International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

GIS-Based Assessment of Potential Biomedical Waste Hotspots and Environmental Health Risk During the COVID-19 Pandemic, Gwalior

Indrani Mukherjee[1], Dr. Aabha Varshney[2]

[1]Research Scholar, [2]HOD,
[1,2]K.R.G College, Gwalior, Madhya Pradesh

1. Introduction

The COVID-19 pandemic placed unprecedented pressure on healthcare systems worldwide, and it also, in a major way, increased the generation of biomedical waste. During the whole outbreak period, the widespread use of personal protective equipment (PPE), plus diagnostic materials, vaccination supplies, and a bunch of other disposable medical products, led to a notable jump in infectious and hazardous healthcare waste (Bagwan, 2023; Lestari et al., 2025). So, managing biomedical waste effectively turned into a key public health issue, because if disposal is done in the wrong way, or if transportation, treatment, or final removal is not managed properly, it could help spread disease, and also worsen environmental conditions. In developing countries, this problem becomes even more complicated, since health care infrastructure and waste treatment facilities are often under strain already, and the sudden increase in biomedical waste production revealed major difficulties in maintaining safe and sustainable waste management routines (Bagwan, 2023).

Biomedical waste can pose real risks to environmental and human health through several ways of exposure, and it can happen indirectly, too. If disposal practices are not done the right way, air, water, and soil resources can get contaminated, while healthcare workers, waste handlers, and even people living nearby may come into contact with infectious materials and other hazardous pollutants (Joyosemito et al., 2025; Widjaja, 2026a). These worries became more noticeable during the COVID-19 pandemic, mostly because the amount of waste generated was unprecedented, and disposal had to be done quickly. So, knowing the spatial distribution of biomedical waste, along with figuring out where waste generation is more concentrated, is very important for lowering environmental health risks and also for backing up management interventions that actually work.

Geographic Information Systems (GIS) provide a useful platform for looking at and showing spatial patterns tied to environmental as well as public health concerns. During the COVID-19 pandemic, GIS was used a lot for disease surveillance, risk mapping, healthcare organizing, and also resource distribution (Ahasan et al., 2022; Samany et al., 2022). When we talk about spatial analytical approaches like Kernel Density Estimation (KDE), Moran's I spatial autocorrelation, and Getis–Ord Gi* hotspot analysis, these have shown they work well for finding geographic clusters, and for checking how spatial variability changes in the level of risk (Rahman et al., 2021; Soni et al., 2023). If we combine those methods with biomedical waste data, it can help point toward "hot" or high-risk locations, and in turn support more data-driven environmental management, which is the whole idea.

Gwalior, as a big urban hub in Madhya Pradesh, saw quite a lot of healthcare-related activity during the COVID-19 pandemic, and it does look like a key place for understanding how biomedical waste is produced and what it does to the environment. Looking at how biomedical waste is spread across space and linking that with environmental health risks can give useful clues for city planning, waste management, and also for protecting public health. So, in this study, we aim to evaluate biomedical waste hotspots along with the environmental health risks during the COVID-19 period by using GIS-based spatial analysis methods. More specifically, we want to produce maps of where biomedical waste generation happens, point out the hotspot zones, check for spatial clumping or clustering patterns, and then demarcate environmental health risk areas in Gwalior city.

2. Review of Literature

2.1 Biomedical Waste Generation During the COVID-19 Pandemic

Due to the COVID-19 pandemic, there has been an enormous increase in the generation of biomedical waste globally as a result of the large amount of personal protective equipment (PPE), testing kits, syringes, chemicals, and other types of disposable health care products that were needed or used (Lestari et al., 2025). The rapid development of new health care services, isolation facilities, vaccination programs, and diagnostic activities caused a very large increase in the amount of infectious waste that needed to be properly collected, treated, and safely disposed of. This increase has created a tremendous strain on existing waste disposal systems and treatment facilities, particularly in many (developing) countries where the ability of the existing facilities to process and monitor waste is often insufficient (Bagwan, 2023).

