4 (22.2%). South America and Europe each contribute 3 (16.7%), highlighting a moderate representation of research from these regions. In contrast, studies from North America, Central America, and Asia are less represented, with each accounting for only 1 (5.6%).

4.3. Data Synthesis and Themes

Table 3 below in Appendix I presents a summary of the included studies, detailing key aspects such as the study authors and year, country, methodology/technique used, study

setting, and identified themes. The extracted themes from these studies include Global Digital Surveillance Practices, Surveillance Effectiveness, Challenges in Digital Rubella Surveillance, and Opportunities for Improvement.

4.3.1. Global Digital Surveillance Practices

The reviewed studies underscore the critical role of digital surveillance systems, such as the World Health Organization (WHO) Immunization Monitoring platform and the District Health Information Software 2 (DHIS2), in tracking vaccine coverage and responding to disease outbreaks across multiple countries. These systems facilitate real-time monitoring, enhance data-driven decision-making, and contribute to the global fight against rubella and congenital rubella syndrome (CRS). For instance, Wang et al. [19] demonstrated how digital health interventions (DHIs), through cost-effective and scalable solutions, have improved vaccination uptake and streamlined health service delivery across various settings. The adoption of these digital tools has been instrumental in ensuring timely interventions and informed public health responses.

Table 2. *Number of Studies Reporting Global Practices in Rubella Surveillance by Country Income Level.*

Income Level	Number of Studies	Common Digital Practices Identified
High-Income Countries (HICs)	5	EMRs, AI/ML integration, high sensitivity diagnostic tools
Upper-Middle-Income Countries	4	Mobile health apps, partial integration of EMRs, infrastructure gaps
Lower-Middle-Income Countries	6	DHIS2, sentinel sites, mHealth, data completeness issues
Mixed/Global	3	WHO platforms, cloud databases, surveillance strategy reviews

1. Electronic Medical Records (EMRs) and Data Management

Wang et al. [19] conducted a systematic review of cost-effectiveness studies of vaccination programs using digital health interventions across multiple countries. The study highlights the use of EMRs, mobile applications, and cloud-based databases for effective data management and immunisation tracking. These digital health interventions (DHIs), including SMS reminders, web-based tools, and recall systems, were found to enhance data timeliness and completeness, improving overall vaccination coverage. Molina et al. [20] examined CRS surveillance in 23 hospitals in Honduras, demonstrating the potential of CRS sentinel sites as scalable models for developing regions. The study underscores the value of structured data collection and reporting to assess vaccination impact. Amendola et al. [21] analysed surveillance data from the Lombardy region of Italy, focusing on data visualisation and genetic profiling as essential tools for tracking rubella and measles outbreaks. Their findings emphasise the role of advanced data analytics in enhancing surveillance accuracy.

2. Mobile Applications and Real-Time Planning

Ismail et al. [22] evaluated a mobile app used for micro-planning in Kenya's rubella campaigns across 46 counties. The study demonstrated the utility of mobile applications in facilitating real-time data entry, tracking, and analysis, ensuring efficient campaign management.

3. Surveillance Implementation in Developing Contexts

Mengouo et al. [23] reported on rubella IgM positivity patterns across 10 regions in Cameroon, highlighting challenges in data reporting accuracy by age and gender. These findings underscore the need for capacity-building initiatives to strengthen surveillance systems in resource-limited settings.

4. Case Studies from Various Countries/Regions

Case studies from various regions provide valuable insights into the practical application of digital surveillance systems, particularly in resource-constrained settings. Mengouo et al. [23] highlighted the implementation of rubella surveillance in Cameroon, showcasing the adaptability of digital tools such as case-based surveillance and laboratory confirmation methods in low-resource environments. In the Democratic Republic of Congo, Knipes et al. [24] demonstrated how digital surveillance systems, including DMF-ELISA, contributed to early outbreak detection despite infrastructural limitations. Conversely, studies from high-income settings, such as Italy (Turiac et al. [25] and Peru (Whittembury et al. [26] emphasised the importance of customising digital tools to fit local epidemiological contexts. These findings underscored the need for tailored surveillance approaches that consider country-specific healthcare infrastructure and workforce capabilities.

