Acta Scientific Microbiology (ISSN: 2581-3226)

Volume 8 Issue 2 February 2025

Conceptual Paper

Digital and Spatiotemporal Epidemiology: Principles and Scopes in Infectious Diseases

Susanta Kumar Ghosh[1,2]* and Chaitali Ghosh[3]

[1]*Former ICMR-National Institute of Malaria Research, Bangalore, India*

[2]*Resource Person (External Support) on Dengue, Government of Karnataka, India*

[3]*Tata Institute for Genetics and Society, Bangalore, India*

***Corresponding Author:** Susanta Kumar Ghosh, Former ICMR-National Institute of Malaria Research, Bangalore, India. **E-mail Id:** ghoshnimr@gmail.com

DOI: 10.31080/ASMI.2025.08.1481

Received: January 15, 2025

Published: January 24, 2025

Abstract

Epidemiology is the backbone of any disease dynamics, its management and control within specific time and space in a specific set-up. In recent years, advancements on digital and spatiotemporal epidemiology have made it possible for fast, efficient data capturing and analyses to take proper steps by the respective policy makers and programme managers. Digital epidemiology uses digital data based on the digital sources. On the other hand, spatiotemporal epidemiology uses the recorded survey data using recent advanced technologies of spatial, statistical and transmission modelling methods uncovering relationships between infectious disease pattern, and host or environmental conditions, generating detailed hotspots or clusters covering disease morbidity and mortality within a specific time. The recent one-in-a-century coronavirus disease 2019 (Covid-19) pandemic has shaken the health system, and at the same time taught us how quickly to find solutions to tackle this disease. Several apps and digital platforms have been developed during the Covid-19 pandemic and enabled contact tracing, information sharing, symptom tracking for effective management and containment. The similar strategies may be followed for many other infectious diseases such as AIDS, Ebola, Influenza, tuberculosis, malaria, dengue, Zika and Mpox including non-communicable diseases. India has made significant contributions forming a single window central dashboard containing the data of Covid-19 cases collected from all over the country. Day-to-day data collection and its analysis helped to defeat the challenge covering over 1.4 billion people. Use of artificial intelligence (AI) and machine learning (ML) and automation for disease modelling, diagnostics, vaccine development and delivery would make the systems more resilient for management of future epidemics. However, ethics, integrity, and data protection need utmost priority in the digital era.

Keywords: Digital Epidemiology; Spatiotemporal Epidemiology; Public Health; Digital Surveillance; Prevention; Monitoring; Management; Evaluation; Apps; Geographic Information System; Geographic Positioning System; Artificial Intelligence; Machine Learning, Automation

Introduction

In general, traditional epidemiology focuses on the triad of person, place and time. Timely action taking plan and programme implementation successfully contain any disease. It is the foundation of public health. Over the last one decade digital platforms have evolved exponentially leading to digital and spatiotemporal epidemiology that have positioned a new paradigm of disease management, for infectious and also non-communicable diseases. Spatiotemporal epidemiology is *inter alia* of digital epidemiology. Spatiotemporal data of infectious diseases rely on two broad aspects: (a) spatial statistical modelling methods and (b) spatial transmission dynamic modelling approaches. This is possible due to the advancement of the computational information system and an increasing amount of diversity of epidemiological and genetic data with spatial and temporal information. This could enable us to uncover relationships between spatiotemporal infectious disease patterns, host, and environmental characteristics, and to generate maps to identify hotspots or clusters and also morbidity and mortality management [1].

Many apps and digital platforms have been developed. Artificial intelligence (AI) and machine learning [ML] platforms are also fast growing to handle big data for validating and refining models with real global data at scale, as well as frameworks to map and track diseases in real time. This would optimize the necessary resources and interventions more efficiently. Automation would make the system more efficient and fast. Hence, modern technologies have made it possible for better understanding of disease dynamics for efficient containment measures [2].

Digital and spatiotemporal epidemiology have grown exponentially during the coronavirus disease 2019 (Covid-19) pandemic caused by the novel coronavirus severe acute respiratory syndrome-2 virus (SARS-CoV-2). The pandemic was noticed at the beginning of 2020. Being an unknown nature of the virus, scientists promptly developed several diagnostic methods and vaccines to combat this pandemic. On 11 March, 2020 World Health Organization (WHO) declared this as pandemic [3], and again on 5 May, 2023 WHO declared end to COVID-19 as a global health emergency [4]. In this process, many digital epidemiological surveillance apps, platforms and predictive models have been developed at an unprecedented pace. Similarly, Mpox, previously referred to as monkeypox, is a self-limiting viral infection caused by Mpox virus (MPXV), a species of the genus *Orthopoxvirus*. It is a self-limiting disease but can lead to death, especially among children and those with weak immune systems. The disease mainly spreads from person to person through close contact. While the infection has been reported in humans since 1970, it mostly affected people in endemic regions in Africa till the 2022 outbreak. Following an upsurge of Mpox in the Democratic Republic of the Congo, WHO declared a public health emergency of international concern on 14 August 2024 [5]. Immediately the Government of India took immediate steps. Alerts were issued to all the states. All necessary emergency arrangements are put on place. Checking of Mpox was initiated at all international airports for the passengers travelling from affected countries. So far only two cases are reported [6]. This momentum should also be continued for routine surveillance for other diseases such as AIDS, Ebola, Influenza, tuberculosis, malaria, dengue, Zika. However issues of ethics, integrity, data protection, individual privacy need to be addressed on priority.

