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Review Article

Spatial Analysis of COVID-19 Case Clusters and Vaccination Gaps in Sri Lanka: A Spatial Review of COVID-19 Trends in Colombo District, Sri Lanka

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Abstract

This review examines how spatial analysis techniques have been applied globally and locally to understand COVID-19 transmission and vaccine accessibility, with a focus on the Colombo District of Sri Lanka. The COVID-19 pandemic revealed critical vulnerabilities in public health systems, particularly in densely populated urban regions. This review examines the role of spatial analysis in understanding and addressing COVID-19 transmission and vaccination accessibility in Sri Lanka, with a specific focus on the Colombo District. Drawing on global and national literature, the study explores how Geographic Information Systems (GIS), spatial statistics, and remote sensing were employed to map infection clusters, analyze social vulnerability, and identify gaps in health service delivery. Spatial tools such as Kernel Density Estimation (KDE), Getis-Ord Gi*, and network accessibility models were instrumental in highlighting persistent clusters in socioeconomically disadvantaged neighborhoods. The review also assesses how spatial planning informed the deployment of mobile vaccination units to underserved areas, to overcome geographical and digital barriers. Finally, the paper offers strategic policy recommendations to institutionalize spatial epidemiology within Sri Lanka's public health governance, advocating for the integration of real-time GIS dashboards, centralized geospatial health units, and capacity building for health professionals. The findings underscore the transformative potential of spatial intelligence in pandemic preparedness, response, and equity-focused health planning. This review synthesizes previously published data and findings and official dashboards.

Introduction

The outbreak of COVID-19 in late 2019 rapidly evolved into a global pandemic, severely affecting healthcare systems, economies, and societal functions across the world [1]. The novel coronavirus (SARS-CoV-2) posed a unique threat due to its high transmission rate, asymptomatic carriers, and rapid mutation into new variants such as Delta and Omicron Zhu, et al. 2020; Wu, et al. 2020. Urban areas characterized by high population density, inadequate housing, and complex mobility patterns, became epicenters of the disease [2], Sun, et al. 2020.

Colombo District, as the administrative and commercial capital of Sri Lanka, reported among the highest COVID-19 infection rates in Sri Lanka. The region's complex urban fabric—including informal settlements, densely populated zones, and major transportation hubs—contributed to rapid viral transmission and public health burden during multiple COVID-19 waves [3,4]. Health authorities frequently faced challenges such as limited testing capacity, hospital overcrowding, and uneven distribution of vaccination services [5].

In this context, spatial analysis became critical in understanding the spread and control of COVID-19. Geographic Information Systems (GIS) and spatial statistics have been widely applied globally to detect infection hotspots, assess healthcare infrastructure, and visualize real-time transmission dynamics [6-8]. Tools such as Kernel Density Estimation (KDE), spatial autocorrelation, Getis-Ord Gi*, and spatial accessibility indices have allowed public health authorities to identify high-risk zones, optimize resource allocation, and plan targeted interventions [9,10](Tables 1,2).

In Sri Lanka, institutions such as the Health Promotion Bureau and various universities developed spatial dashboards

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and mapping tools to support pandemic response. These systems facilitated the identification of underserved areas, planning of mobile vaccination units, and management of hospital resource distribution [11-13].

This review paper seeks to consolidate existing global and national literature related to spatial analysis in COVID-19 management, with a specific emphasis on Colombo District. The aim is to evaluate methodological approaches, highlight practical applications, and suggest how spatial tools can be better integrated into Sri Lanka's pandemic preparedness and response frameworks (Table 3).

Methodological framework

The methodological approaches discussed are drawn from existing global and national studies, no primary spatial data analysis was performed in this review. The use of geospatial technologies, including Geographic Information Systems (GIS), remote sensing, and spatial statistical methods, has played a pivotal role in the study of COVID-19 transmission dynamics. Globally, these tools have supported a wide array of epidemiological applications such as mapping disease incidence, identifying hotspots, analyzing environmental risk factors, and assessing the accessibility of healthcare services [8,10].

One of the most widely used spatial analysis techniques during the pandemic is Kernel Density Estimation (KDE), which produces continuous surface maps indicating areas of high event concentration. For instance, KDE has been applied in the United States to identify spatial clusters of COVID-19 at the county level, providing critical inputs for targeted interventions Zhou, et al. 2020. In Brazil, KDE helped public health authorities monitor urban slums (favelas) where traditional surveillance methods were difficult to apply [14]. In Sri Lanka, KDE was effectively used to map case clusters in high-density regions of Colombo, including Maradana, Borella, Dematagoda, and Grandpass—areas characterized by a mix of commercial and low-income residential zones [15].