The production of biomedical waste caused by the COVID-19 pandemic has led to significant problems for both the environment and public health. Waste from improper disposal and oversight of biomedical waste can lead to contamination of air and water systems, increased exposure to the infectious agents present in the biomedical waste of both workers and the general population and create environmental hazards which are pollutants (Joyosemito et al., 2025; Widjaja, 2026a; Widjaja, 2026b). Another area of concern identified in related studies has been the environmental impacts of biomedical waste disposal processes with regard to emissions from medical waste incinerators and their potential impacts on surrounding communities (Joyosemito et al., 2025). The concentration and proximity of healthcare facilities to the density of the urban population may exacerbate the quantity of biomedical waste produced and the vulnerability of the environment (Lestari et al., 2025).

In recent studies, there is a focus on the integration of environmental monitoring and spatial analysis into biomedical waste management systems to support informed decision-making and reduce risk (Bagwan, 2023; Lestari et al., 2025; Widjaja, 2026a). Therefore, understanding both the spatial distribution and potential environmental impact of biomedical waste is critical to improving public health through preparedness for pandemics and promoting environmental sustainability during and after pandemic-related events.

2.2 GIS Applications in Pandemic and Health Research

Geographic Information Systems (GIS) are often used to help study, monitor, and respond to issues related to health and the environment by allowing users to connect, analyze, and display information with a spatial component. In health research, GIS has been extensively used for disease surveillance, evaluating how people can access care, providing information about the health of the environment, distributing resources, and modeling how diseases are transmitted (Manjunatha et al., 2024; Chandran & Roy, 2024). The use of GIS technology has become increasingly evident during the COVID-19 pandemic, as it has provided support for evidence-based decision-making and planning during emergencies in the area of public health.

Studies related to many forms of GIS have looked at how various diseases are transmitted, who is vulnerable to them according to their location, how disease outbreaks progress over time, and how health care facilities are impacted by the ongoing pandemic (Ahasan et al., 2022; Samany et al., 2022; Huang et al., 2022). Different geospatial analyses have been performed to assess the risk from COVID-19 across a range of different spatial scales to inform targeted response measures and the allocation of health care resources (Rahman et al., 2021; Usman et al., 2021). Furthermore, many studies of GIS have provided evidence for the value of a GIS-based multi-criteria decision-making framework in assisting with risk assessment and prioritization of those communities or areas most in need of immediate support during health crises (Soni et al., 2023).

In addition to analyzing disease proliferation, GIS has played an increasingly important role in programs related to environmental management and waste. Spatial technologies have allowed for monitoring hazardous waste sites, routing medical waste collection, evaluating environmental risk, and planning for sustainable waste management (Cahyadi & al., 2023; Lestari & al., 2025). GIS can integrate multiple variables, including those related to the environment, population, and infrastructure, resulting in comprehensive spatial analyses. Therefore, GIS provides a strong basis for assessing the distribution of biomedical waste and evaluating the environmental health effects in those areas using biomedical waste.

2.3 GIS-Based Hotspot Analysis and Environmental Health Risk Assessment

Geographic Information Systems (GIS) have been extensively utilized as a means of applying spatial analytical methods to locate geographic clusters of events, evaluate the spatial variation across locations, and facilitate decision-making based on identified risks. A number of the GIS-based analytical methods that are frequently used to identify spatially clustered events and statistically significant hotspots of environmental and public health-related phenomena are Kernel Density Estimation (KDE), Moran's I spatial autocorrelation, and Getis–Ord Gi* hotspot analysis (Afolayan et al., 2022; Feizizadeh et al., 2022). These methods provide useful means for the identification of spatial locations exhibiting disproportionately high degrees of risk and for creating an opportunity for targeted management interventions.