Search methods

A global literature review was conducted related to the topics. Search keywords “disease epidemiology”, “digital analysis”, “spatiotemporal analysis”, “geographic information systems (GPS)”, “disease mapping”, “infectious diseases”, “communicable diseases”, “cluster analysis”, “public health”, “digital platforms”, “apps”, “artificial intelligence”, machine learning”, “automation”, “ethics”, data integrity were utilized to search on the MEDLINE (PubMed), Scopus, CABS Abstract, and Web Science databases. Examined references listed in review articles and previously compiled bibliographies. After applying the inclusion and exclusion criteria, 16 relevant studies from an initial pool of 36 were included in the text.

Digital epidemiology

Digital epidemiology is based on the data captured from digital sources from several digital platforms. In the last one decade digital epidemiology has developed a new platform on data generation and analysis for further action taken by the policy and programme managers. This is classified into four categories based on the laws of demand and supply such as, descriptive, exploratory, explanatory and predictive [7]. Descriptive study emphasizes on the presenting incidence or attributable data. Exploratory study uses nature, its manifestations, and other relevant issues following correlation analysis. Such study focuses on the underlying causes and systematic relationship between variables. Predictive studies attempt to predict a trend based on the relevant findings [7].

Sometimes the concept of information technology and digital epidemiology causes confusion. In 2002, information epidemiology was introduced as an emerging method for the study of the determinants and distribution of health information and also misinformation [8]. However in 2020, WHO made it clear that information technology is a part of digital epidemiology, and warned about misinformation during disease outbreaks [9].

Digital epidemiology works on the digital surveillance platform. The biggest use of digital epidemiology is in public health surveillance. Disease prevention, health promotion, contact tracing and effects of intervention are under the purview of digital epidemiology. There are many such web-based platforms that are now in operation. This came on the forefront after the Covid-19 pandemic. The whole world has changed and many online courses, data capture, data review and data analyses are performed within the reach of several stakeholders. This is really a change maker in the history of traditional epidemiology. Web spider or spiderbot generally known as web crawler is an internet bot that systematically browses the World Wide Web (www). This is operated by search engines for web indexing which is the foundation of digital epidemiology collecting and collating data from different heterogeneous sources. Googlebot is one such search engine and widely used. Four web crawlers such as General Purpose Web Crawler, Focused Web Crawler, Incremental Web Crawler, and Deep Web Crawler are parts of actual crawler systems. Web crawlers scan three main elements on the webpage such as content, code and link [10].

Spatiotemporal epidemiology

Modern epidemiology increasingly incorporates both spatial (place) and temporal (time) for better understanding of disease dynamics, determinants and timely action for fast containment. Spatiotemporal epidemiology uses the recent advanced technologies of spatial, statistical and transmission modelling methods uncovering relationships between infectious disease patterns, host or environmental conditions, and generates detailed hotspots or clusters covering disease morbidity and mortality. The role of time and place on health appears in writings as early as the 4th century BCE [11]. They identified five domains critical to the developing field of spatiotemporal epidemiology: (a) spatiotemporal epidemiological theory, (b) selection of appropriate spatial scale of analysis, (c) choice of spatiotemporal method for pattern identification, (d) individual-level exposure assessment in epidemiological studies, and (e) assessment and consideration of locational and attribute uncertainty [11].

In the 1850s, John Snow used geographic information and linked a street water pump to the cholera outbreaks in Soho, London [12]. Following this, spatial analysis became an important part of epidemiology. In the 1990s, the geographic information systems (GIS) using advanced computing technology transformed dramatically its scope and applications [13]. Such technological innovations prompted the application of spatial analyses and visualization techniques in public health [14]. Now GIS technology makes it possible to visualize maps and assess spatial variability using more dynamic information incorporating temporal information that changes over a short period [15]. These technological advancements have encouraged us to utilize more advanced spatiotemporal epidemiology considering both place and time [16].

On the other hand, recent technological advancements for tracking and mapping individuals through global positioning systems (GPS) have introduced mobile populations as an important element in spatiotemporal epidemiology. GPS is a system that correctly determines location and guidance using satellite signals. This technology provides geocoding, distance estimation, record linkage and data integration i.e. disease mapping, spatiotemporal clustering including small area estimation and Bayesian application for disease mapping [16,17].

Digital platforms, devices, apps for disease surveillance

In the recent digital era several digital platforms, devices and apps have been developed and are successfully deployed.

Digital platforms

Two prominent digital platforms namely District Health Information Software 2 (DHIS2) and Integrated Health Information Portal (IHIP) are used for disease management.

District health information software 2 (DHIS2)

DHIS2 is a free open-source web-based platform for data collection, reporting and analysis. The software is developed at the Department of Informatics, University of Oslo coordinated by the Health Information Service Provider (HISP). This HISP is the official collaborating centre of the WHO. DHIS2 is commonly used for data implemented for individual health programmes and/or at a national level under Health Management Information System (HMIS) [18].