Getis-Ord Gi* and Moran's I are other spatial statistical techniques employed to assess spatial autocorrelation and determine statistically significant hotspots and cold spots of infection. These methods have been used in India, China, and Italy to reveal the spatial dependence of case incidence and guide containment strategies [7,9]. In the Sri Lankan context, such techniques have the potential to improve micro-level planning at the Grama Niladhari (GN) Division level, especially in rapidly urbanizing regions of Colombo.

Remote sensing data, including night-time lights, vegetation indices (e.g., NDVI), and Land Surface Temperature (LST), have also been integrated into spatial models to evaluate environmental and urban risk factors associated with viral transmission. Studies in India and China demonstrated correlations between lands cover changes, pollution levels, and COVID-19 incidence, suggesting the utility of satellite data in health vulnerability mapping [16] Sannigrahi, et al. 2020. In Sri Lanka, although underutilized, Sentinel-2 and Landsat imagery may be employed to monitor lockdown effectiveness or urban density indicators.

Network analysis and spatial accessibility modeling have been applied to examine inequalities in the distribution of healthcare facilities and vaccination centers. For instance, the Two-Step Floating Catchment Area (2SFCA) method and cost-distance analysis were used in the Philippines and Bangladesh to assess travel time to COVID-19 treatment centers [17,18]. In Colombo, preliminary studies showed that populations living in peripheral urban areas like Kolonnawa and Homagama faced mobility barriers due to limited public transport and digital registration systems [12]. The use of OpenStreetMap data combined with GPS travel surveys can further enhance spatial accessibility assessments in future applications.

Table 1: Status of COVID-19 during 27.01.2020 - 27.11.2023.

Status of COVID		
Confirmed Cases	672,629	
Recovered	655,741	
Total Death	16,888	Male - 9,521
		Female - 7,367

(Source: COVID-19 Epidemiological Report – Sri Lanka, Epidemiological Unit, Ministry of Health).

Table 2: Summary of COVID-19 Status during Waves 1, 2, and 3.

Duration	No. of cases	No. of Deaths	Case Fatality Rate
1st wave 27.01.2020-03.10.2020	3,396	13	0.38
2nd wave 04.10.2020-14.04.2021	92,341	591	0.64
3rd wave 15.04.2021-31.12.2022	576,434	16,238	2.81

(Source: COVID-19 Epidemiological Report – Sri Lanka, Epidemiological Unit, Ministry of Health).

Table 3: Status of Vaccination during 27.01.2020 - 30.04.2023.

COVID-19 Vaccination	
Astra Zeneca Vaccine	
1st dose	1479,631
2nd dose	1,418,593
Sino pharm Vaccine	
1st dose	12,054,824
2nd dose	11,267,138
1st dose	159,110
2nd dose	155,812
Pfizer	
1st dose	2,645,395
2nd dose	1,123,923
1st Booster dose	8,220,002
2nd Booster dose	202,571
Moderna	
1st dose	804,801
2nd dose	787,361

(Source: COVID-19 Epidemiological Report – Sri Lanka, Epidemiological Unit, Ministry of Health).

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Additionally, spatio-temporal modeling approaches such as SaTScan and time-series kriging have been used to capture the dynamic evolution of case spread over time [6]. These techniques allow researchers to assess the lag effect of policy interventions such as curfews or travel bans and to identify emerging clusters in near real-time.

Data for these analyses are typically sourced from national health surveillance systems, census databases, and real-time dashboards. In Sri Lanka, the Ministry of Health, Epidemiology Unit, and Department of Census and Statistics provided vital demographic and epidemiological datasets. The Health Promotion Bureau's dashboard, which combined administrative-level case reports with hospital availability data, served as a cornerstone for national spatial decision-making.

In summary, the methodological framework for spatial analysis of COVID-19 in Colombo and globally incorporates a rich blend of statistical tools, remote sensing inputs, and network-based accessibility modeling. These techniques, when integrated with public health infrastructure and governance, form a robust toolkit for epidemiological intelligence and pandemic preparedness (Figure 1).