4.3.2. Surveillance Effectiveness

The effectiveness of rubella surveillance systems varies widely across different regions, influenced by factors such as laboratory capacity, healthcare infrastructure, and reporting mechanisms.

1. Sensitivity and Specificity of Diagnostic Tools

Knipes et al. [24] evaluated the performance of the

DMF-ELISA diagnostic tool for measles and rubella outbreaks in the Democratic Republic of Congo. The study found moderate sensitivity (82-89%) and specificity for IgG and IgM detection, suggesting its potential application in outbreak settings. Hiebert et al. [27] conducted a diagnostic accuracy evaluation of eight rubella IgM diagnostic tools in Canada. The study revealed performance variability across different methods, highlighting the importance of selecting reliable diagnostic tools to ensure accurate surveillance data.

2. Timeliness and Completeness of Data

Patel et al. [28] conducted an ecological analysis of WHO rubella data from 2007-2018, reporting higher data completeness among vaccine-eligible cohorts. However, underreporting remained a challenge, particularly among vaccine-ineligible women and congenital rubella syndrome (CRS) cases. Murhekar et al. [29] assessed sentinel site-based CRS surveillance in India, showing improvements in case detection and timeliness but highlighting the need for enhanced data quality to address mortality risks associated with CRS. Turiac et al. [25] evaluated an integrated measles and rubella surveillance system in Italy, reporting high sensitivity but identifying gaps in genotyping completeness.

4.3.3. Challenges in Digital Rubella Surveillance

1. Data Accuracy and Completeness Issues

A recurring challenge across multiple studies is the issue of data accuracy and completeness. Patel et al. [28] and Vynnycky et al. [30] reported significant discrepancies in CRS case reporting, particularly among vaccine-ineligible populations. These data inconsistencies hinder reliable burden estimation and compromise the effectiveness of targeted intervention strategies. Inaccurate or incomplete records can lead to misallocation of resources and delayed outbreak response, underscoring the need for standardised data collection protocols and enhanced reporting mechanisms. Coppeta et al. [31] performed a retrospective serological study of healthcare workers in Italy, highlighting gaps in rubella immunity and vaccination compliance due to incomplete data reporting. Gavhi et al. [2] evaluated South Africa's rubella surveillance system, identifying privacy and data quality issues as significant challenges to effective surveillance. Moreover, Metcalf et al. [9] reported data accuracy and completeness issues, which highlighted the importance of age-structured rubella surveillance in Peru and Murhekar et al. [29]

2. Technological Barriers

Technological infrastructure limitations and connectivity challenges pose significant obstacles to the effective deployment of digital surveillance systems, particularly in low- and middle-income countries (LMICs). In Peru, Hiebert et al. [27] and Whittembury et al. [26] identified infrastructure-related challenges that hindered the efficiency of CRS sentinel surveillance sites, limiting their ability to collect and transmit real-time data. Similarly, Mengouo et al. [23] highlighted the resource constraints affecting rubella surveillance efforts in Cameroon, emphasising the urgent need for investments in infrastructure and digital literacy to bridge the technological divide.

3. Privacy, Security, and Ethical Concerns

As digital surveillance systems become more prevalent, concerns regarding privacy, data security, and ethical considerations are increasingly coming to the forefront. Gavhi et al. [2] discussed privacy-related challenges in South Africa's rubella surveillance system, pointing to potential risks associated with data breaches and unauthorised access. These findings highlight the importance of establishing robust regulatory frameworks and implementing stringent data protection measures to safeguard patient confidentiality and maintain public trust in digital health initiatives.