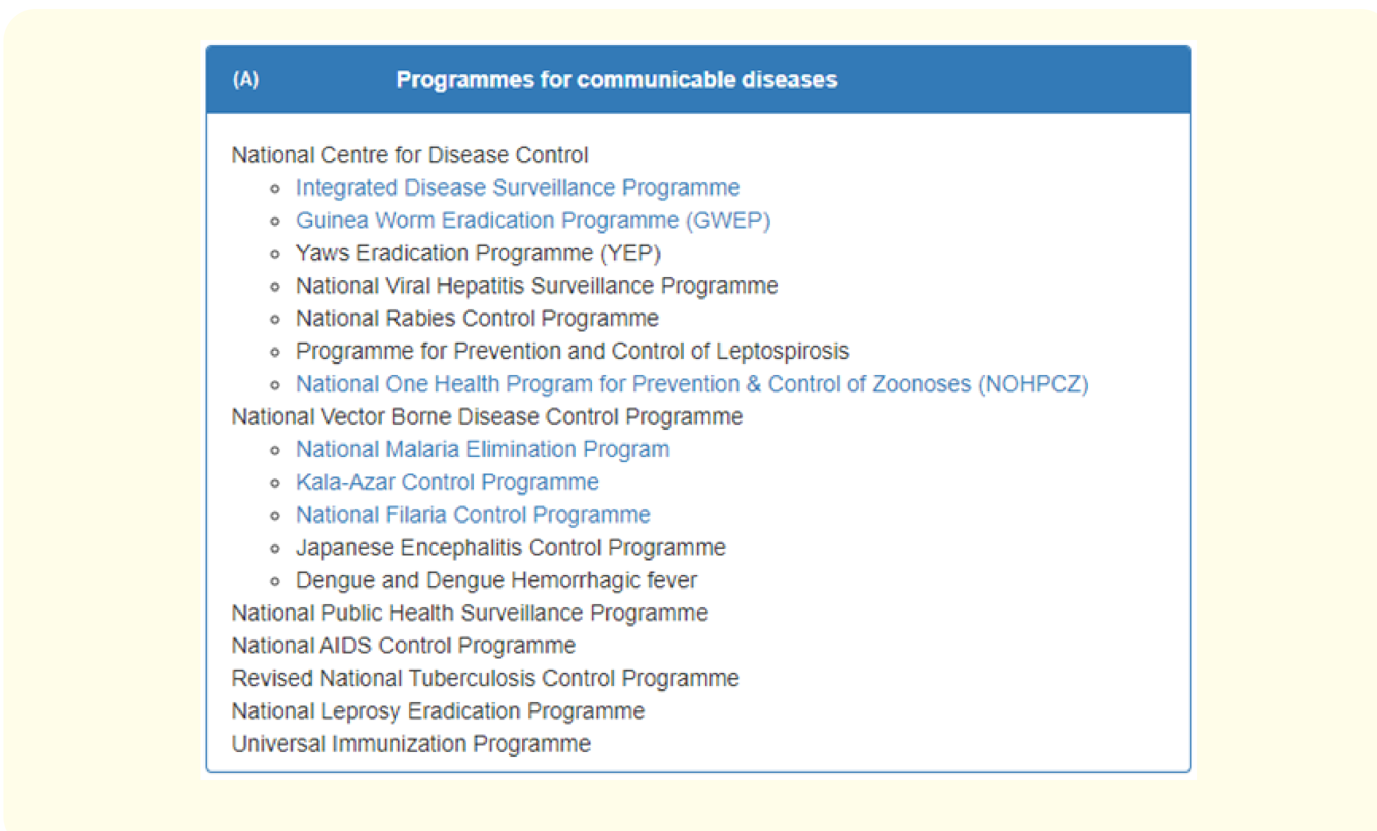
All data are captured on a server that can be accessed either by the ownership countries or cloud-based through any web browsers. In addition the DHIS2 can be operated on mobile and tablets devices that have the Android operating system. By 2022, this was in use by the Ministries of Health in more than 75 low- and middle-income countries (LMICs), with 69 countries at national level. Besides, health, DHIS2 is used in other sectors such as education, water and sanitation, nutrition and food security, agriculture and land management, and e-governance [18].

DHIS2 is extensively supported financially by WHO, Bill & Melinda Gates Foundation, the Global Fund to fight AIDS, Tuberculosis and Malaria (GFATM), the U.S. Centres for Disease Control and Prevention, The University of Oslo, UNICEF, and many more [18].

Many modules are prepared for effective implementation of specific diseases. For example, modules for burden reduction and elimination settings and modules for entomological surveillance and vector control interventions for malaria [19].

Integrated health information platform (IHIP) in India

India is a federal republic country having 1.4 billion people in 28 states and 8 union territories. In the last two decades several initiatives have been undertaken to provide proper health care services. IHIP is a special platform in India to strengthen disease surveillance in the country by establishing a decentralized state-based surveillance system for epidemic prone diseases. The system detects the early warning signals, so that timely and effective public health interventions can be initiated at the Districts, State and National level. In November 2004, Integrated Disease Surveillance Programme (IDSP) was launched with World Bank assistance. Subsequently this programme is functioning funded from the domestic budget under the National Health Mission. It has been playing an important role in disease surveillance in every state [20]. Details of communicable and non-communicable diseases are presented in Figure 1 (A and B).



