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Applications of geographical information system and spatial analysis in Indian health research: a systematic review

Anupama Chandran[1] and Pankaj Roy[1*]

Abstract

Background Health is a fundamental right intricately linked to geographical factors, as evidenced in the health geography literature. The application of geographical information systems (GISs) plays a pivotal role in mapping diseases and evaluating healthcare accessibility and is acknowledged by the World Health Organisation as a solution for enhancing health system resilience and achieving universal health coverage. This study focuses on the geographical perspectives to provide insights into the evolving role of GIS in addressing challenges and shaping healthcare strategies in health research within India. The primary objective was to analyse the utilisation of GISs in health studies specifically on three thematic areas: disease surveillance, health risk assessment, and healthcare access.

Methods The databases were searched using sixteen keywords for peer-reviewed articles published during 2000–2022. A systematic literature survey was conducted, drawing from peer-reviewed literature available in the PubMed, Web of Science and Scopus databases. Out of 162 search results, 58 articles were selected for review after three rounds of eliminations based on the predefined specific criteria. A systematic literature review was conducted following PRISMA guidelines addressing two research questions.

Results This review reveals the extensive use of GIS in health studies since its inception, with particular prominence as a decision-making tool in the aftermath of the COVID-19 outbreak. The analysis of scientific articles focused on disease surveillance, risk assessment, and healthcare access in the Indian context demonstrates the effectiveness of GIS in managing and planning healthcare resources and services. GIS has proven to be an indispensable instrument for understanding spatial patterns in disease and optimising health interventions.

Conclusion This systematic review underscores the critical role of GIS in health research, particularly in the Indian context. The versatile applications of GIS in disease surveillance, risk assessment, and healthcare access highlight its effectiveness as a tool for managing and planning healthcare strategies, contributing to a more resilient and accessible healthcare system in India and beyond.

Keywords GIS, Spatial analysis, Risk mapping, Disease, Healthcare, Pandemic management

*Correspondence:
Pankaj Roy
pkpathsala.roy@gmail.com
[1]Department of Geography, School of Earth Sciences, Central University of Karnataka, Kadaganchi, Aland Road, Kalaburagi, Karnataka PIN-585367, India

Introduction

A geographical information system (GIS) is a computer-based technology used to collect, store, analyse, manipulate and display geographical information. GIS integrates spatial data with nonspatial data. It is a geospatial technology with a broad scope of mapping and performing analysis. Many GIS software applications, such as ArcGIS and QGIS, are available on the market. Spatial analysis is an essential component of GIS. Spatial analysis can be defined as the process of studying geographical entities by examining spatial and nonspatial data and their relationships with each other [1]. Spatial analysis helps explore, understand and solve location-oriented problems. It goes beyond mapping features. Some major examples of spatial analysis techniques are overlay analysis, proximity analysis, spatial interpolation, network analysis, and hot spot analysis.

Statement of the problem

The application of spatial analysis in health research traced back to 1854, when John Snow, the father of modern epidemiology, prepared two maps to plot the cholera outbreak in London [2]. His maps helped to identify the spatial clusters of cholera cases and proved that cholera spread through the contaminated water supply. Since then, maps have become an integral part of health studies. A geospatial approach in health is primarily in the identification of spatial patterns. The recent advancements in GIS technology have broadened its scope. GIS combined with statistics assists in quantitatively assessing the relationships between geoenvironmental factors and diseases. Location-based analysis reveals the specific locations of diseases with high incidence rates.

GIS has a wide range of applications, from simple mapping and presenting spatial distribution patterns to more complex location-specific spatial analysis and modelling. For example, Franch-Pardo et al. [3] reviewed scientific articles on geospatial and spatial‒statistical analysis of the geographical dimension of COVID-19, focusing on five main themes of disease mapping: (i) spatiotemporal analysis, (ii) health and social geography, (iii) environmental variables, (iv) data mining, and (v) web-based mapping. Similarly, Ahasan et al. [4] reported that either a GIS or other geospatial tools were directly used as part of their analysis for COVID-19. In a review of geospatial technologies for infectious disease surveillance [5], cited case studies on COVID-19 worldwide to describe the application of GIS in disease mapping, data management and geostatistical analysis. However, to our knowledge, no recent reviews have explored the application of GIS in India in the context of COVID-19.

Khashoggi and Murad [6], while reviewing the potential of GIS in healthcare planning, reported that a GIS is an effective tool for supporting spatial decision-making in public health because of its analytical ability to address healthcare planning issues. Nykiforuk and Flaman [7] attempted to identify how GIS applications have been used in global health-related research, especially concerning four dominant themes: disease surveillance, risk assessment, healthcare access and planning, and community health profiling. Recently few studies have been conducted in India that followed such a systematic approach in selecting articles and reviews. In the past, Ruiz and Sharma [8] investigated geospatial technologies and spatial statistical methods used to address public health concerns in India.

After a quick evaluation of the previous reviews, a few notable gaps were identified. First, there is an urgent need for an updated assessment of advancements in current methodologies and applications of GIS. Second, there is a lack of reviews specifically exploring how GIS has been applied to COVID-19 scenarios in India. Hence, this study attempted to explore the recent development of the GIS as an important tool for health research in India. The main objectives of this study are to identify the diverse spatial analysis and GIS techniques employed in Indian health research over the last two decades and to review and critically analyse them from a geographical perspective.

Research questions

i. What are the various applications of GIS in Indian health research?
ii. What are the findings and limitations that emerge from the utilisation of GIS in the current context of health research in India?

Materials and methods

This review is a qualitative synthesis that provides an overview of the applications of GIS and spatial analysis in Indian health studies. The review involved comprehensive searches across three databases: Scopus, Web of Science, and PubMed. Scopus and Web of Science are multidisciplinary databases offering peer-reviewed journal articles in various fields, including life sciences, social sciences, physical sciences, and health sciences. PubMed specialises in life sciences, health, and biomedical research. A systematic literature review was conducted following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Fig. 1) to address the research questions.

The following keywords were used as search terms to locate relevant literature:

i. 'GIS' OR 'Geographic Information System' OR 'Spatial Analysis' OR 'Geospatial'