4. Capacity Building and Training Gaps

A major barrier to the successful implementation of digital rubella surveillance systems is the lack of adequate training and capacity building for healthcare personnel. Studies from Brazil (Da Silva Alves et al., 2024) and Italy (Coppeta et al. [31]) emphasise the pressing need for comprehensive training programs to equip healthcare workers with the necessary skills to utilise digital tools for CRS prevention and rubella monitoring effectively. Addressing these gaps through targeted capacity-building initiatives will be crucial in ensuring the long-term sustainability and effectiveness of digital surveillance systems.

4.3.4. Opportunities for Improvement

1. Artificial Intelligence and Machine Learning (AI/ML) Applications

Van Den Boogaard et al. [32] highlighted the potential of AI/ML in immunogenicity analysis and vaccine safety assessments. These technologies present opportunities for improving predictive modelling and data-driven decision-making in rubella surveillance.

2. Strengthening Routine Immunisation Efforts

Biellik and Orenstein.[33] reviewed measles-rubella elimination strategies across 23 countries, emphasising the importance of strengthening routine immunisation and fostering cross-border collaborations to enhance global rubella control efforts.

3. Age-Structured Surveillance Strategies

Metcalf et al. [9] conducted a metapopulation modelling study in Peru, emphasising the importance of age-structured rubella surveillance for better CRS burden estimation and targeted intervention planning to provide valuable insights into the global efforts to enhance rubella and CRS surveillance, emphasising the need for improved data quality, technological advancements, and capacity-building efforts to overcome existing challenges.

4. Cross-Border Collaboration and Integration with Other Surveillance Programs

Cross-border collaboration is a critical component of rubella elimination strategies. Metcalf et al. [9] emphasised the need for regional integration to address spatial dynamics of rubella and CRS transmission.

5. Discussion

The findings from this scoping review offer significant insights into the current state of digital rubella surveillance and its global implementation. By synthesising data from 18 studies, all sourced from journal articles published over the 15 years (2010-2024), this review highlights key themes, regional distribution, challenges, and opportunities in leveraging digital technologies for rubella and congenital rubella syndrome (CRS) surveillance.

5.1. Global Digital Surveillance Practices

Digital surveillance systems, such as the WHO Immunization Monitoring platform and DHIS2, have revolutionised public health responses to rubella and CRS by enabling real-time monitoring and data-driven decision-making. These systems provide scalable and cost-effective solutions that have been instrumental in improving vaccination uptake and addressing outbreaks. The findings of Wang et al. [19] which emphasise the role of electronic medical records (EMRs), mobile applications, and cloud-based databases, align with the growing trend of integrating digital health interventions into routine immunisation programs. For example, Molina et al. [20] demonstrated how CRS sentinel sites in Honduras effectively assessed the impact of vaccination programs, highlighting the role of structured and centralised data collection. This review aligns with findings from Rota et al. [34] who highlighted the effectiveness of the Global Measles and Rubella Laboratory Network (GMRLN) in providing high-quality surveillance and supporting national vaccination programs. Similarly, Liu et al. [35] emphasised the global trend of integrating electronic medical records (EMRs) and cloud-based databases into vaccination programs, underscoring their role in enhancing vaccination uptake and addressing outbreaks. Moreover, the review is supported by findings from Marzouk et al. [36], who highlighted the importance of robust monitoring frameworks for national vaccination programs.

Despite their potential, the review reveals varying levels of implementation and effectiveness across regions. High-income countries like Italy and Peru demonstrate the ability to tailor digital surveillance tools to specific epidemiological contexts, while low- and middle-income countries (LMICs) such as Cameroon and the Democratic Republic of Congo face significant infrastructural and resource challenges. The findings are corroboration by Goel et al. [37] and Ahmad et al. [8], who reported that LMICs experience significant barriers, including resource constraints and technological gaps, hinder the full potential of digital surveillance systems. This agreement points out the necessity of context-specific strategies to maximise digital surveillance utility globally. These disparities underscore the need for context-specific strategies to maximise the utility of digital surveillance systems globally.