Hotspot analysis and spatial risk modeling are widely used to analyze how COVID-19 spreads, where people are most vulnerable to the virus, and any public health risks associated with the spread of COVID-19 (Rahman et al., 2021; Soni et al., 2023). Similarly, the use of GIS-based multi-criteria assessments for spatial risk assessments and prioritization of at-risk areas has been applied to develop integrated spatial risk assessments by using environmental, demographic, and infrastructure data (Hariz et al., 2017; Soni et al., 2023). Many environmental-based studies have used GIS techniques to assess hazardous waste sites and the potential pollution risks and exposure patterns associated with human activities in urban areas (Lestari et al., 2025; Agarwal et al., 2023).

The combination of hotspot analysis with environmental health assessments creates a unique opportunity to examine the relationship among waste production, environmental vulnerability, and potential human exposure over space. The combined use of these two approaches will help identify areas that need to be monitored and will improve the effectiveness of both environmental management and public health planning activities.

2.4 Research Gap and Conceptual Framework

According to the literature reviewed, there is significant research on the production of biomedical waste resulting from the COVID-19 pandemic, geographic information systems (GIS) in public health, and spatial risk assessment. Studies conducted indicate that COVID-19 has caused a large increase in the production of biomedical wastes and that there are many difficulties associated with disposing of these wastes and managing them environmentally (Bagwan, 2023; Lestari et al., 2025; Joyosemito et al., 2025). Similarly, many studies have demonstrated that GIS-based applications have been used to conduct disease surveillance, mapping of vulnerable populations, healthcare planning, and respond to pandemics (Ahasan et al., 2022; Samany et al., 2022; Huang et al., 2022).

Research that includes a review of spatial analysis techniques such as Kernel Density Estimation (KDE), Moran's I, Getis–Ord Gi* hotspot analysis, and GIS-based multi-criteria analysis for identifying spatial clusters/risk zones has successfully identified spatial clusters/risk zones (Rahman et al., 2021; Soni et al., 2023; Afolayan et al., 2022; Hariz et al., 2017). On the contrary, the majority of the studies reviewed focus on the dynamics of COVID-19 transmission, accessibility to healthcare, hazardous waste management, or environmental risk assessment in general. There has been little research pertaining to the spatial assessment of biomedical waste hotspots in urban environments and their impact on public health during the pandemic period.

Studies about using Geographic Information Systems (GIS) for health and environmental research have been increasing; however, there is still not much research combining all three of these fields—biomedical waste production, identifying hotspots, and assessing the risks to environmental health—into one analytical framework. An example of this is Gwalior, Madhya Pradesh, where little spatial data is available for biomedical waste and the associated risks to environmental health from producing this type of waste.

To fill this gap, the current study uses a GIS framework to assess biomedical waste hotspot locations and their associated environmental health risks during the COVID-19 pandemic. This study is based upon the premise (conceptual framework) that increased healthcare utilization during the pandemic has resulted in an increase in the amount of biomedical waste generated, which may have created spatial concentrations of debris/biomedical waste and subsequently increased environmentally related health risks. The overall goal of this research is to provide an overall understanding of the environmental vulnerability to biomedical waste in Gwalior through mapping the spatial distribution of biomedical waste, identifying the locations of hotspots, clustering of hotspot locations, and determining environmental risks.