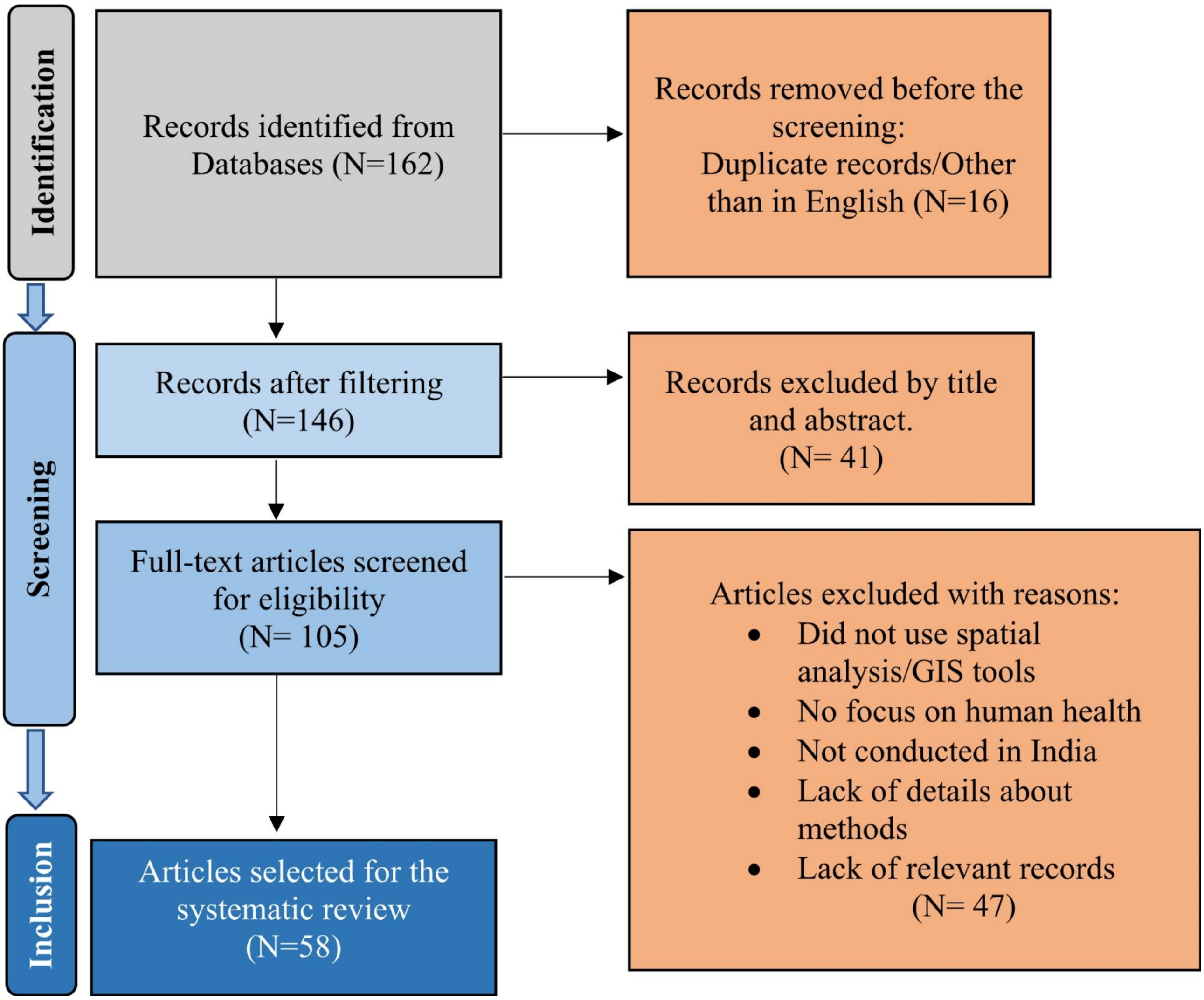

Fig. 1 PRISMA flow chart of the literature survey and review

Table 1 Criteria for the selection of journal articles

Sl. No.	Eligibility Criteria for Inclusion
1.	Articles in the English language
2.	Peer reviewed
3.	Available as full-text
4.	Studies conducted in India
5.	Primary focus on Geographic Information Systems or spatial analysis
6.	Demonstrated application of GIS in health
7.	Use of geospatial data in spatial analysis

ii. ‘Health’ OR ‘Public Health’ OR ‘Disease’ OR ‘COVID-19’
iii. ‘Surveillance’ OR ‘Mapping’
iv. ‘Risk Analysis’ OR ‘Risk Assessment’
v. ‘Accessibility’
vi. ‘Health Care’ OR ‘Health Services’
vii. ‘India’

The databases were searched using above mentioned sixteen keywords for peer-reviewed articles published during 2000–2022. Out of 162 search results, 58 articles were selected for review after three rounds of eliminations based on the predefined specific criteria outlined in Table 1. Studies that did not utilise GIS or spatial analysis tools and those without a focus on human health were excluded. Additionally, articles employing remote sensing techniques to analyse health problems were not considered. The selection process has been illustrated in Fig. 1. To ensure a comprehensive and unbiased selection of articles, the following processes were implemented:

Review team

A team of two independent reviewers was engaged to perform the article selection process. Each reviewer had expertise in the relevant field to ensure the selection criteria were appropriately applied.

Initial screening

Articles were initially identified through a systematic search of electronic databases such as Web of Science, PubMed, and Scopus via (above mentioned) predefined keywords and search terms.

Application of selection criteria

Each reviewer independently screened the titles and abstracts of the identified articles against the inclusion and exclusion criteria. Full-text articles were retrieved for those meeting the criteria in the initial screening.

Consensus and conflict resolution

The reviewers compared their selections. In cases of disagreement, a discussion was held to reach a consensus. If consensus could not be reached, a second round of discussion was conducted to make the final decision.

Final selection

After any conflicts were resolved, the final set of articles was agreed upon and documented. A detailed evaluation of the selected articles by the same reviewers resulted in a summary table (Table 2) capturing 'author, year, objectives, methods, and software'. This iterative process ensured that the selection was thorough and unbiased.

Categorisation

The applications of the GIS in healthcare were categorised into three themes: disease surveillance, risk assessment, and healthcare accessibility.

i. Disease Surveillance and Mapping ($N=30$): This involves identifying and mapping major disease events.
ii. Health Risk Assessment ($N=14$): This tool examines population exposure to health hazards and uses geostatistical methods to analyse the sources and impacts of dangers. Health risk analysis offers detailed insights into specific health threats, while health risk assessment provides a comprehensive framework for understanding and managing those risks. Health risk analysis and health risk assessment are intrinsically linked, with the former being a critical step in the latter. In short, health risk analysis is often seen as a component of the larger health risk assessment process.
iii. Healthcare Accessibility ($N=14$): This assesses the network of health services and the population's ability to utilise these services.

Results

The literature survey identified 58 peer-reviewed articles that focused on applying GIS and spatial analysis methods in health-related studies. These articles were grouped into three primary themes. While distinct themes were identified, some articles overlapped across categories, employing multiple spatial analysis methods or GIS software. Integrated approaches combining statistical methods and spatial analysis were also noted. The most commonly used spatial analysis techniques include the following:

- Geospatial interpolation via Inverse Distance Weighting (IDW) ($N=13$).
- Hotspot analysis via the Getis–Ord Gi* statistic ($N=11$).
- Spatial autocorrelation analysis via Moran's I ($N=9$).
- Overlay analysis ($N=6$).

ArcGIS software was predominantly used ($N=40$), with other software, such as GeoDa, QGIS, STATA, Accessmod, Map Window, and SaTScan also utilised in various studies.

Disease surveillance and mapping

Use of ArcGIS

One of the earliest uses of GIS since its development in public health has been disease surveillance. Disease tracking, identifying clusters, risk mapping, and modelling are the essential aspects of disease or epidemic surveillance. The most fundamental application of GIS in health is identifying and displaying the geographical distribution of a disease. Madhu et al. [9] attempted to depict the spatial distribution of breast cancer incidence via a point map and displayed the temporal distribution via thematic maps using ArcGIS software. ArcGIS is a geospatial software that was developed by the Environmental Systems Research Institute to view, edit, store, manage, analyse and display geographical information. MapInfo software, developed by Pitney Bowes Software and the MapInfo Corporation, is another powerful geospatial application for spatial analyses. Sabesan et al. [10] attempted to develop an empirical map of filariasis, a major vector-borne public health problem in India, in terms of both spatial and temporal aspects using MapInfo software. An endemicity map was produced via the quantile mapping approach, the simplest method of deciding which regional units have exceptionally high or low disease prevalence.