5.2. Surveillance Effectiveness

The review underscores the importance of robust diagnostic tools and reliable reporting mechanisms in ensuring the effectiveness of digital rubella surveillance. Studies such as Knipes et al. [24] and Hiebert et al. [27] evaluated the sensitivity and specificity of diagnostic tools like DMF-ELISA, highlighting their utility in outbreak detection while emphasising the need for further improvement in diagnostic accuracy. Similarly, Patel et al. [28] and Murhekar et al. [35] demonstrated the importance of data timeliness and completeness in enhancing surveillance effectiveness, particularly in vaccine-eligible cohorts. However, challenges such as underreporting, especially among vaccine-ineligible women and CRS cases, continue to hinder comprehensive burden estimation. This finding aligns with Tshimula et al. [38], who highlighted the potential of AI-powered systems to enhance detection accuracy and optimise resource allocation. This review also agrees with Craig et al. [39], who found that formal event-based surveillance systems in the Pacific islands improved outbreak detection despite infrastructural challenges, emphasising the need for streamlined reporting processes; but in disagreement with findings from Psihogios et al. [40] (2022) and Liu et al. [35], who argued that while active surveillance systems improve detection, their implementation often lacks consistency in LMICs due to limited policy support and ethical considerations. These findings indicate that while digital surveillance systems have improved case detection and monitoring, significant gaps remain in ensuring the accuracy, completeness, and timeliness of data. Addressing these gaps through investments in diagnostic infrastructure, enhanced reporting protocols, and routine monitoring will be critical for improving the overall effectiveness of rubella surveillance systems.

5.3. Challenges in Digital Rubella Surveillance

The review highlights several persistent challenges that limit the effectiveness of digital rubella surveillance. Chief among these are issues of data accuracy and completeness. Studies by Patel et al. [28] and Gavhi et al. [2] identify significant discrepancies in CRS case reporting, which hinder resource allocation and timely outbreak response. Similarly, Mengouo et al. [23] and Metcalf et al. [9] highlight the impact of incomplete or inaccurate records on intervention strategies, particularly in resource-constrained settings.

Technological barriers, including limitations in infrastructure and connectivity, pose additional challenges, particularly in LMICs. For instance, studies in Cameroon and Peru identify resource constraints and technological gaps as significant obstacles to real-time data collection and transmission. Privacy, security, and ethical concerns also emerge as critical challenges, with Gavhi et al. [2] emphasising the need for robust data protection measures to maintain public trust and safeguard patient confidentiality.

Another recurring theme is the lack of adequate training

and capacity-building initiatives. Studies from Brazil and Italy highlight the pressing need for healthcare personnel to be equipped with the skills necessary to utilise digital tools for rubella and CRS surveillance effectively. These align with findings from Huy et al. [41] (2024), who reported that skill gaps and resistance to change impeded digital transformation. Addressing these capacity gaps is essential for ensuring the sustainability and effectiveness of digital surveillance systems. Ahmad et al. [8] and Maddah et al. [42] highlight the lack of real-time data collection and connectivity in LMICs, emphasising the need for investments in infrastructure and digital tools. These studies also agree with this review's findings, highlighting the pressing need for capacity-building initiatives and training for healthcare personnel to utilise digital tools effectively.

5.4. Opportunities for Improvement

Despite these challenges, the review identifies several opportunities for enhancing digital rubella surveillance. The application of artificial intelligence (AI) and machine learning (ML) in immunogenicity analysis and vaccine safety assessments presents significant potential for improving predictive modelling and data-driven decision-making [43-45]. Van Den Boogaard et al. [32] highlight the role of these technologies in streamlining surveillance processes and enhancing outbreak preparedness.