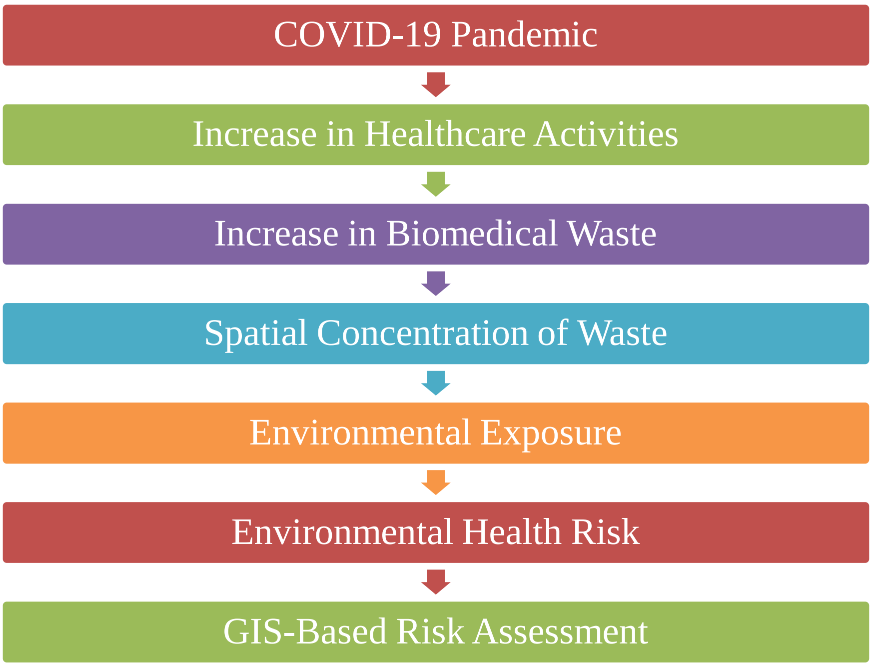

Figure 1: Conceptual framework

3. Study Area

Gwalior, in northern Madhya Pradesh (India), is a major city in that state and an important center for administration, business, education, and health care. Gwalior's geographic location falls between 26°13'N -26°17'N and 78°10'E -78°18'E. Gwalior has a municipal government called the Gwalior Municipal Corporation that provides services to the people of the city. With growing urbanization and population within the city (which has a current estimated population of ~ 1 million), there is an increasing demand for the provision of health care and environmental management services.