To understand the endemicity patterns of dengue fever, Mutheneni et al. [11] tried a novel approach by integrating a self-organising map (SoM) and spatial analysis in GIS. The SoM algorithm, also known as the Kohonen map, is an unsupervised neural network that can be used

Table 2 Summary of the selected articles

Sl. No.	Authors	Year	Objectives	GIS/Spatial Analysis Methods	Software
Disease Surveillance (*N* = 30)					
1	Madhu, B., Srinath, K. M., Rajendran, V., Devi, M. P., Ashok, N. C., & Balasubramanian, S	2016	To visualise the spatiotemporal distribution of breast cancer incidences	Thematic mapping and creation of point maps	ArcGIS
2	Sabesan, S., Palaniyandi, M., Das, P. K., & Michael, E.	2000	To map lymphatic filariasis in India	Probability mapping	MapInfo
3	Mutheneni, S. R., Mopuri, R., Naish, S., Gunti, D., & Upadhyayula, S. M.	2018	To understand the epidemiology and spatial distribution of dengue fever	Spatial mapping, Getis-Ord Gi* statistic, SoM	ArcGIS
4	Mala, S., & Jat, M. K	2019	To study the spatiotemporal distribution of dengue fever	Kernel density, directional distribution, Spatial Scan Statistic	ArcGIS
5	Raghava, M. V., Prabhakaran, V., Jayaraman, T., Muliyil, J., Oommen, A., Dorny, P., Vercruysse, J., & Rajshekhar, V	2010	To map spatial clusters of Taenia Solium infections	Spatial mapping, cluster analysis	SaTScan, ArcGIS
6	Sowmyanarayanan, T. V., Mukhopadhya, A., Gladstone, B. P., Sarkar, R., & Kang, G	2008	To investigate the disease pattern of viral hepatitis in children	Spatial mapping, cluster analysis	Arc View GIS, SaTScan
7	Sarkar, R., Prabhakar, A. T., Manickam, S., Selvapandian, D., Raghava, M. V., Kang, G., & Balraj, V	2007	To study outbreaks of acute diarrhoeal disease	Spatial mapping, cluster analysis	Arc View GIS, SaTScan
8	Mandal, R., Kesari, S., Kumar, V., & Das, P	2018	To study spatiotemporal dynamics of visceral leishmaniasis cases	Spatial mapping, overlay analysis Moran's I Index	ArcGIS
9	D'Mello, M. K., Badiger, S., Kumar, S., Kumar, N., D'Souza, N., & Purushothama, J.	2022	To geospatially analyse hotspots of diarrheal cases	Moran's I Index, Getis-OrdGi* statistic	QGIS, GeoDa
10	Felix, C., Kaur, P., Sebastian, I. A., Singh, G., Singla, M., Singh, S., Samuel, C. J., Verma, S. J., & Pandian, J. D.	2021	To identify high-incidence areas of transient ischemic attack for stroke prevention interventions	Spatial mapping, Moran's I Index, Getis-OrdGi* statistic	ArcGIS
11	Gupta, A. K., & Santhya, K. G.	2020	To understand proximal and contextual correlates of childhood stunting	Moran's I Index, ordinary least square (OLS) regression, spatial error model (SEM)	GeoDa
12	Krishnamoorthy, Y., Majella, M. G., Rajaa, S., Bharathi, A., & Saya, G. K.	2021	To assess the spatial pattern and determinants of HIV	Moran's I Index	GeoDa
13	Krishnamoorthy, Y., Rajaa, S., Verma, M., Kakkar, R., & Kalra, S.	2022	To find the spatial pattern and determinants of diabetes mellitus	Moran's I Index, Getis-OrdGi* statistic, ordinary least square (OLS) regression	GeoDa
14	Kumar, C., Singh, P. K., & Rai, R. K.	2012	To study under five mortality rates at the district level	Buffer, Moran's I Index, Getis-OrdGi* statistic, ordinary least square (OLS) regression, spatial error model (SEM)	GeoDa, ArcGIS
15	Garg, S., Dewangan, M., & Barman, O.	2020	To study malaria amongst symptomatic and asymptomatic pregnant women	Spatial mapping, correlation	Map Window
16	Nath, M. J., Bora, A. K., Yadav, K., Talukdar, P. K., Dhiman, S., Baruah, I., & Singh, L.	2013	To identify the malaria hot spots	GPS survey, spatial mapping	ArcGIS
17	Yadav, K., Nath, M. J., Talukdar, P. K., Saikia, P. K., Baruah, I., & Singh, L.	2012	To understand the geographical distribution of malaria	GPS survey, spatial mapping	ArcGIS
18	Rai, P. K., Nathawat, M. S., & Rai, S.	2014	To malaria-susceptibility modelling for predicting malaria occurrence	GPS survey, thematic mapping, malaria inventory mapping	Ilwis, ArcGIS, ERDAS Imagine
19	Qayum, A., Arya, R., Kumar, P., & Lynn, A. M.	2015	To identify the malaria hot spots	Thematic mapping, IDW, overlay analysis	ArcGIS
20	Singh, P. S., & Chaturvedi, H. K	2021	To map dengue cases and to identify the hotspots	IDW, Getis-OrdGi* statistic	ArcGIS
21	Mopuri, R., Mutheneni, S. R., Kumaraswamy, S., Kadiri, M. R., Upadhyayula, S. M., & Naish, S.	2019	To study the spatiotemporal distribution of malaria	Moran's, I Index, Getis-OrdGi* statistic, cluster analysis	ArcGIS, SaTScan

Table 2 (continued)