Case clusters in Colombo district

Drawing upon published sources and government reports, this section reviews spatial patterns of COVID-19 transmission observed in Colombo. The Colombo District, home to Sri Lanka's commercial and administrative capital, was one of the most severely affected regions during the COVID-19 pandemic. The high incidence of COVID-19 cases in Colombo was closely associated with population density, socio-economic disparities, housing conditions, and mobility networks. Urban settlements characterized by overcrowding, informal housing, and inadequate sanitation provided conditions conducive to rapid viral transmission [19].

A spatial analysis of case data between March 2020 and December 2021 indicated that the northern, central, and eastern parts of Colombo—particularly in Colombo North, Borella, Slave Island, Maradana, Grandpass, and Dematagoda—experienced repeated clustering of infections. These areas are home to a significant proportion of low-income households, migrant workers, congested housing complexes, and highly interactive commercial hubs [4,15]. For example, during the second wave in late 2020, Colombo North recorded over 25% of the district's total new cases within a span of three weeks, with market vendors and public transit users identified as primary vectors [3] (Figure 2).

The real-time dashboard developed by the Sri Lanka Health Promotion Bureau enabled the visualization of GN-division level outbreaks and supported decision-makers in allocating isolation centers and COVID-19 treatment units. This dashboard integrated Ministry of Health case reports, GIS location data, and population distribution layers, enabling real-time micro-level surveillance [11]. It was particularly instrumental in managing outbreaks at institutional settings like factories, religious gatherings, and congested housing schemes in areas such as Mattakkuliya and Wanathamulla.

Furthermore, spatio-temporal analysis performed by Amarasinghe, et al. [13] confirmed that many of the case clusters persisted over multiple months, indicating long-term

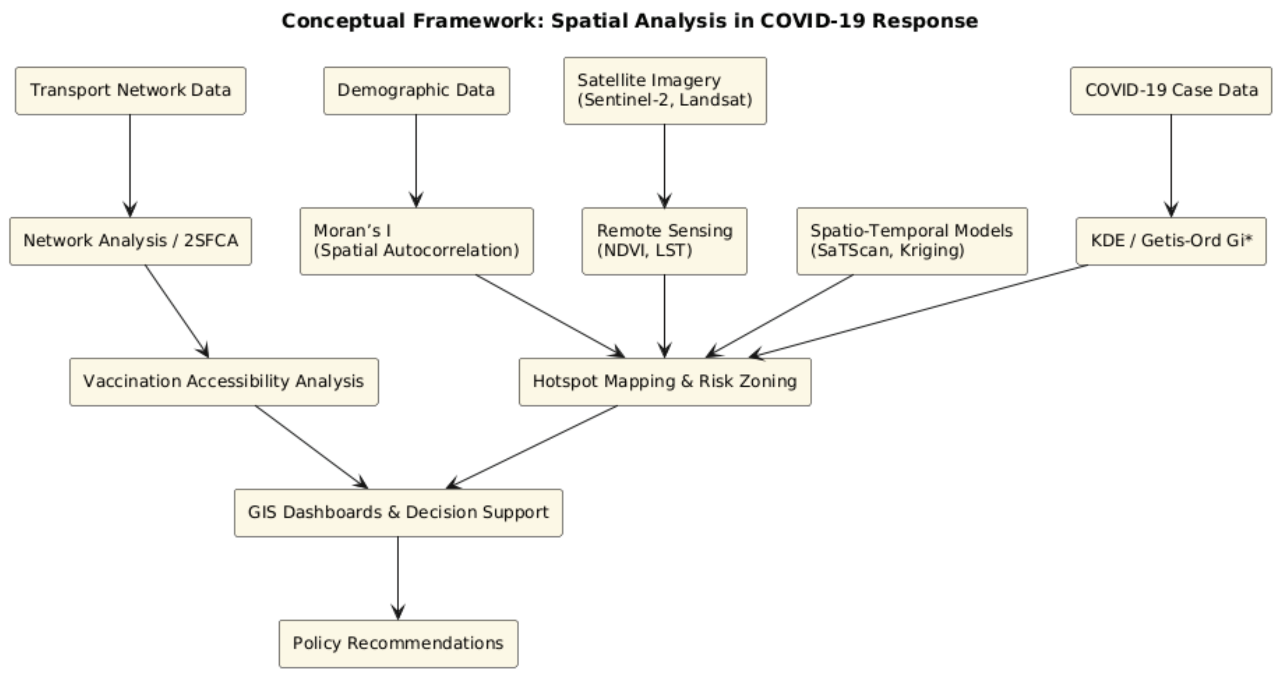

Figure 1: Conceptual Framework for Spatial Analysis of COVID-19 in Colombo District. This diagram summarizes the integration of key spatial data sources and analytical tools used in the COVID-19 context. The framework illustrates how Geographic Information Systems (GIS), spatial statistics, remote sensing, and network models were applied to identify infection hotspots, analyze vaccination accessibility, and inform public health policies in Colombo District.