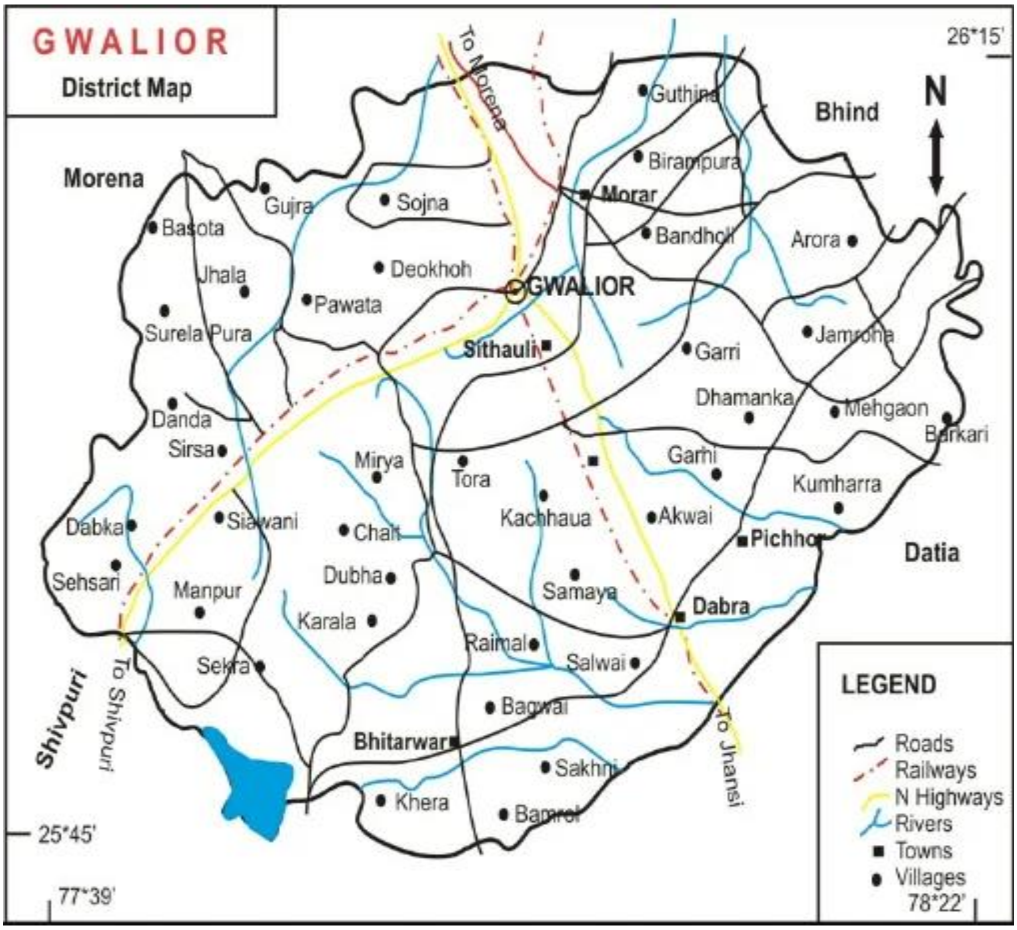

Figure 2: Location Map of Study Area

Source: https://www.researchgate.net/figure/Location-map-of-Gwalior-District_fig1_237099246

Gwalior has an expansive range of healthcare services, which includes several private and public hospitals as well as nursing homes, diagnostic centers, and other healthcare service provisions for both urban populations and rural communities in the surrounding areas. The increased number of patterns created by each hospital during the COVID-19 Pandemic – i.e., hospitalized patients needing diagnostic testing, quarantining, and vaccination – has resulted in an increased generation of biomedical waste in this area. The availability of so many types of healthcare facilities in such proximity aids in determining geographical variances in the generation of biomedical waste and the environmental health risks related to it.

Mixed land-use patterns (such as residential as well as commercial and institutional), along with a high population density in multiple wards, and the existence of residential, commercial, institutional, and transport (or transitory) zones, will create patterns (mixed land-use) of waste generation, create exposures to the environment, and ultimately create vulnerabilities to public health. Due to Gwalior's significant amount of biomedical activity and urban complexity, GIS-based spatial analysis of Gwalior will provide a suitable location for the identification of hotspots for biomedical waste generation, as well as determining the potential impact of that waste on the outcome of public health through environmental health risks.

4. Research Questions

RQ1. What are the spatial patterns and distribution characteristics of biomedical waste generation in Gwalior city during the COVID-19 pandemic?
RQ2. Where are the significant biomedical waste hotspots located, and to what extent do these patterns exhibit spatial clustering within the study area?
RQ3. What are the environmental health risks associated with biomedical waste generation, and how can GIS-based analysis support sustainable waste management planning in Gwalior city?

5. Objectives of the Study

i. To analyze the spatial distribution patterns of biomedical waste generation in Gwalior city during the COVID-19 pandemic.
ii. To identify biomedical waste hotspots and examine the spatial clustering characteristics of biomedical waste generation using GIS-based spatial analytical techniques.
iii. To assess environmental health risks associated with biomedical waste generation and develop GIS-based recommendations for sustainable biomedical waste management in Gwalior city.

6. Materials and Methods

6.1 Research Design

This research uses a framework based on GIS to examine the spatial distribution of biomedical waste in Gwalior, Madhya Pradesh, as well as the potential environmental health risks that have occurred during the time of the COVID-19 pandemic. This methodology includes analyzing the spatial distribution of biomedical waste, identifying hotspots, and assessing environmental health risks using GIS. The analytical hierarchy process (AHP) with a multi-criterion weighted overlay approach was employed to assess environmental health risk while integrating environmental and socio-demographic factors; QGIS software was used for spatial database development, mapping the data and visualizing hotspots, as well as creating the risk zones.

6.2 Data Sources and Preparation

Geospatial and socio-environmental datasets appear to have been derived from publicly accessible datasets. A geographic information system (GIS) is the means by which healthcare facilities (e.g., hospitals) are mapped or located via administrative boundaries (e.g., states), census tracts (e.g., populations that reside in those facilities), geographic transportation networks (e.g., roads, rivers), land use (e.g., residential, commercial), and physical environments. All of the data sets that built this project were georeferenced (i.e., given geographical coordinate locations) and then re-projected into a uniform common data set (projection) before conducting spatial analyses.