(A) Programmes for communicable diseases

National Centre for Disease Control
- Integrated Disease Surveillance Programme
- Guinea Worm Eradication Programme (GWEP)
- Yaws Eradication Programme (YEP)
- National Viral Hepatitis Surveillance Programme
- National Rabies Control Programme
- Programme for Prevention and Control of Leptospirosis
- National One Health Program for Prevention & Control of Zoonoses (NOHPCZ)

National Vector Borne Disease Control Programme
- National Malaria Elimination Program
- Kala-Azar Control Programme
- National Filaria Control Programme
- Japanese Encephalitis Control Programme
- Dengue and Dengue Hemorrhagic fever

National Public Health Surveillance Programme

National AIDS Control Programme

Revised National Tuberculosis Control Programme

National Leprosy Eradication Programme

Universal Immunization Programme

(B) **Programmes Non-communicable diseases,Injury and Trauma**

National Programme on Climate Change and Human Health
Disaster Management Cell
National Tobacco Control Programme(NTCP)
National Programme for Prevention and Control of Cancer, Diabetes, Cardiovascular Diseases & Stroke (NPCDCS)
National Programme for Control Treatment of Occupational Diseases
National Programme for Prevention and Control of Deafness (NPPCD)
National Mental Health Programme (NMHP)
National Programme for Control of Blindness (NPCB)
National Nutritional Programmes (NNP)
National Iodine Deficiency Disorders Control Programme (NIDDCP)
Mid-Day Meal Programme (MMP)
National Oral Health Programme (NOHP)
National Programme for Prevention and Control of Fluorosis (NPPCF)
Reproductive Maternal Newborn Child and Adolescent Health (RMNCH+A)
National Rural Health Mission(NRHM)
National Urban Health Mission(NUHM)
National Water Supply and Sanitation Programme
Department of Animal Husbandry Dairying & Fisheries(DADF)
National Animal Disease Reporting System(NADRS)
Environment, Forest and Climate Change(MoEFCC)

Figure 1: A. Several Programmes for communicable diseases and B. non-communicable disease under Integrated Disease Surveillance Programme (IDSP) [20,21].

Developed under the IHIP, Health Management Information System (HMIS) a web-based Monitoring Information System (MIS) under the Ministry of Health and Family Welfare, Government of India to monitor the National Health Mission programme since 2008-2009. HMIS assists health programme managers at all levels in managing, planning, monitoring and evaluating the health programmes in India. Currently, mental health, child-health and immunization, family planning, vector-borne diseases, tuberculosis, morbidity and mortality management, OPD and IPD services etc. are being provided [21].

Digital surveillance devices

We have developed a GPS-tagged smart digital surveillance device in Mangaluru that has changed the epidemiological course of malaria elimination [22,23]. It works on a locally developed malaria control software operated by a web-based server. The hand-held case-based tablets (tabs) are deployed through the local health workers including some diagnostic centres (Figure 2). The device works on 1-3-7-14 malaria surveillance strategy and produces instant hotspots on the map of malaria cases on every event. On day 1 each case is diagnosed and on day 3 treatment is completed and within day 7 vector control activities are successfully deployed. In case of *Plasmodium vivax* cases complete radical treatment with primaquine within day 14. Malaria cases came down drastically over a 5-year period (Figure 3). Now malaria is on the verge of elimination in Mangaluru. Such innovative platform has made it possible to use paper-less data management and can be synced with the national IHIP portal.

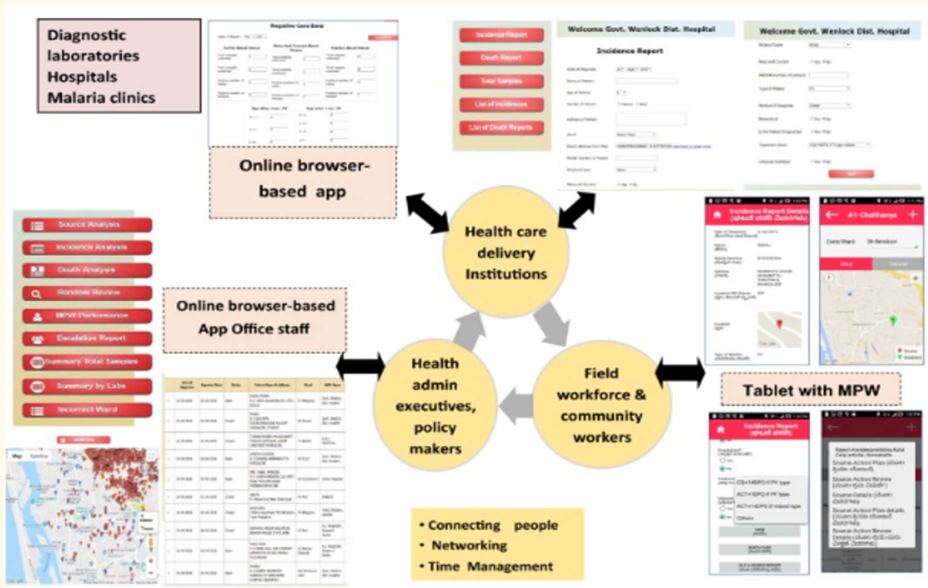


Figure 2: Concept, design and functioning of malaria control software [22].