Sl. No.	Authors	Year	Objectives	GIS/Spatial Analysis Methods	Software
22	Oinam, B., Anand, V., & Kajal, R.	2021	To detect the hotspot regions of HIV	Getis-OrdGi* statistic, ordinary least square (OLS)	ArcGIS
23	Tyagi, N., & Sahoo, S.	2019	To identify areas of encephalitis and to create an encephalitis risk model	Thematic mapping, Map algebra	ArcGIS
24	Sabesan, S., Raju, K. H. K., Subramanian, S., Srivastava, P. K., & Jambulingam, P.	2013	To find areas with lymphatic filariasis transmission risk	Geo-Environmental Risk model (GERM) & Standardised Filariasis Transmission Risk Index (SFTRI) based mapping, cluster analysis	STATA
25	Joseph, P. V., Balan, B., Rajendran, V., Prashanthi, D., & Somnathan, B.	2015	To study small area clustering of diseases and to find probable chances of high disease prevalence	Probability mapping	ArcGIS
26	Das, A., Ghosh, S., Das, K., Basu, T., Dutta, I., & Das, M.	2021	To examine the impact of living environment deprivation on COVID-19 hotspots	Getis-OrdGi* statistic, Geographically Weighted Principal Component Analysis (GWPCA), data regression models	ArcGIS, R
27	Das, S. K., & Bebortta, S.	2022	To understand the role of GIS in tracking the spread of COVID-19	Choropleth maps, heatmap analysis, cluster analysis, Getis-OrdGi* statistic	QGIS
28	Murugesan, M., Venkatesan, P., Kumar, S., Thangavelu, P., Dash, N., John, J., Castro, M., Manivannan, T., Mohan, V. R., & Rupali, P.	2022	To analyse patterns of spread and hotspots of COVID-19	Spatial mapping, density map	ArcGIS
29	Soni, P., Gupta, I., Singh, P., Porte, D. S., & Kumar, D.	2022	To evaluate the occurrence and distribution pattern of COVID-19	Analytical Hierarchy Process (AHP), overlay analysis	ArcGIS
30	Wani, M. A., Kawoosa, W., & Mayer, I. A.	2019	To conduct a block-level analysis of respiratory diseases	Zonation map, hotspot mapping	ArcGIS
Risk Assessment (*N* = 14)					
31	Bohra & Andrianasolo	2001	To evaluate spatial relationships between sociocultural practices and the incidences of dengue fever	IDW, spatial modelling	GIS
32	Ali, S., Ali, H., Pakdel, M., Ghale Askari, S., Mohammadi, A. A., & Rezania, S.	2021	To assess the risk due to exposure to fluoride concentration in drinking water	IDW, spatial mapping	ArcGIS
33	Shukla, S., Saxena, A., Khan, R., & Liu, P.	2021	To assess the overall groundwater quality and the spatial distribution of the physicochemical parameters	IDW, spatial mapping	ArcGIS
34	Singh, Rani., Upreti, P., Allemailem, K. S., Almatroudi, A., Rahmani, A. H., & Albalawi, G. M.	2022	To assess the quality of groundwater for drinking purposes	IDW, spatial mapping	ArcGIS
35	Vikrma, A., & Sandhu, H. A. S.	2022	To conduct a risk assessment based on the quality of groundwater	IDW, spatial mapping	ArcGIS
36	Gugulothu, S., Rao, N. S., Das, R., Duvva, L. K., & Dhakate, R	2022	To assess the sources of low groundwater quality and to understand the human health risk	IDW, spatial mapping	ArcGIS
37	Singh, A., Raju, A., Chandniha, S. K., Singh, L., Tyagi, I., Karri, R. R., & Kumar, A.	2022	To assess the human risk exposure due to consumption of groundwater	Overlay analysis, mapping	ArcGIS
38	Ananth, M., Rajesh, R., Amjith, R., A L, A., Valamparampil, M. J., Harikrishnan, M., Resmi, M. S., Sreekanth, K. B., Sara, V., Sethulekshmi, S., Prasannakumar, V., Deepthi, S. K., Jemin, A. J., Krishna, D. S., Anish, T. S., Insija, I. S., & Nujum, Z. T.	2018	To assess the sanitary condition and water quality of household wells	DGPS survey, IDW	ArcGIS
39	Ravindra, K., & Mor, S.	2019	To assess risk due to distribution of arsenic and selected heavy metals in groundwater	Kriging interpolation	ArcGIS
40	Sargaonkar, A., Nema, S., Gupta, A., & Sengupta, A.	2010	To assess the risk of contamination of water in water distribution systems	Spatial and thematic mapping	AutoCAD, ArcGIS
41	Bidhuri, S., & Jain, P.	2018	To analyse the spatial risk of waterborne diseases	GPS, analytical hierarchical process (AHP), IDW, buffer	GIS

Table 2 (continued)

Sl. No.	Authors	Year	Objectives	GIS/Spatial Analysis Methods	Software
42	Singh, D., Dahiya, M., & Nanda, C.	2022	To analyse the variability in air pollutants, AQI and ER% in three scenarios, viz. prelockdown, during lockdown, postlockdown	IDW, spatial mapping	GIS
43	Kanga, S., Meraj, G., Sudhanshu, Farooq, M., Nathawat, M. S., & Singh, S. K.	2021	To analyse the risk of COVID-19 infection	Spatial mapping, overlay analysis, kriging interpolation	ArcGIS
44	Nath, B., Majumder, S., Sen, J., & Rahman, M. M.	2021	To study the degree of risks associated with COVID-19 infections	Cosine Similarity Index (CSI) by similarity search tool	ArcGIS Pro
Healthcare Access (*N*=14)					
45	Pramod Nayak, P., Mitra, S., Pai, J. B., Vasthare Prabhakar, R., & Kshetrimayum, N.	2022	To map distribution and accessibility to oral health care	Geo-coding, spatial mapping, kernel density estimation	QGIS
46	Ghosh, A., & Mistri, B.	2020	To investigate spatial disparities in the provision of rural health facilities	Buffer, Euclidean distance, IDW	ArcGIS
47	Parvin, F., Ali, S. A., Hashmi, S. N. I., & Khatoon, A.	2020	To study accessibility and site suitability for healthcare services	Kernel density, Euclidean distance, buffer, weighted linear combination method, site suitability analysis	ArcGIS
48	Rekha, R. S., Wajid, S., Radhakrishnan, N., & Mathew, S.	2017	To study the distribution of healthcare facilities	Three-step floating catchment area method, GPS survey, Origin-Destination cost function, site suitability analysis	ArcGIS
49	Ranga, V., & Panda, P.	2014	To analyse spatial access to inpatient rural healthcare	Three-step floating catchment area method, Euclidean distance	QGIS, R
50	Vadrevu, L., & Kanjilal, B.	2016	To study spatial access to maternal health services	Enhanced two-step floating catchment area method	ArcGIS, STATA
51	Roberts, T., Shiode, S., Grundy, C., Patel, V., Shidhaye, R., & Rathod, S. D.	2019	To assess the relation between distance to health services and treatment-seeking for depressive symptoms	Network analysis	ArcGIS
52	Oinam, B., Oinam, J., & Kajal, R. K.	2020	To assess health coverage of healthcare facilities	Thematic mapping, spatial catchment analysis, scaling-up analysis	ArcGIS, AccessMod
53	Dutta, B., Das, M., Roy, U., Das, S., & Rath, S.	2022	To analyse the spatial pattern of healthcare facilities and to determine the possible sites for the provision of healthcare facilities	GPS survey, overlay analysis, network analysis, analytical hierarchy process (AHP) and ordinary least square (OLS)	ArcGIS
54	Singh, N., Patel, R., & Chauhan, S	2021	To investigate the utilisation of maternal health care services	Ordinary least square (OLS) and spatial error model (SEM), Moran's I Index	ArcGIS
55	Kumar, N.	2004	To study access to and locational efficiency of health services	Location-allocation models (LAM), Euclidean distance	ArcInfo
56	Dare, A. J., Ng-Kamstra, J. S., Patra, J., Fu, S. H., Rodriguez, P. S., Hsiao, M., Jotkar, R. M., Thakur, J. S., Sheth, J., & Jha, P.	2015	To analyse access to surgical care regarding deaths from acute abdominal conditions	Geo-coding, Clustering analysis, Getis-OrdGi* statistic, kriging, Euclidean distance	SaTScan
57	Verma, V. R., & Dash, U.	2020	To measure accessibility and model spatial coverage of public healthcare networks.	Thematic mapping, Euclidean distance, overlay analysis, accessibility analysis, geographical coverage analysis	AccessMod, ArcGIS
58	Sabde, Y., Diwan, V., Mahadik, V. K., Parashar, V., Negandhi, H., Trushna, T., & Zodpey, S.	2020	To analyse the geographical distribution of medical schools	Spatial mapping, Near neighbourhood analysis	QGIS, ArcGIS

to understand endemicity patterns. Even though SoM has many health applications, this study of coupling the SoM clusters of disease-endemic regions with the GIS is the only example of disease mapping identified for the review. Mala & Jat [12] used kernel density and directional distribution tools to determine the spatial diffusion patterns of dengue fever incidence in Delhi, India. In this work, a continuous density surface map was produced via kernel density analysis to show the infection density. Kernel density is one of the spatial analyst tools used in the GIS environment for density analysis of features in a neighbourhood around those features. It calculates point and line features around each output raster cell by considering the total number of intersections of the individual features.