Table 1. Data Sources Used in the Study

Data Layer	Source	Format	Purpose
Healthcare Facilities (Hospitals, Clinics, Diagnostic Centers)	OpenStreetMap (OSM), Government Health Directory	Point	Biomedical waste generation proxy
Population Density	Census of India 2011	Polygon/Raster	Human exposure assessment

Water Bodies and Drainage Network	OpenStreetMap / Bhuvan	Line/Polygon	Environmental vulnerability
Road Network	OpenStreetMap	Line	Accessibility assessment
Administrative Boundaries	Municipal Corporation / Census GIS	Polygon	Spatial reference and mapping

6.2.1 Data pre-processing

All spatial datasets were pre-processed before beginning the analyses to provide for spatial consistency and compatibility within the Geographic Information Systems (GIS) environment. Georeferencing and projection of the collected datasets were performed to convert the collected datasets into the Universal Transverse Mercator (UTM)/WGS 84 projections. The vector datasets were then cleaned of all duplicate records and topological errors. The raster datasets were then clipped to the administrative boundaries of Gwalior City. The attribute tables were standardized and integrated into a single geospatial database that was developed in QGIS. Finally, the final datasets were converted to raster layers with a common spatial resolution for use in overlay analysis and environmental health risk assessment.

6.3 Spatial Distribution Analysis

By analyzing the space relationships of different areas using Point-Based GIS mapping methods, we were able to determine how many healthcare facilities, such as doctors' offices, clinics, diagnostic centers, and COVID-19 treatment facilities, are located in an area and how this relates to the generation of biomedical waste from these facilities. To create a map of where healthcare facilities are located, we generated spatial distribution maps through QGIS that indicated where areas with many activities associated with healthcare exist.

The type of spatial statistic used to assess the geographic distribution patterns of these healthcare facilities was descriptive spatial statistics. The resulting distribution map(s) can be utilized to give a preliminary understanding of areas that have a higher potential to generate biomedical waste, as well as be the basis for further developing hotspot and risk analyses.

6.4 Hotspot Analysis

Utilizing Kernel Density Estimation (KDE), a continuous density surface was produced using QGIS to depict where there are concentrations of healthcare facilities; this surface can also represent a potential area for biomedical waste generation. By using this method, KDE provides not only the ability to see where clustering of spatial features occurs, but it also provides an opportunity to visualize hotspot locations based on the density of these identified clusters. The end product of the density surface produced through KDE will serve as a basis for delineating hotspots within Gwalior City to identify biomedically generated waste hotspots. As such, those areas of high density can also be identified as having the greatest potential for increased generation of biomedical waste, as well as the need for enhanced environmental management.

6.5 Environmental Health Risk Assessment

Using a GIS-based multiple criteria evaluation framework, an evaluation of the environmental health risk was conducted. The evaluation utilized information that represents the potential for waste generation, the population's exposure, and environmental vulnerability as indicators. The selected four criteria and their associated indicators were:

- Healthcare facility density
- Population density
- Distance from water bodies
- Road accessibility

Each criterion has been converted to raster format, standardized, and reclassified based on its relative contribution to environmental health risk.

Table 2. Environmental Health Risk Indicators

Criterion	Indicator Description	Risk Relationship
Healthcare Facility Density	Concentration of healthcare facilities	Positive
Population Density	Human exposure potential	Positive
Distance from Water Bodies	Pollution vulnerability	Negative
Road Accessibility	Waste transportation intensity	Positive

Environmental health risk assessment was conducted through independent spatial analysis of biomedical waste hotspots, population density, waterway accessibility, and road accessibility layers using GIS-based proximity and density modeling techniques.

6.6 Environmental Health Risk Mapping

Through raster overlay analysis, the combination of weighted criteria resulted in calculating an Environmental Health Risk index based upon the biomedical waste generated (m) and the potential exposure associated with that same waste (e). The higher the index value assigned to an area, the greater the environmental health risk associated with biomedical waste generation & exposure risk will be. The final risk zonation map is created with QGIS (Geographic Information System software) to provide healthcare administrators with evidence-based data for prioritizing regions with the most need (ecosystem & community) regarding the management of biomedical waste and protecting the environment.