Strengthening routine immunisation efforts and fostering cross-border collaboration also emerge as critical strategies for improving rubella control. Biellik and Orenstein.[33] emphasise the importance of integrating rubella surveillance with other immunisation programs to maximise resource utilisation and address spatial dynamics of transmission. Additionally, age-structured surveillance strategies, as discussed by Metcalf et al. [9], offer valuable insights into CRS burden estimation and targeted intervention planning. Emerging technologies, such as AI and machine learning, were also highlighted by Tshimula et al. [38] as promising tools for public health surveillance. AI-driven solutions have been shown to improve outbreak prediction and enhance data analysis capabilities, particularly in resource-constrained settings. The integration of rubella surveillance with other immunisation programs also aligns with studies like Steffen et al. [46], which emphasised the value of multi-disease surveillance strategies. Additionally, Evtushenko et al. [47] advocate for leveraging digital tools to improve training and capacity building, further supporting your recommendations.

5.5. Regional Disparities and Context-specific Strategies

The distribution of included studies across continents highlights regional disparities in digital rubella surveillance research. While global studies and research from Africa represent a significant proportion of the literature, regions such as North America, Central America, and Asia remain underrepresented. This uneven distribution is consistent with findings from Goel et al. [37], who report limited research on laboratory-based surveillance in the WHO Southeast Asia region. This distribution underscores the need for increased research and investment in these regions to develop context-specific strategies that address unique epidemiological and infrastructural challenges. The possible reasons for this disparity could stern from the act that In North America, particularly the United States and Canada, rubella has been effectively eliminated for over a decade, with the U.S. achieving elimination status as early as 2004 [48]. As a result, rubella surveillance has largely been integrated into broader immunisation and notifiable disease systems, reducing the perceived need for standalone digital rubella-specific systems or new research on the topic. The success of these integrated systems may also lead to a publication bias, where fewer dedicated rubella surveillance studies are conducted or published, especially in the context of digital innovation. Also, much of the research conducted in Asian countries may be published in local languages or domestic journals not indexed in major international databases. This creates an accessibility barrier in global scoping reviews, which often rely on English-language and internationally indexed publications. Consequently, relevant work may be omitted despite active engagement in digital rubella surveillance. To address these disparities, Lapidus [49] suggests adopting tailored digital transformation strategies to overcome regional challenges. Similarly, Evtushenko et al. [47] recommended leveraging digital tools and capacity-building initiatives to enhance the effectiveness of public health programs in underrepresented regions.

6. Lessons from Other Infectious Disease Surveillance Programs

The review draws valuable lessons from other infectious disease surveillance programs, such as COVID-19, measles, and polio, which can be applied to rubella surveillance.

1. COVID-19 Pandemic: The COVID-19 pandemic underscored the importance of real-time data sharing and global collaboration in managing infectious diseases. Digital health interventions, including mobile apps and electronic medical records, played a pivotal role in contact tracing and vaccine distribution. Lessons from the pandemic suggest that robust data-sharing agreements and international collaboration are critical for rubella surveillance. As highlighted by Ted et al. [14], COVID-19 surveillance demonstrated the value of genomic monitoring and real-time data sharing for outbreak management, reinforcing the importance of integrating these approaches into rubella surveillance.
2. Measles Surveillance: Integrated measles-rubella surveillance, as observed in studies such as Turiac et al.

[25] in Italy, offers insights into combining surveillance efforts for multiple vaccine-preventable diseases. This approach can enhance efficiency and resource utilisation. Integrated measles-rubella systems discussed by Rota et al. [34] demonstrated the efficiency of combined surveillance for vaccine-preventable diseases. This approach also aligns with findings from Schilling and Seuring. [50], who highlight the importance of integrating digital and sustainable practices in public health surveillance.

3. Polio Eradication Efforts: The global polio eradication initiative has demonstrated the effectiveness of combining traditional and digital surveillance approaches to reach remote populations. Strategies such as age-structured surveillance and community-based reporting, as discussed by Metcalf et al. [9], can be adapted to rubella control programs.