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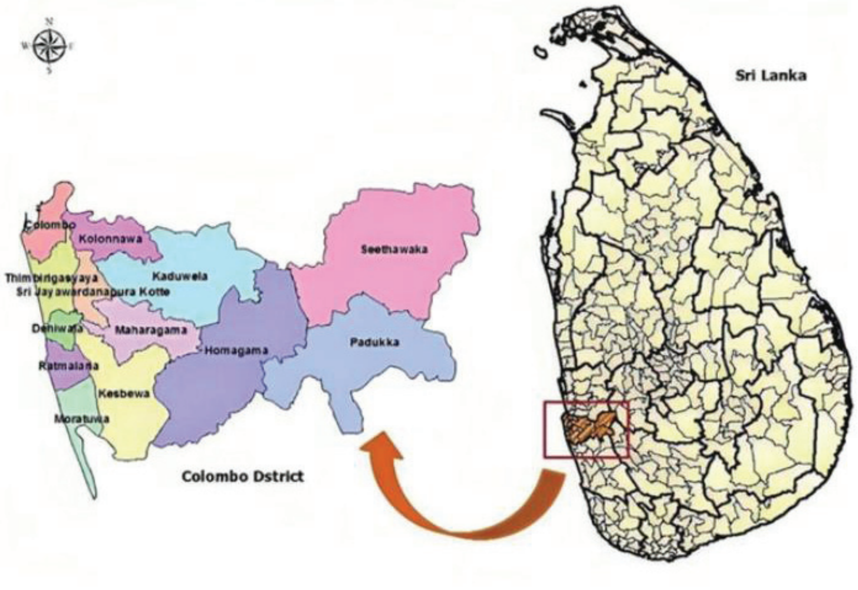

Figure 2: Divisional Secretariat Map of Colombo District.

vulnerability rather than transient outbreaks. The persistence of these clusters aligned with indices of social vulnerability, such as lack of access to piped water, high dependency ratios, and informal employment [19]. These findings mirror international experiences, such as the Dharavi slum in Mumbai and Kibera in Nairobi, where structural poverty amplified COVID-19 transmission despite national containment efforts [20,21].

Field surveys and spatial correlation analyses also demonstrated that Colombo's high-risk clusters overlapped with zones of poor health service accessibility, reinforcing the need for localized interventions. For instance, GN Divisions like Mahawatta and Wanathamulla had minimal access to walk-in testing centers or public hospitals during the height of the outbreak, exacerbating undetected community spread [22].

In addition to permanent settlements, transient and mobile populations—such as construction workers, port laborers, and tuk-tuk drivers—contributed to inter-divisional transmission, as observed in GIS mobility overlays during curfew relaxations. The integration of mobility data sources (e.g., Google Community Mobility Reports) with confirmed case data helped public health officials understand the spatial reach of cluster outbreaks beyond initial epicenters [23].

Overall, this case study illustrates how urban inequalities, spatial congestion, and limited infrastructure collectively shaped the geography of COVID-19 risk. The identification of such clusters enabled more efficient zoning policies, lockdown strategies, and mobile healthcare deployments—lessons that remain vital for managing future infectious disease threats in Sri Lankan urban environments

Vaccination accessibility disparities

Despite the commendable efforts of national governments to implement mass vaccination programs against COVID-19, significant geographic and socio-economic disparities in vaccine accessibility have been documented worldwide—including in Sri Lanka. Spatial disparities often reflect broader structural inequities such as income level, urban infrastructure, population density, digital connectivity, and transport availability [24].

In Sri Lanka, while Colombo District benefited from early vaccine availability due to its urban status and administrative priority, peripheral urban and semi-urban localities faced substantial challenges in accessing vaccination services. GIS-based overlay analysis conducted by Weerakoon, et al. [12] revealed the existence of "vaccine deserts"—areas with poor proximity to vaccination centers—particularly in the outer regions of Kolonnawa, Homagama, and Kottawa. These areas, often inhabited by informal workers and underserved populations, lacked adequate fixed vaccination facilities and faced logistical challenges in reaching the nearest centers.