Use of SaTScan

Many studies focused on investigating the spatial clustering of diseases. SaTScan was the most commonly used software programme to identify spatial clusters. The SaTScan, analysis involves systematically moving a circular window over the study area to detect significant spatial clusters. The radius of the window may vary from zero to any value defined by the user [13]. Sowmyanarayanan et al. [14] investigated hepatitis A via SaTScan under the assumption that regions with poor living conditions, such as inadequate water supply, poor sewage facilities, and sanitary conditions, have increased chances of hepatitis A outbreaks. The use of GIS helped reveal any spatial clustering of cases and led to the conclusion that the outbreak could be due to contamination of the water supply. Similarly, Sarkar et al. [15] also used SaTScan to investigate an outbreak of acute diarrhoeal disease and prepared maps of the water supply system, sewage channels, and areas with observed faecal soil contamination within the study area. The vulnerable areas with potential for contamination were identified from maps. Surveillance of water pipelines can reduce the risk of piped water contamination and prevent diarrhoeal disease outbreaks.

Use of Moran's I index

Moran's I index is a spatial-correlation statistic that many researchers use to evaluate the clustering patterns expressed by features [16–19]. In a study of the spatiotemporal dynamics of visceral leishmaniasis cases, Mandal et al. [20] used Moran's I index to explore the spatial pattern of the case incidence rate (CIR) between endemic villages. There are two main types of Moran's I: global Moran's I and local Moran's I, both are valuable tools in disease clustering analysis. To determine the spatial pattern of diabetes mellitus, 21. Krishnamoorthy et al. [21] assessed global autocorrelation via the global Moran's I statistic. Kumar et al. [22] used local Moran's I statistics to show spatial clustering and outliers while geospatially analysing under-five mortality. Local Moran's I is a local spatial autocorrelation statistic based on global Moran's I. It is computed in GeoDa, a free software package for spatial analysis.

Hotspots analysis

Understanding the clustering of hotspots of any disease is an important application of GIS in health research. Few studies prepared GIS-based maps to identify vulnerable pockets called malaria hot spots [23–25]. GIS was primarily employed to examine the relationships between variables such as land use, the NDVI, climatic factors, population, distance to health centres, streams, and roads that influence the distribution of mosquitoes responsible for malaria transmission. Maps were then prepared by integrating socioeconomic, epidemiological, and geographical dimensions to find malaria hotspots. Similarly, Rai et al. [26] attempted to create a model for predicting malaria via GIS and remote sensing. The malaria susceptibility index (MSI) map was generated by superimposing thematic layers of different variables via the weighted overlay method. An overlay is a spatial operation in which two or more maps are superimposed to show the relationships between features that occupy the same geographical space.

Use of Getis-OrdGi*

Qayum et al. [27] employed the overlay method to prepare a malarial risk map and used the IDW method to map vulnerable zones. Singh & Chaturvedi [28] used IDW interpolation along Getis-OrdGi* statistics to identify clusters with a high frequency of dengue cases. Getis-OrdGi* statistics identify different spatial clustering patterns, such as hot and cold spots, over a geographical area with statistical significance. Mopuri et al. [29], used the Getis-OrdGi* index to detect hotspots of malaria incidence. Oinam et al. [30] evaluated the spatiotemporal variations in HIV/AIDS incidence via the Getis–OrdGi* statistic and identified the factors that influence HIV in Manipur. The hotspot analysis tool in ArcGIS software calculates the Getis–OrdGi* statistic for each feature in a dataset. The results of z and p scores showed where the features cluster at high and low values. Another example of hotspot analysis using the Getis–OrdGi* statistic is the generation of the encephalitis risk model. Encephalitis is a disease with high mortality, with seasonal outbreaks in several parts of India. Tyagi & Sahoo [31] prepared thematic maps of selected parameters, such as LULC, population distribution, pig population, and disease occurrence, and classified all the thematic layers via Reclassify, a spatial analyst tool in ArcGIS. Finally, the encephalitis risk model was created via the map algebra function to highlight risk areas and identify risk factors.

Geospatial modelling

Initially, the geoenvironmental risk model (GERM) was utilised to create a filariasis transmission risk map at the regional scale. Later, the GERM, integrated with the GIS, proved more beneficial for Filariasis spatial delimitation, especially at the macro scale. This new model uses a Standardised Filariasis Transmission Risk Index (SFTRI) to predict transmission risk [32]. The index was derived by encompassing all geoenvironmental variables influencing filariasis transmission, such as soil texture, altitude, temperature, rainfall, and relative humidity. The authors argued that GERM could be used for controlling filariasis delimitation worldwide. Probability maps are useful for depicting more specific regions of relative spatial risk. These maps are prepared via probabilistic values (P values). Typically, when studies are performed in small unpopulated areas, rates are unstable because of the small number problem. If the population of an area is small, the rate of disease estimates is relatively high. It tends to give rise to the most extreme disease rates. Probability mapping via GIS is the most suitable method for detecting and monitoring spatial clusters, as the small number problem disappears. The areas with the largest populations dominate the probability map results [33]. However, this approach to mapping clusters is not widely used for several reasons.

The case of COVID-19

The ability of a GIS to understand and respond to infectious diseases has proven invaluable in managing the spread of COVID-19. The COVID-19 pandemic emerged as a threat to humans worldwide. A highly populated country such as India was significantly affected by the pandemic. GIS has aided in zonation mapping, hotspot mapping, contact tracing, healthcare facility mapping, and producing real-time dashboards to visualise COVID-19 statistics and trends. COVID-19 zonation maps are essential tools for controlling the spread of COVID-19. Das et al. [34] prepared COVID-19 hotspot maps in the Kolkata megacity via the Getis-OrdGi* statistic with the help of ArcGIS software. Similarly, different studies [35–37] have demonstrated the effective utilisation of GIS for studying COVID-19 in different locations in India. Mapping hotspots of COVID-19 was the most employed operation identified in this review. There has been a recent shift towards integrating advanced spatial analysis and real-time data management into public health, reflecting the importance of GIS-based mapping in routine surveillance activities to understand the various spatial factors associated with emerging pandemic diseases such as COVID-19.

Health risk assessment

Location-oriented causation

GIS provides an understanding of epidemiological linkages with potential risk factors for identifying the spread of diseases. One of the crucial applications of GIS in risk assessment is identifying regions with the highest risk of infection and disease. The risk of disease is the result of the integration of various variables. GIS integrates spatial data with nonspatial data to predict disease risk based on sociocultural factors such as housing patterns, irregular water supplies, poorly managed waste disposal, etc., that could lead to many epidemics. Socioeconomic factors such as education and income also affect disease incidence. The prediction of dengue risk based on sociocultural factors and their possible spatial relationships was investigated in the dengue-endemic area of Jalore in Rajasthan [38]. The IDW interpolation and statistical tools such as correlation, regression, and discriminant analysis were also employed in the study. Most of the works especially for water resources with similar objectives for health risk assessment and spatial distributions of physio-chemical parameters were assessed through GIS mapping via IDW [39–41].