7. Implications for Public Health Practice

The findings of this review have important implications for public health practice. Policymakers and stakeholders must prioritise investments in digital infrastructure, capacity-building, and regulatory frameworks to address the identified challenges. Enhancing data quality, improving diagnostic tools, and fostering international collaboration will be critical for strengthening global rubella surveillance efforts. Furthermore, integrating digital surveillance systems with routine immunisation programs and leveraging emerging technologies such as AI/ML can enhance the effectiveness and sustainability of these systems.

Additionally, the findings of this review strongly align with the World Health Organization's Digital Health Resolution (WHA71.7), which calls upon Member States to harness the potential of digital technologies to advance universal health coverage and strengthen health systems [51]. WHA71.7 underscores the need for evidence-based digital health strategies, interoperable systems, and capacity building, principles that resonate with the challenges and opportunities identified in digital rubella surveillance. As this review highlights, issues such as infrastructure deficits, limited digital literacy, and lack of interoperability in LMICs hinder the effective implementation of digital surveillance systems. Addressing these barriers aligns with the WHA71.7 mandate to ensure equity, data security, and system integration.

8. Recommendations

The scoping review findings provide several policy implications to enhance rubella surveillance globally. Governments and public health organisations, such as the WHO, should prioritise the integration of digital surveillance systems while addressing the identified challenges.

1. Standardisation and Interoperability: Governments and health institutions should establish standardised data collection protocols and ensure interoperability between different digital platforms to improve data accuracy and completeness.
2. Capacity Building: Training and capacity-building initiatives for healthcare workers are essential to maximise the effectiveness of digital tools. As highlighted in studies from Brazil (Da Silva Alves et al. [52]) and Italy (Coppeta et al. [31]), comprehensive training programs can enhance digital literacy and data management skills.
3. Investment in Infrastructure: Technological barriers remain a significant challenge in low-resource settings, such as those reported by Mengouo et al. [23] in Cameroon. Governments should invest in digital infrastructure, particularly in rural and underdeveloped areas, to bridge the technological divide.
4. Data Privacy and Security Regulations: Strengthening data privacy and security measures is critical to gaining public trust and ensuring compliance with ethical guidelines. Gavhi et al. [2] emphasised the importance of regulatory frameworks to address privacy concerns.
5. Integration with Routine Immunization Programs: Strengthening routine immunisation efforts and integrating digital surveillance systems with existing healthcare infrastructure can improve rubella control and prevention strategies, as highlighted by Biellik and Orenstein. [33].

9. Conclusion

This scoping review underscores the transformative potential of digital surveillance systems in enhancing rubella and CRS monitoring globally. While significant progress has been made, persistent challenges related to data accuracy, technological barriers, and capacity gaps must be addressed to realise the benefits of these systems fully. By leveraging emerging opportunities and prioritising context-specific strategies, stakeholders can improve global rubella surveillance and contribute to the broader goal of disease elimination.

Abbreviations

AI	Artificial Intelligence
CDC	Centers for Disease Control and Prevention
CRS	Congenital Rubella Syndrome
DHHS	Department of Health and Human Services
DHIS2	District Health Information Software 2
DHI	Digital Health Intervention
DRC	Democratic Republic of Congo
HER	Electronic Health Record
EMR	Electronic Medical Record

GMRLN	Global Measles and Rubella Laboratory Network
GIS	Geographic Information Systems
HIC	High-income Countries
IgG and IgM	Immunoglobulin G and Immunoglobulin M, Respectively
JBI	Joanna Briggs Institute
LMIC	Low- and Middle-income Countries
mHealth	Mobile Health
PRISMA-ScR	Preferred Reporting Items for Systematic Reviews and Meta-analyses Extension for Scoping Reviews
VPD	s Vaccine-preventable Diseases
WHO	The World Health Organization

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Conflicts of Interest

The authors declare no conflicts of interest.

Appendix

Appendix I: Data Extraction

Table 3. Data Extraction/Synthesis.