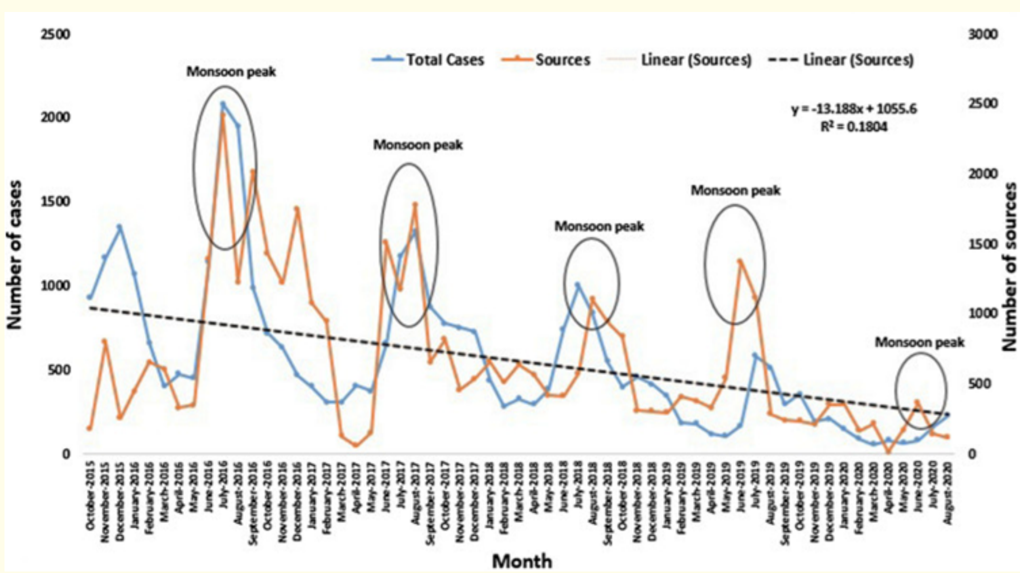


Figure 3: Sources reported vs malaria incidence over past five years post-digitization in Mangaluru [23].

Digital apps

About 30 digital apps have developed during the Covid-19 pandemic [24]. In India, several apps and portals were developed. *Arogya Setu* (the bridge to health) as a mobile for individual contact tracing to record details of all the around have come in contact with the disease. This app was developed by the Indian Government in collaboration with public and private stakeholders, including the National Informatics Centre (NIC) under the Ministry of Electronics and Information Technology, to deliver real-time contact tracing and self-assessment information to individuals, helping them to remain informed during critical periods. Similarly Co-Win portal was developed for booking vaccination [25]. During the ongoing Covid-19 period the *Air Suvidha* Self Declaration Form was a mandatory declaration that needed to be completed by all travellers planning to visit India. The declaration form must be filled out and submitted online 3 business days of one's scheduled arrival in India [26]. These digital devices greatly helped in efficient management of Covid-19 cases [25,26]. Data for all the Covid-19 cases were processed on a single window dashboard at the Head Office of the Indian Council of Medical Research at New Delhi. On the similar line, the National Centre for Vector Borne Diseases Control (NCVBDC) has launched a web-based Malaria Monitoring Information System (MMIS) in 2018 to foster malaria elimination by 2030 [27].

Use of artificial intelligence (AI), machine learning (ML) and automation

The 2024 Nobel Prize in physics was awarded to John J. Hopfield and Geoffrey E. Hinton for foundational discoveries and inventions that enable machine learning with artificial neural networks. AI and ML can be used to study the signalling pathways and metabolic networks, our understanding of various biological processes, and improve the diagnosis and treatment of diseases [28-30]. These can be used to analyse large datasets, such as genomic data, to identify patterns and trends of infectious diseases [31].

AI aims to mimic human cognitive functions [2]. The increasing availability of medical data and rapid advances in analytical techniques are leading to a paradigm shift in healthcare. AI-based epidemiological surveillance is a promising approach to detecting, monitoring, and predicting the spread of diseases. This technique helps to analyse data from multiple sources, such as electronic health records, social media, and news articles [32]. This adaptive learning capability means that AI systems are superior to traditional methods, which are more static and lack the sensitivity required to accurately forecast outbreaks and identify emerging diseases, empowering public health officials to take proactive and preventive measures at an early stage. Moreover, AI-based systems dynamically learn from new data, continuously improving their predictive accuracy thereby enhancing the effectiveness of disease surveillance [33]. BlueDot" is a notable AI-powered platform that was developed by epidemiology and data science experts in Canada, using ML algorithms to analyse various data sources [34]. This AI-based driven software provides insights about disease attributes, case counts, healthcare capacity analyses, epidemic preparedness, environmental suitability, and risk alert warming. For example, BlueDot provided early warnings to public health officials regarding the emergence of COVID-19 in Wuhan, China, in late 2019, thus influencing the global response to the pandemic. The Centers for Disease Control and Prevention (CDC) in the United States adopted an AI-based and ML algorithms system known as "BioSense". This uses epidemiological surveillance to monitor the spread, analyse data from electronic health records, emergency department visits, and other sources to identify infectious diseases outbreaks [35]. An application of `Chatbot' under Open AI, known as `ChatGPT' can process language text and can be used to perform complex analysis. In this system there is no language barrier, and provides several scientific contents, generating prevalence of any disease including risk factor maps.