A key barrier to equitable access was the reliance on online registration portals for vaccine appointments. As highlighted by WHO Sri Lanka [5], many elderly individuals, daily wage earners, and slum dwellers lacked smartphones, internet access, or digital literacy, resulting in exclusion from initial vaccination phases. Furthermore, public transport limitations during lockdowns exacerbated physical inaccessibility, particularly for those residing far from central bus and rail corridors.

Global case studies echo similar patterns. In India, GIS mapping in the state of Maharashtra identified low vaccination rates in marginalized tribal belts and urban slums due to administrative neglect and logistical hurdles [25]. A study in Brazil by Santos, et al. [14] used spatial clustering and 2SFCA accessibility models to demonstrate that wealthier urban neighborhoods received earlier and higher vaccine coverage

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than favelas and peripheral areas. These insights reinforced the need for equity-focused spatial planning in vaccine deployment.

In response to such disparities, Sri Lankan authorities—particularly in partnership with Municipal Councils and local health officers—introduced mobile vaccination units guided by spatial analytics. GIS platforms such as ArcGIS Online were utilized to overlay demographic density maps, case clusters, and existing health facility locations to identify gaps in coverage. These mobile units were deployed in high-risk and hard-to-reach zones such as Wanathamulla, Mattakkuliya, and urban housing complexes in Borella and Dematagoda [13].

In addition, spatial accessibility modeling techniques—including cost-distance analysis and network-based service area mapping—were employed to assess travel time to the nearest vaccine centers. Rahman, et al. [17] applied these techniques in South Asia to recommend optimal placement of new temporary centers. In Colombo, such methods could be replicated using OpenStreetMap data, transportation routes, and census-based population layers to improve service equity.

Importantly, the implementation of community outreach programs in collaboration with religious organizations, Grama Niladhari officers, and Public Health Inspectors (PHIs) proved effective in encouraging vaccination uptake in underserved areas. These locally tailored interventions, when aligned with spatially identified priority zones, improved vaccine delivery efficiency and reduced community resistance.

Gender-based disparities in vaccination accessibility were also evident. Women, especially in Muslim and Tamil minority areas of Colombo North and East, faced cultural and logistical barriers in accessing public vaccination centers [26]. Integrating gender-sensitive spatial planning—such as providing female-staffed mobile clinics and adjusting operating hours—was essential to overcoming these obstacles.

Overall, the integration of spatial tools in Sri Lanka's vaccination rollout has demonstrated the potential of data-driven, location-specific strategies in overcoming accessibility challenges. These approaches not only improve current health outcomes but also lay the foundation for more resilient and equitable health service delivery systems in the future

Policy implications and recommendations

The COVID-19 pandemic has underscored the critical need to integrate **spatial epidemiology** into mainstream public health decision-making. GIS-based technologies—when linked with real-time case surveillance, demographic databases, and mobility trends—offer powerful insights into outbreak patterns, resource gaps, and high-risk populations. However, for these tools to have a lasting impact, institutional adoption and capacity-building are imperative [10,27].

Globally, several countries have demonstrated the transformative role of spatial analysis in pandemic governance. South Korea's real-time contact tracing and exposure mapping system significantly reduced response times during outbreaks [28]. In the United States, Johns Hopkins University's COVID-19 Dashboard became the gold standard for global case tracking and informed federal and state-level policy responses [29]. In India, the CoWIN portal integrated GIS data to guide vaccine distribution, while Brazil deployed vulnerability mapping to prioritize slum interventions [14].

In Sri Lanka, although spatial tools were used effectively by institutions such as the Health Promotion Bureau and local research teams, their integration into national health policy and disaster management frameworks remains limited. The response to the pandemic revealed several bottlenecks in geospatial data coordination, workforce training, and inter-agency collaboration. These gaps present opportunities for structural reform. Based on the evidence reviewed, the following policy recommendations are proposed:

Institutionalize GIS-based surveillance within the national public health system

Sri Lanka should establish a centralized geospatial health unit under the Ministry of Health, linked to the Epidemiology Unit, Disaster Management Centre, and Department of Census and Statistics. This unit should coordinate the development and maintenance of national spatial databases on communicable diseases, healthcare infrastructure, and demographic vulnerabilities.

For example, Thailand's Department of Disease Control maintains an integrated GIS-based Early Warning and Response System (EWARS) that automatically flags disease clusters [30].

Develop and Deploy real-time GIS dashboards and Spatial Decision Support Systems (SDSS)

Local government authorities (e.g., Municipal Councils) should be empowered with customized dashboards that display real-time COVID-19 metrics, hospital capacity, vaccination progress, and localized risk indicators. SDSS platforms should be incorporated into emergency response protocols for dynamic resource allocation.