S/N	Study (Authors/Year)	Country	Method/Technique	Setting and Participant	Themes
1	Wang et al. [19]	Global	Systematic review of cost-effectiveness studies	Vaccination programs using digital health interventions across multiple countries	Global Digital Surveillance Practices: Use of electronic medical records (EMRs), mobile applications, and cloud-based databases. DHIs, including SMS, web-based tools, and recall systems for immunisation, were evaluated. Surveillance Effectiveness: Sensitivity, specificity, timeliness, completeness. Digital interventions showed improved timeliness and completeness of vaccination data reporting.
2	Knipes et al. [24]	DRC	Field evaluation of rapid DMF-ELISA	Suspected measles/rubella cases and household serosurvey participants in Kinshasa	Global Digital Surveillance Practices: Examined DMF-ELISA in the Democratic Republic of Congo for measles/rubella outbreaks. Case study on rubella outbreak detection. Surveillance Effectiveness: Moderate sensitivity and specificity. DMF-ELISA showed 82-89% sensitivity and specificity for IgG and IgM detection.
3	Patel et al. [28]	Global	Ecological analysis of	Rubella cases re-	Surveillance Effectiveness: Higher complete-

S/N	Study (Authors/Year)	Country	Method/Technique	Setting and Participant	Themes
			WHO rubella data	ported globally between 2007-2018	ness among vaccine-eligible cohorts. Challenges: Data accuracy and completeness issues. Underreporting noted in CRS cases. Underreporting in vaccine-ineligible women.
4	Vynnycky et al. [30]	Global	A systematic review and mathematical modelling	Seroprevalence and CRS incidence in regions without rubella vaccines	Challenges: Data accuracy and completeness issues. Gaps in data completeness and CRS estimates.
5	Hiebert et al. [27]	Canada	Diagnostic accuracy evaluation of IgM kits	Laboratory testing of sera from diverse clinical cases	Surveillance Effectiveness: Sensitivity, specificity. Evaluation of eight rubella IgM diagnostic tools for accuracy and reliability. Performance variability across diagnostic methods. Challenges: Adoption barriers for certain kits. Technological barriers- Identified challenges with diagnostic tool adoption across regions.
6	Mengouo et al. [23]	Cameroon	Measles and rubella case-based surveillance	Samples from suspected measles cases across 10 regions	Global Digital Surveillance Practices: Surveillance in developing contexts. Surveillance Effectiveness: Data reporting challenges by age and gender. Completeness of data reporting- Reported on rubella IgM positivity and patterns by age and sex.
7	Van Den Boogaard et al. [32]	Global	Systematic review and meta-analysis	Immunogenicity, vaccine effectiveness, and safety assessments	Opportunities: AI/ML applications for immunogenicity analysis and safety. Highlighted AI's role in immunogenicity studies and vaccine safety assessments.
8	Coppeta et al. [31]	Italy	Retrospective serological study	Healthcare workers in a hospital	Challenges: Gaps in rubella immunity and vaccination compliance. Data accuracy and completeness issues - Rubella immunity screening in Italian healthcare workers revealed gaps in coverage.
9	Molina et al. [20]	Honduras	Hospital-based CRS surveillance	Suspected CRS cases in 23 hospitals	Global Digital Surveillance Practices: CRS sentinel sites as models for developing regions. CRS surveillance in Honduras provided insights into vaccination impacts.
10	Gavhi et al. [2]	South Africa	Surveillance system evaluation	Retrospective data and surveys with stakeholders	Challenges: Privacy and data quality issues. Discussed difficulties in South Africa's rubella surveillance system, including data privacy issues
11	Biellik & Orenstein. [33]	Global	Review of measles-rubella elimination strategies	23 countries using routine immunisation improvements	Opportunities: Strengthening routine immunisation alongside rubella elimination. Cross-border collaboration - Improved routine immunisation via measles-rubella elimination efforts in multiple countries.
12	Da Silva Alves et al. [52]	Brazil	Comprehensive review of rubella and CRS prevention	Pre-pregnancy vaccination programs	Challenges: Training gaps in healthcare delivery for CRS prevention. Capacity building and training gaps - Brazil's emphasis on pre-pregnancy vaccination highlighted training needs.
13	Ismail et al. [22]	Kenya	Mobile app for micro-planning	Measles-rubella campaign in 46 counties	Global Digital Surveillance Practices: Mobile applications for real-time planning. Mobile app use for micro-planning in Kenya's Rubella campaigns demonstrated real-time data utility.