Ethics, integrity, data biasness, data protection, limitations

Several issues such as ethical, digital integrity, data biasness and protection are involved using digital surveillance systems, early warning systems, big data analytics using AI, ML, and computational biology for detecting, monitoring, or tracing infectious diseases [24,36]. Several data on individual, organizational, societal levels, awareness on digital surveillance implementation, trust, privacy and confidentiality, civil rights, and governance must be protected. These measures were understandable during a pandemic. The public had concerns about the adequate information, lack of privacy protection, unclear government activities and autonomy when implementing infectious disease digital surveillance. These barriers could widen existing health care disparities or digital divides not properly involving the vulnerable and at-risk populations. Highly sensitive data of patients, such as their movements and contacts, could be exposed to outside sources, impinging significantly upon basic human and civil rights [36]. However, such prevailing concerns were outnumbered when AI-driven drug and vaccine delivery addressed some inequities during Covid-19 pandemic [2].

The critical limitations related to the digital epidemiology are protection of individual data, access to the facility where internet and smart phones are unavailable. During the COVID-19 pandemic, "digital epidemiology" has been proposed to complement traditional reporting and surveillance systems. Instruments such as smartphone contact apps, fitness trackers, and apps for voluntary reporting are intended to be used to monitor or contain the spread. Furthermore, the sensitivity and specificity of the suggested apps are unknown and not discussed in open forum. From a statistical and methodological perspective, the use of smart devices may suffer from under-coverage and nonresponse, which are rarely addressed by the proponents of digital epidemiology [37,38]. For example, in India two-third people have access to the internet and smart phones meaning one-third of the population could not use such facilities [39,40]. Moreover, misinformation during pandemic may affect the optimal execution of disease containment programme such as vaccine hesitancy during Covid-19 pandemic [2].

Discussion and Conclusion

Every year, 14 million people die from infectious diseases worldwide, accounting for 25% of all fatalities. Infectious diseases have severely impacted humankind all over the world and are the leading cause of mortality [2]. In this review we address the employment of current digital epidemiology, disease transmission and propagation models, accounts based on social networks, contact tracing, mobility analysis and spatiotemporal expansion of infectious diseases. Application of modern technologies such as information science (*Infodemic)*, AI, ML and automation on the digital epidemiology has the potential to create new operational mechanisms for prevention, containment, monitoring of the evolution of epidemics. In the digital era barring some limitations, we should focus on innumerable opportunities of digital and spatiotemporal epidemiology to tackle epidemics more effectively focusing on human-centric designs.

Here we describe how an ongoing dengue epidemic in Karnataka, India is tackling following the principles of digital and spatiotemporal epidemiology. In a recent article we have mentioned dengue would be a `disease of concern' and the serious consequences of dengue following the end of Covid 19 pandemic [41]. This year in 2024, an unprecedented epidemic outbreaks of dengue cases are underway since in the beginning of July surpassing all earlier records. A `Dengue War Room' has been established at the Commissionerate of Health and Family Welfare (Arogya Soudha) to closely monitor the dengue situation in the state. This initiative aims to manage and take up mitigation efforts to effectively tackle the spread of the disease. This apart, the Bruhat Bengaluru Mahanagara Palike (BBMP) and all districts will have control rooms to oversee the situation and gather data in their respective areas. A task force, chaired by the District Commissioners, will oversee the daily management of the situation [42]. All data were recorded in the IHIP portal on a day-to-day basis. Areas with two or more dengue cases within a 100-meter radius `hotspots' are identified followed by all necessary anti-vector measures [42]. All positive dengue cases were treated following national guidelines [43]. As of 3 December, 2024 a total of 32,323 dengue cases are reported from Karnataka. A detailed outlay is underway to contain dengue cases [44].

Here we have drawn detailed public health interventions and managements of Covid-19 pandemic based on the experience from dengue and *Aedes* surveillance as shown in Figure 3. This is a modified schematic presentation from an article reported earlier [45]). Three main pillars like COVID-19 control, COVID-19 transmission, and Social and Demographic Context cover the entire process of COVID-19 surveillance, containment and management in a given area. This would help the public health professionals and researchers engaged in Covid-19 management. This model can be applied for management for other diseases also.