A substantial number of studies emphasised risk analysis related to water resources. Contamination of water resources was recognised as a significant cause of waterborne diseases [42]. Gugulothu et al. [43] noted the importance of analysing the spatial distribution and concentration of fluoride in drinking water to determine risk areas. Fluorosis in water resources was a major public health problem identified in many states of India. Singh et al. [44] assessed the potential human health risk from the drinking of poor-quality groundwater in Lucknow. Groundwater contamination, whether physical, chemical, or microbiological, can cause many health hazards. Ananth et al. [45] performed spatial health risk assessment via ArcGIS, which revealed that GIS platforms are efficient tools for analysing nearby contamination sources in a well. Ravindra and Mor [46] used the kriging method for the risk assessment of arsenic in groundwater. Kriging is another geospatial interpolation technique for contaminants that helps identify hot spots of contamination and health risks that can be assessed. An integrated risk assessment model via ArcView software was developed to assess risks within water distribution systems [47]. This revealed a high risk of waterborne diseases while the pipeline system was in direct contact with pollution sources. For this purpose, different layers of the network for water supplies, sewers, stormwater drains, open drains, and roads were extracted from ArcMap 9.2. They tried to integrate GIS and mathematical models. Mapping high-risk areas revealed critical points where the pipe was in poor condition.

Weightage-based assessment

Bidhuri and Jain [48] conducted a spatial risk analysis of waterborne diseases via the analytical hierarchy process (AHP) on the GIS platform. The integrated geospatial approach that relies on AHP and GIS-automated techniques helps delineate waterborne disease-prone areas. Thematic maps of different variables were prepared, and the weights were assigned to each factor through the AHP method. The rating scale in the AHP helps to identify how much more critical one criterion is. Parameters such as the water quality index (WQI) are inversely related to waterborne diseases. Thomas Saaty introduced the AHP method in the 1970s as a multicriteria analysis model that helps in the decision-making process. Like water, air pollutant concentrations are also important for assessing health risks. A GIS-based environmental health information system was developed [49] to identify the geographical distribution and variation in diseases, to correlate spatial and temporal trends in disease and air pollution and to map population at risk. They assessed the air quality index (AQI) and excess risk (ER%) during the pre-COVID-19 lockdown, lockdown, and post-COVID-19 lockdown periods via statistics and GIS. Pollutant concentrations for the AQI and ER percentages were processed in a GIS environment through IDW.

The case of COVID-19

The use of GIS in the context of COVID-19 has often been confined to visualising spatial patterns. However, it also has practical applications in modelling risk assessment frameworks. The study conducted at Jaipur Municipal Corporation of India was the first to use spatial sciences and GIS for risk assessment for COVID-19 [50]. Weighted overlay analysis was used to generate risk maps from hazard and vulnerability maps. The authors reported the limitations of incomplete knowledge of the operational mechanism of COVID-19 infections. The cosine similarity index (CSI) is an efficient method for identifying locations with the highest risk of contracting COVID-19. Nath et al. [51] performed this analysis via the "Similarity Search" tool in ArcGIS Pro software. One of the important limitations highlighted by COVID-19-related studies is the lack of data in the initial days of the outbreak. This constrained authors from incorporating potentially important variables into their analyses.

Health care accessibility

Considering distance

Spatial accessibility can be defined as the regional availability of any service. Access to healthcare facilities, especially in rural areas, is a significant concern for developing countries such as India. The UN Sustainable Development Goals (SDG Target 3.8) seek to achieve universal health coverage, including financial risk protection; access to quality essential healthcare services; and access to safe, adequate, quality, and affordable essential medicines and vaccines by 2030. Accessibility to healthcare providers is an important parameter that reveals how much distance have to travel for healthcare. Greater distance from healthcare centres is a natural barrier to seeking treatment. Many studies retrieved for review have comprehensively shown how GISs can be utilised to assess spatial accessibility in health services research. For example, Pramod Nayak et al. [52] analysed the geographical distribution of private and public dental healthcare providers in a GIS environment to identify regions with limited access. The kernel density estimation algorithm was used to produce a heatmap to identify poorly served areas. Ghosh and Mistri [53] employed buffer analysis in ArcGIS to identify influence zones of rural healthcare services in the Birbhum district of West Bengal. Buffer analysis is the most common way to measure the proximity and accessibility of healthcare facilities. However, none of these selected studies used it as a primary analysis.

Accessibility modelling

The gravity model using GIS is one of the best methods for measuring spatial accessibility. The two-step floating catchment area model (2SFCA) and enhanced two-step floating catchment area method (E2SFCA) are improved versions of the simple gravity model proposed to overcome limitations such as distance decay [54]. The three-step floating catchment area (3SFCA) method was developed from E2SFCA [55]. Ranga & Panda [56] calculated spatial access via 3SFCA and argued that spatial access in rural India was still very far from a satisfactory level. Vadrevu & Kanjilal [57] measured spatial access to maternal health services via E2SFCA. They employed network analysis in ArcGIS to prove that there was no equitable accessibility to maternal health facilities, especially in remote areas. Network analysis via ArcGIS revealed that travel distance from households to the nearest public depression treatment provider was not the primary barrier to seeking treatment for depression in rural India [58]. Network analysis is the GIS operation that examines real-world networks to understand the flow of movement. It is commonly used to find the best routes. The origin distance cost distance function in the network analysis module can be used to generate travel times.

Multicriteria analysis

Several works suggested using 3SFCA and multicriteria decision analysis to find the optimal site for new healthcare facilities in the disparity region. While new healthcare infrastructure projects are considered, preferences should be given to inaccessible areas. It is important to study the spatial distribution of existing healthcare facilities to identify locations where new services must be established to increase accessibility. Oinam et al. [59] performed a scaling-up analysis indicating the need to establish new healthcare centres in remote hilly areas of Manipur. Scaling-up analysis, which was performed to identify the optimum location for building new healthcare centres in a region, considers topographic factors, the existing road network, the existing LULC, the population distribution, and the location of existing health facilities for the assessment. ArcGIS software was used to generate thematic layers of these geographical parameters, which were then imported into AccessMod software to perform scaling-up analysis. AccessMod is a free and open-source standalone software developed by the World Health Organisation (WHO) to evaluate the physical accessibility of the existing network of healthcare facilities. Dutta et al. [60] attempted to develop a model using AHP and ordinary least squares (OLS) in the GIS environment to analyse existing facility patterns and identify suitable locations for new health centres. The study revealed that existing centres needed to be located appropriately in Central Singapore (Midnapore) in West Bengal. The AHP suitability and OLS suitability maps were compared and concluded that no significant difference between the AHP and OLS existed. Singh et al. [61] also employed OLS along with the spatial error model (SEM) to measure maternal healthcare utilisation in India.

Location-allocation models (LAMs) and euclidean distance

Another spatial analysis method called location-allocation models (LAMs) was used for the locational analysis of healthcare services. Kumar [62] described how to implement location-allocation problems in the GIS environment via the ArcInfo software. Since there was topographic homogeneity in the study area, the LAM uses Euclidian distances. Euclidean distance is the simplest method of proximity analysis. Several studies used Euclidean distances from health centres as the main indicator for spatial access [63, 64] and interpolated it with IDW to obtain a map of physical access. Dare et al. [63] employed Euclidean distance to calculate the distance to hospitals, and the spatial clustering analysis in the study used the Getis−OrdGi* method to locate spatial clusters of deaths from acute abdominal conditions. The study revealed that full access to well-resourced hospitals within 50 km could have prevented approximately 50,000 deaths from acute abdominal conditions in India. Verma & Dash [64] developed a raster-based travel time cost surface model to study the spatial distribution of travel time toward the nearest health facility. For this purpose, they employed Euclidean distance and overlay analysis to create buffer zones of accessibility and evaluate the adequacy of health facilities within the zones.