S/N	Study (Authors/Year)	Country	Method/Technique	Setting and Participant	Themes
14	Whittembury et al. [26]	Peru	CRS sentinel surveillance analysis	Sentinel sites across 16 facilities	Challenges: Infrastructure limitations in CRS surveillance. Technological barriers - Challenges in CRS sentinel surveillance in Peru due to limited resources.
15	Murhekar et al. [29]	India	Sentinel site-based CRS surveillance	645 suspected cases across five sites	Surveillance Effectiveness: Timeliness and case detection improvements. Sensitivity, completeness - CRS sentinel surveillance in India improved case detection but revealed significant mortality.
16	Metcalf et al. [9]	Peru	Metapopulation modelling and analysis	Age-structured rubella dynamics across regions	Challenges: Age incidence and its implications on CRS burden. Data accuracy and completeness issues - Highlighted the importance of age-structured rubella surveillance in Peru. Opportunity: Data accuracy and completeness issues - Highlighted the importance of age-structured rubella surveillance in Peru.
17	Turiac et al. [25]	Italy	Integrated measles and rubella system evaluation	Public health data from 2013-2016	Surveillance Effectiveness: High sensitivity, issues with genotyping completeness.
18	Amendola et al. [21]	Italy	Retrospective analysis of rubella and measles cases	Surveillance data from the Lombardy region	Global Digital Surveillance Practices: Data visualisation and genetic profiling.

Appendix II: Full Search Strategy

1. Databases Searched

The following databases were systematically searched for relevant literature from January 2010 to March 2024:

(1) PubMed

(2) Scopus

(3) Web of Science

(4) Google Scholar (for grey literature and supplementary searches)

2. Grey Literature Sources

Grey literature was sourced from:

(1) World Health Organization (WHO) official website

(2) Centers for Disease Control and Prevention (CDC)

(3) National health ministry websites

(4) Institutional repositories of global health organizations

3. Search Terms and Keywords

Searches included both Medical Subject Headings (MeSH) and free-text terms, combined using Boolean operators (AND, OR). Below is a sample of the search terms used:

("Digital transformation" OR "eHealth" OR "mHealth" OR "electronic health records" OR "digital health interventions" OR "mobile applications" OR "health information systems" OR "digital surveillance" OR "geographic information systems" OR "GIS" OR "machine learning" OR "artificial intelligence")

AND

("Rubella" OR "German measles" OR "Rubella surveillance" OR "Congenital Rubella Syndrome" OR "CRS")

AND

("surveillance systems" OR "public health surveillance" OR "disease monitoring" OR "data systems" OR "reporting systems")

4. Search Limits

(1) Publication Dates: 2010 to 2024

(2) Language: English

(3) Publication Types: Peer-reviewed articles, government reports, policy briefs, and relevant grey literature

5. Search Execution

(1) Each database was searched independently using tailored search strings based on its indexing system.

(2) Search results were exported to a reference manager (e.g., EndNote/Zotero) to remove duplicates.

(3) A Preferred Reporting Items for Systematic Reviews and Meta-Analyses for Scoping Reviews (PRISMA-ScR) flowchart was used to track the identification, screening, eligibility, and inclusion process.

6. Search Outcome

(1) Total records identified: 246 (databases) + 16 (other sources) = 262

(2) Duplicates removed: 45

(3) Screened: 217

(4) Full-text assessed for eligibility: 55

(5) Final studies included: 18

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