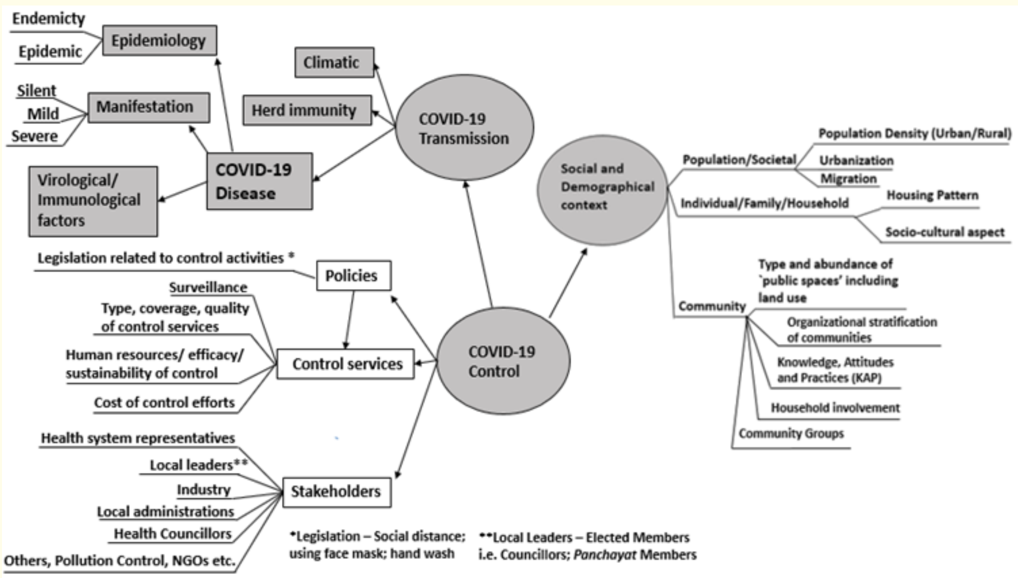


Figure 4: Schematic representation of COVID-19 surveillance, prevention and management.

Author's Contributions

SKG and CG jointly conceived of the theme and direction of the review. SKG conducted the review and wrote the first draft of the paper. CG edited the final draft.

Conflict of Interest

The authors declare no conflict of interest.

Bibliography

1. Chowell G and Rothenberg R. "Spatial infectious disease epidemiology: on the cusp". *BMC Medicine* 16 (2018): 192. https://doi.org/10.1186/s12916-018-1184-6.
2. Nema S., *et al*. "Automation techniques in infectious diseases". In: Kumar S, Kumar A (eds) Automated Diagnostic Techniques in Medical Microbiology. Springer, Singapore (2024): 145-160. https://doi.org/10.1007/978-981-99-9943-9_10.
3. Prabhu SR., *et al*. "Malaria epidemiology and COVID-19 pandemic: are they interrelated?" *OMICS* 26.4 (2022): 179-188.
4. United Nations. UN News. "WHO Chief declares end to COVID-19 as a global health emergency". 5 May (2023). https://news.un.org/en/story/2023/05/1136367.
5. World Health Organization (WHO). Mpox (2024). https://www.who.int/health-topics/mpox#tab=tab_1.
6. Mpox outbreak. Indian airports, borders on high alert; officials to increase surveillance (2024). https://timesofindia.indiatimes.com/travel/travel-news/mpox-outbreak-indian-airports-borders-on-high-alert-officials-to-increase-surveillance/articleshow/112643271.cms.
7. Park HA., *et al*. "Digital epidemiology: use of digital data collected for non-epidemiological purposes in epidemiological studies". *Healthcare Information Research* 24.4 (2018): 253-262.
8. Eysenbach G. 'Infodemiology: the epidemiology of (mis)information". *American Journal of Medicine* 113.9 (2002): 763-765.
9. World Health Organization (WHO). 1st WHO Infodemiology Conference, 29 June to 21 July 2020 (2020). https://www.who.int/teams/epi-win/infodemic-management/1st-who-infodemiology-conference.
10. Dearie K. "Website crawlers: what they are & how to use them" (2023). https://www.semrush.com/blog/website-crawler/?kw=&cmp=IN_SRCH_DSA_Blog_EN&label=dsa_pagefeed&Network=s&Device=c&utm_content=676232809836&kwid=dsa-2185834088336&cmpid=18364821001&agpid=153934787429&BU=Core&extid=105136990084&adpos=&gad_source=5&gclid=EAIaIQobChMI4pqYwvnphQMVhqNmAh0M-QzYEAAYASAAEgLCqPD_BwE.
11. Meliker JR and Sloan CD. "Spatio-temporal epidemiology: principles and opportunities". *Spatial and Spatio-temporal Epidemiology* 2.1 (2011): 1-9.
12. Snow J. "On the mode of communication of cholera". *Edinburgh Medical Journal* 1.7 (1856): 668-670.
13. Pickle LW. "A history and critique of U.S. mortality atlases". *Spatial and Spatio-temporal Epidemiology* 1.1 (2009): 3-17.
14. Pfeiffer DU and Stevens KB. "Spatial and temporal epidemiological analysis in the big data era". *Preventive Veterinary Medicine* 122.1-2 (2015): 213-220.
15. Musa GJ., *et al*. "Use of GIS mapping as a public health tool-from cholera to cancer". *Health Service Insights* 6 (2013): 111-116.
16. Luque Fernandez MA. "Introduction to Spatial Epidemiology Analyses and Methods". Universidad de Granada. London School of Hygiene and Tropical Medicine. TH Chan Harvard School of Public Health. 29 November (2018). https://scholar.harvard.edu/files/malf/files/spepi.pdf.
17. Wang Y., *et al*. "A Review of Bayesian Spatiotemporal Models in Spatial Epidemiology". ISPRS International Journal of Geo-Information 13.3 (2024): 97.
18. DHIS2 (2024). https://en.wikipedia.org/wiki/DHIS2.
19. World Health Organization (WHO). "Digital solutions for malaria surveillance" (2021). https://www.who.int/teams/global-malaria-programme/surveillance/digital-solutions-for-malaria-surveillance).
20. Integrated Health Information Platform, Integrated Disease Surveillance Programme Ministry of Health and Family Welfare, Government of India (2024). https://ihip.mohfw.gov.in/idsp/#!/history.