Many studies were conducted especially during and post-COVID-19 period to assess health care accessibility via geospatial tools. Collectively, these studies demonstrate that integrating and analysing spatial data via the GIS techniques can help in policy decisions related to accessibility, optimal resource allocation and site suitability.

Discussion

Numerous techniques, such as spatial mapping, geospatial interpolation, floating catchment area, buffer zone analysis, hotspot analysis, cluster analysis, Moran's I method, ordinary least squares, network analysis and location-allocation analysis methods are effective in addressing various health issues in India. One of the most common applications of GIS is mapping the spatial patterns of diseases. Maps produced with the help of GIS software, such as ArcGIS and QGIS, are widely used as monitoring and evaluation tools for different infectious diseases, such as malaria, HIV, and COVID-19. Choropleth and Dot maps were used to represent disease incidence and display death and illness rates in a geographical area. Mapping diseases aids in interpreting areas with infectious diseases more effectively for better epidemiological planning [65]. Another advantage of GIS for mapping and analysing distribution patterns is its effectiveness across various levels of application, from the microscale to the macroscale. In other words, the GIS can efficiently assist local/regional, national, and global studies. For example, Wani et al. [66] observed the relevance of the applications of GIS at the block level with effective mapping of the morbidity patterns of respiratory diseases.

Mapping disease not only helps in the identification of infected areas but also in the exploration of the relationships between the incidence of disease and certain factors that influence health. Several studies have incorporated demographic, socioeconomic, behavioural and geoenvironmental factors to investigate how they are correlated with the incidence of different diseases. Similarly, the assessment of these risk factors assists in the identification of the population at risk [67]. Another area of focus in GIS and the spatial analysis of health studies is the analysis of accessibility to healthcare services. Uneven distributions of population and healthcare services lead to spatial inequality. The distance between the service location and the population determines their access. Many studies have performed Euclidean distance and network analyses to identify underserved areas. Sabde et al. [68] reported the efficiency of density maps while understanding the distribution of medical schools in India to identify such under- and overseeing areas. They reported that medical schools were located as clusters in certain parts of the country, whereas large areas had no medical schools. This underscores the disparity in both the distribution of healthcare services and the availability of healthcare education institutions across the country. Site suitability analysis is another important concept related to healthcare services. Suitable sites for new health infrastructures are proposed by analysing existing site structures, patterns and conditions via spatial analysis techniques [54].

One significant recent development in GIS application is its contribution to COVID-19 pandemic management. Several studies have tracked the spatial patterns of COVID-19 and delineated potential risk areas. GIS helped in the effective integration of spatial and nonspatial data. Fatima et al. [69] reported some challenges in the application of GIS during the pandemic across the world, such as (i) data bias due to low testing rates and the presence of asymptomatic individuals, (ii) underreporting of cases and deaths and (iii) a lack of spatial data. These challenges were also observed in the context of India. The regulations to track contact persons were another limitation [70]. Although some studies have reported data unavailability most COVID-19-related data are publicly available in India. National security concerns could restrict Access to spatial data in India [8]. Consequently, the GIS has limitations in countries such as India because of a lack of valid routine data to enter into the GIS.

Limitations of GIS in healthcare research

Ethical insinuations

This article reviews the ethical considerations addressed in the applications of GIS in healthcare based on the specified literature. GIS has been increasingly used (Table 2; Fig. 2) in healthcare for visualising, analysing and interpreting spatial data related to health. The methods are promising to enhance healthcare delivery and public health outcomes through improved data visualisation and analysis. However, its ethical use requires addressing critical issues such as privacy and confidentiality, equity and accessibility, transparency and accountability, consent and agency, data security, and bias and fairness [71, 72]. This review of the specified literature (Table 2) has evident that none of the studies explicitly addressed the key ethical concerns related to the use of GIS in healthcare. However, some investigators suggest strategies to overcome these challenges, including improving the data infrastructure, training healthcare professionals in GIS, and developing policies to ensure the ethical use of spatial data [73].

Privacy and confidentiality

GIS technology can expose sensitive patient information. Protecting patient data from unauthorised access is crucial for maintaining trust and confidentiality. For example, the mapping of breast cancer incidences [9] and lymphatic filariasis [10] could inadvertently reveal private health information without proper safeguards if privacy and confidentiality are not maintained properly [71].

Transparency and accountability

Significant power and responsibility lie with healthcare professionals using GIS. Transparent decision-making and clear methodologies prevent misuse and misinterpretation of data. The study on dengue fever's spatiotemporal distribution [12] and Taenia solium infections [13] emphasises transparency [72].

Consent and agency

Patients should be informed about how their data will be used. Respecting patient agency and obtaining consent align with medical ethics [71]. The investigation of viral hepatitis patterns in children [14] must ensure parental consent and clear communication [74].

Data security

Ensuring the integrity and security of data is critical. Preventing data breaches and maintaining cybersecurity are essential for protecting patient information. Studies on diarrheal cases [16] and transient ischemic attack incidence [17] must implement strong data security measures [75].

Bias and fairness

GIS data and analyses may contain biases, leading to unfair outcomes. Regular audits and validations are needed to ensure data accuracy and fairness. The

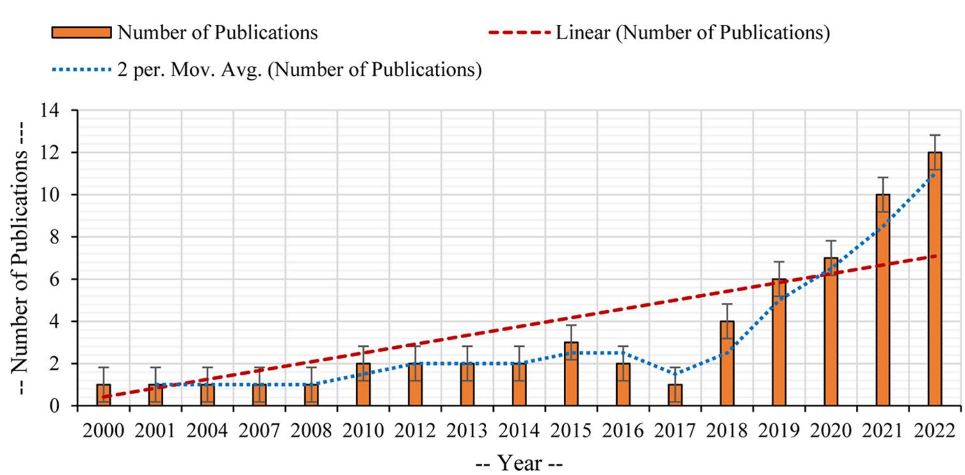

Fig. 2 Indian publications using GIS and spatial analysis in health research

epidemiology of diseases requires unbiased data to avoid discriminatory public health interventions [76].

Data availability and quality

In rural regions, the availability of reliable and comprehensive health data is a major barrier to effective GIS implementation. Health data required for spatial analysis may be missing, incomplete, or outdated. Standardised data collection mechanisms are often absent in these areas, leading to fragmented datasets. The limited availability and poor quality of data reduce the effectiveness of GIS tools in providing accurate spatial analyses. This limitation can significantly hinder public health interventions in rural areas, where precise data is essential for tackling endemic diseases like malaria and dengue. For example, breast cancer incidences mapping using GIS in rural areas would be constrained by data limitations [9].