Example: In New York City, the COVID-19 Neighborhood Health Dashboard provided borough-level metrics to guide vaccine center placement and community outreach [31].

Optimize health facility siting and outreach planning through spatial analysis

GIS tools should be used routinely in locating new healthcare facilities, mobile vaccination units, and temporary treatment centers, especially in underserved areas. Multi-Criteria Decision Analysis (MCDA) integrated with GIS can help identify priority zones based on travel time, population density, and social vulnerability.

For instance, Rahman, et al. [17] employed 2SFCA models in Bangladesh to propose optimized locations for COVID-19 treatment centers in urban slums.

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Strengthen interagency data sharing and open Geospatial data infrastructure

A national geospatial health data sharing framework is needed to facilitate interoperability between ministries, universities, NGOs, and international partners. Data formats, metadata standards, and privacy safeguards must be clearly defined to ensure ethical use of geospatial health information.

Example: The African CDC developed a continent-wide Health GeoPortal that integrates data from member states into a harmonized platform for disease monitoring and response [32].

Build capacity in spatial data analytics within the public health workforce

A national capacity development strategy should be introduced to train public health officials, epidemiologists, and urban planners in GIS software (e.g., QGIS, ArcGIS), remote sensing, and spatial statistics. Partnerships with universities and international agencies can provide curricula, workshops, and certifications.

Example: The Philippine Department of Health partnered with the WHO and the University of the Philippines to offer GIS training for COVID-19 response teams in all regional offices [33].

Integrate spatial tools into national emergency and urban planning policies

Beyond the health sector, spatial tools should be embedded in urban development, transportation, and housing policies to address the social determinants of pandemic vulnerability. Risk-sensitive land use planning and climate-resilient urban infrastructure can mitigate future outbreaks.

Example: Colombo's Megapolis Plan can incorporate epidemic risk maps into zoning laws and transportation planning, guided by spatial epidemiology.

Conclusion

As a review, this paper aggregates and analyzes secondary sources to highlight the role of spatial tools in public health planning, especially within the Colombo context. The COVID-19 pandemic has demonstrated the indispensable role of spatial analysis in understanding, managing, and mitigating public health emergencies. Across the globe, Geographic Information Systems (GIS), spatial statistics, and remote sensing have been central to identifying disease transmission hotspots, planning equitable vaccine distribution, and guiding targeted interventions. In the case of Sri Lanka—and particularly within the Colombo District—spatial tools offered critical insights into spatial patterns of vulnerability, enabling more responsive and localized public health actions.

The review highlighted the application of spatial methods such as Kernel Density Estimation (KDE), Getis-Ord Gi*, network analysis, and accessibility modeling were applied to map and monitor COVID-19 clusters in Colombo's urban core. These analyses revealed persistent correlations between case incidence and factors such as informal settlements, population density, limited healthcare access, and social vulnerability. Moreover, the integration of real-time GIS dashboards helped visualize outbreak dynamics and prioritize resource allocation, laying the groundwork for data-driven pandemic governance.

The investigation of vaccination accessibility further underscored spatial inequities in health service delivery. These disparities, driven by digital exclusion, transport constraints, and geographic remoteness resulted in "vaccine deserts" even within a relatively urbanized region like Colombo. GIS-enabled mobile vaccination strategies, when effectively deployed, demonstrated the effectiveness of spatially informed outreach in addressing these disparities—especially for marginalized populations.

From a policy perspective, the findings make it unequivocally clear that spatial intelligence must be institutionalized within Sri Lanka's public health infrastructure. Global case studies—from South Korea to Brazil—emphasize the long-term benefits of embedding GIS platforms, spatial data integration, and trained personnel into national emergency preparedness systems. In Sri Lanka, the creation of a centralized geospatial health unit, development of spatial decision support systems, and mainstreaming of spatial tools into urban planning and disaster risk management could dramatically enhance resilience to future epidemics.

In conclusion, this review illustrates the strategic importance of spatial analysis in health planning but a transformative public health enabler. By adopting a geographically nuanced lens, policymakers and practitioners can better anticipate outbreak dynamics, reduce health disparities, and build a more equitable and responsive healthcare system. As Sri Lanka prepares for future health challenges, integrating geospatial technologies into public health planning, surveillance, and service delivery will be key to building an adaptive, inclusive, and scientifically informed public health future.

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