21. Ministry of Health and Family Welfare, Government of India. Health Management Information System (HMIS) (2024). https://main.mohfw.gov.in/sites/default/files/HMIS%20 Brief.pdf.

22. Baliga BS., *et al*. "Indigenously developed digital handheld Android-based Geographic Information System (GIS)-tagged tablets TABs in malaria elimination programme in Mangaluru city, Karnataka, India". *Malaria Journal* 18 (2019): 444.

23. Baliga BS., *et al*. "Digitized smart surveillance and micromanagement using information technology for malaria elimination in Mangaluru, India: an analysis of five-year post-digitization data". *Malaria Journal* 20 (2021): 139.

24. Mello MM and Wang CJ. "Ethics and governance for digital disease surveillance". *Science* 368.6494 (2020): 951-954.

25. Aarogya Setu (2024). https://en.wikipedia.org/wiki/Aarogya_Setu.

26. Air Subidha Portal (2024). https://airsuvidha.org/.

27. Ghosh SK. "Hammering the last nail on the malaria coffin in India: It's time to address the grey areas. Blog, India Health Fund - a Tata Trusts Initiative". (2023). https://www.indiahealthfund.org/hammering-the-last-nail-on-the-malaria-coffin-in-india-its-time-to-address-the-grey-areas/.

28. Arora G., *et al*. "Artificial intelligence in surveillance, diagnosis, drug discovery and vaccine development against COVID-19". *Pathogens* 10 (2021): 1048.

29. Thiebaut R and Thiessard F. "Artificial Intelligence in Public Health and Epidemiology". *Yearbook of Medical Informatics* 27 (2018): 207-210.

30. Cuperlovic-Culf M., *et al*. "Machine Learning and Hybrid Methods for Metabolic Pathway Modeling". *Methods in Molecular Biology* 2553 (2023): 417-439.

31. Nagpal S., *et al*. "Genomic Surveillance of COVID-19 variants with language models and machine learning". *Frontiers in Genetics* 13 (2022): 858252.

32. Zeng D., *et al*. "Artificial intelligence-enabled public health surveillance—From local detection to global epidemic monitoring and control". In Artificial Intelligence in Medicine; Academic Press: Cambridge, MA, USA (2020): 437-453.

33. Hua H., *et al*. "Review of distributed control and optimization in energy internet: From traditional methods to artificial intelligence-based methods". *IET Cyber-Physical Systems: Theory and Applications* 6 (2021): 63-79.

34. Goldust Y., *et al*. "COVID-19 and artificial intelligence: experts and dermatologists perspective". *Journal of Cosmetic Dermatology* 22 (2023): 11-15.

35. Bradley CA., *et al*. "BioSense: Implementation of a National Early Event Detection and Situational Awareness System". *MMWR Suppl* 54 (2005): 11-19.

36. Zhao IY., *et al*. "Ethics, Integrity, and Retributions of Digital Detection Surveillance Systems for Infectious Diseases: Systematic Literature Review". *Journal of Medical Internet Research* 23.10 (2021): e32328.

37. Klingwort J and Schnell R. "Critical limitations of digital epidemiology: why COVID-19 Apps are useless". *Survey Research Methods* 14.2 (2020): 95-101. https://doi.org/10.18148/srm/2020.v14i2.7726.

38. Butler D. "When Google got flu wrong: US outbreak foxes a leading web-based method for tracking seasonal flu". *Nature* 494 (2013): 155-156.

39. Behera TR. "Internet users in India: Statistics and Data" (2024). https://www.grabon.in/indulge/statistics/internet-users-statistics/.

40. Press Trust of India. India to have 1 bn smartphone users by 2026: Deloitte Study (2022). https://www.businesstoday.in/technology/story/india-to-have-1-bn-smartphone-users-by-2026-deloitte-study-323519-2022-02-22.

41. Ghosh SK and Ghosh C. "COVID-19's impacts on dengue transmission: Focus on neighbourhood surveillance of *Aedes* mosquitoes". *Asian Pacific Journal of Tropical Medicine* 15.8 (2022): 339-340.

42. "Bengaluru sets up war room to combat dengue spread". The New Indian Express (2024). (https://www.newindianexpress.com/cities/bengaluru/2024/Jul/12/bengaluru-sets-up-war-room-to-combat-dengue-spread).

43. National Center for Vector Borne Diseases Control. National Guidelines for Clinical Management of Dengue (2023).

44. Dengue, Chikungunya and H1N1 - Daily Report. "Commissionerate of Health & Family Welfare, Government of Karnataka" (2023). https://hfwcom.karnataka.gov.in/info-4/Dengue+&+Chikungunya+-+-Malaria+&+H1N1-Reports/en.

45. Arunachalam N., *et al*. "Eco-bio-social determinants of dengue vector breeding: a multicountry study in urban and periurban Asia". *Bulletin of the World Health Organization* 88.3 (2018): 173-184.