Data integration challenges

Integrating diverse datasets (such as socio-economic, environmental, and health data) necessary for comprehensive GIS analysis is particularly difficult in rural regions. These datasets are often maintained by different government and non-government organisations, with limited coordination for data sharing and integration [77, 78]. GIS tools cannot provide a holistic analysis to inform healthcare strategies without integrated data. For instance, Sabesan et al. [10] mapped lymphatic filariasis in India, likely facing challenges in integrating environmental data with health records, leading to potential gaps in the analysis.

Technical capacity and infrastructure

The technical infrastructure necessary for GIS implementation is often underdeveloped in rural areas. Limited access to high-speed internet, advanced GIS software (such as ArcGIS or QGIS), and trained personnel are significant barriers [76]. The lack of infrastructure hinders the use of GIS for real-time monitoring and analysis. For example, Mala and Jat [12] utilised sophisticated tools like ArcGIS for dengue fever distribution studies, but similar efforts in rural areas are constrained by inadequate resources and expertise.

Social barriers

Ethical concerns related to data privacy, as well as social barriers such as mistrust of authorities or a lack of awareness, can hinder data collection in rural communities. Engaging local populations in the data collection process is difficult, leading to reduced participation [71]. Without local engagement, the data required for accurate GIS analyses may be incomplete or inaccurate, particularly in areas where disease mapping is crucial for public health interventions [74].

GIS technology has the potential to significantly improve healthcare outcomes, especially in rural regions of India. However, limitations related to data availability, integration, technical capacity, and ethical considerations must be addressed to fully realize its benefits. Overcoming these challenges through better infrastructure, training, and data-sharing frameworks will enable more effective GIS applications in these underserved areas, promoting equitable healthcare access for all.

Emerging trends and potential advancement

Machine learning integration

Machine learning (ML) algorithms are increasingly being combined with GIS to process vast amounts of spatial health data, uncovering patterns those traditional methods might miss. This integration allows for predictive modelling and trend analysis in healthcare. For example, ML models can predict disease outbreaks or assess environmental risk factors by analysing large datasets from past outbreaks and spatial health data [76]. This integration improves the accuracy and timeliness of interventions. For instance, dengue fever prediction models could combine GIS-based spatial mapping with ML algorithms to target public health interventions more precisely and reduce disease transmission in real-time.

Real-time data mapping

The development of real-time data mapping within GIS is transforming public health surveillance. This trend allows for the continuous monitoring of health data through integration with wearable devices, hospital records, and environmental sensors. During public health crises, real-time data can be used to track disease outbreaks, monitor air quality, or assess hospital capacity [12]. In the case of infectious disease outbreaks like COVID-19, real-time GIS mapping enables dynamic decision-making by providing up-to-date information on disease spread, vaccination coverage, and resource allocation. This ability enhances the efficiency of public health responses by allowing immediate intervention where it's needed most.

Big data analytics

The integration of big data analytics with GIS enables the processing and analysis of massive datasets from diverse sources, including electronic health records (EHRs), genomics, and social determinants of health. By incorporating multi-layered health data, GIS systems can provide more comprehensive insights into public health trends and patterns [71]. This combination allows healthcare providers to understand disease patterns at a more granular level, facilitating personalised healthcare interventions. For example, spatial data analysed alongside genetic information can predict disease susceptibility in specific populations, improving precision medicine approaches.

Cloud-based GIS platforms

Cloud-based GIS platforms are enabling more accessible and scalable healthcare data analysis. These platforms provide the capacity to store and process large amounts of spatial data without requiring significant on-site infrastructure [74]. Cloud-based systems facilitate collaboration among healthcare organisations by allowing data to be shared more easily across different regions and institutions. This capability enhances large-scale epidemiological studies and cross-regional health interventions. The cloud-based GIS can support regional health departments in sharing spatial data to monitor disease patterns and collaborate on broader public health strategies.

The integration of machine learning, real-time data mapping, big data analytics, and cloud-based GIS platforms represents the future of GIS technology in healthcare. These advancements promise to transform public health monitoring, disease prevention, and healthcare delivery by enabling more accurate, timely, and scalable analysis of complex health data.

A few major shortcomings of incorporating GIS in healthcare research in India were identified. *First,* the majority of the studies were post-outbreak investigations focused on analysing the spread and impact of a disease outbreak. There is a lack of studies that could use spatial modelling to identify and predict the location of any potential outbreak in the future. *Second,* most studies are confined to common diseases such as malaria, lymphatic filariasis, and COVID-19, whereas GIS techniques can be utilised to study several infectious and non-infectious diseases, such as cardiovascular diseases, cancer, chronic kidney disease, and thyroid disorders. *Third,* there is a lack of technical expertise. Obtaining GIS data is the least time-consuming but requires technical skills to retrieve, store and analyse it. Most studies have used ArcGIS software to map and analyse the spatial distribution of diseases. However, many of these studies failed to utilise its capabilities for more complex analyses beyond mapping. Similarly, other concerns, such as privacy, informed consent, data accuracy and ownership arise when a GIS is used in health research in India. Addressing these challenges requires more efforts to expand the scope of studies using advanced GIS, develop technical expertise, improve spatial data infrastructure, availability and transparency, and ultimately ensure robust data governance.

Conclusion

This study has attempted to critically review different GIS and spatial analysis applications in Indian health research, emphasising their importance in representing and analysing the incidence of diseases. GIS analysis provides not only useful maps for spatial patterns and clusters but also insight into epidemiological linkages with potential risk factors and outbreaks of various diseases. Different studies have revealed many aspects of health risk, mostly related to water resources. Some studies have used GIS to assess physical accessibility. However, none of these investigations provides information about the quality of healthcare since the GIS necessarily emphasises accessibility and the geographical dimension of access. Socioeconomic factors are not included within their model framework to assess feasibility and cost. Researchers have engaged in developing and applying spatial analytical approaches, mainly in disease mapping. The review underscores the need to be more focused on assessing health risks or evaluating the spatial inequalities of access to healthcare. Some reviews [72] have explored the use of GIS and spatial analysis in health research, focusing on the context of COVID-19. Mapping hotspots of COVID-19 was the most employed operation identified in this review. However, there have been recent shifts towards integrating advanced spatial analysis and real-time data management.

The application of GIS techniques in health and disease mapping has gradually increased (Fig. 2) after the advent of the COVID-19 pandemic. Studies conducted during the first wave of COVID-19 helped to implement control measures more effectively during the second wave. The use of the GIS in health studies can be summarised as identifying areas where a particular disease is prevalent, performing disease zonation mapping, identifying vulnerable populations at risk, examining factors responsible for diseases, locating health care centres and assisting in policy and decision-making.

This article not only lists various GIS and spatial analysis applications in health but also identifies some existing gaps. Even though GIS has witnessed a growing scope in recent times, the tool has not yet been used to its full potential in Indian health systems. Understanding the different applications of GIS in addressing health problems from a geographical perspective is critical to healthcare planning and management, which is why such work is being done.

The literature (Table 2) on GIS applications in healthcare highlights significant gaps in addressing ethical concerns. While GIS offers powerful tools for enhancing healthcare delivery and public health outcomes, it is crucial to integrate stringent ethical standards to ensure its responsible and equitable use. Future research should focus on explicitly addressing these ethical considerations to harness the full potential of GIS technology in a manner that benefits all stakeholders.

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Authors' contributions
Anupama Chandran contributed to the conception, acquisition, analysis, and interpretation of the data and drafted the manuscript; Pankaj Roy wrote the main manuscript text and prepared Figs. 1 and 2. He reviewed it thoroughly, redesigned the work, made necessary corrections and substantively revised the manuscript several times.

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