6.7 Methodological Framework

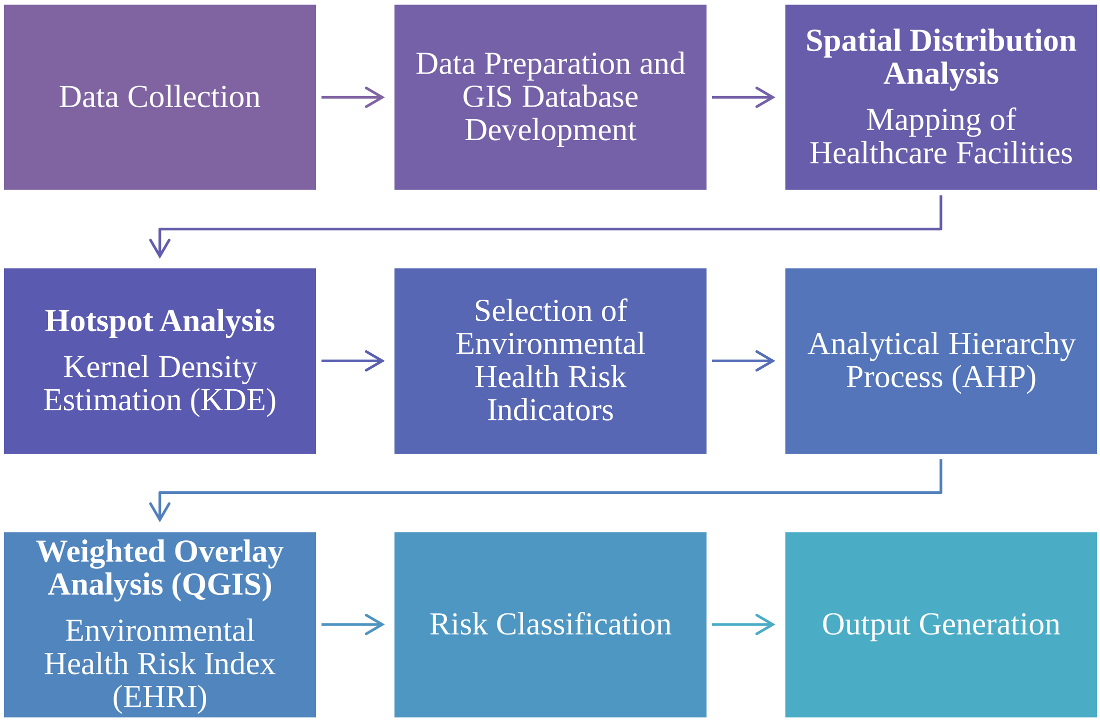

Figure 3: Methodological Framework

7. Results

Spatial analysis that utilized GIS found a distinct spatial variation of the distribution of health care facilities, generation potential of biomedical waste, and environmental health risks in the state of Gwalior (India) during the COVID-19 pandemic. Health care facilities were located primarily in clustered urban areas or as part of the urban core of the city of Gwalior, which created clear clusters of potential biomedical waste generation. Thus, the Kernel Density Estimation (KDE) identified significant hotspot zones that contain the major healthcare facilities and potential biomedical waste generating facilities; however, the comparison of environmental vulnerability along the transport network and waterways, or the analysis of the accessibility of the population within the cities of Gwalior, revealed a large variability in the local area. The identification of the relationship between population density and density of potential biomedical waste generation indicates that areas of higher population density have a greater generation potential of biomedical waste and of human exposure to biomedical waste. Overall, the results suggest that the potential environmental health risks associated with biomedical waste are concentrated geographically within specific urbanized areas within the district and underscore the need for targeted management and monitoring plans for biomedical waste. Each spatial analysis provides detailed results or findings and will be discussed in the following sections.

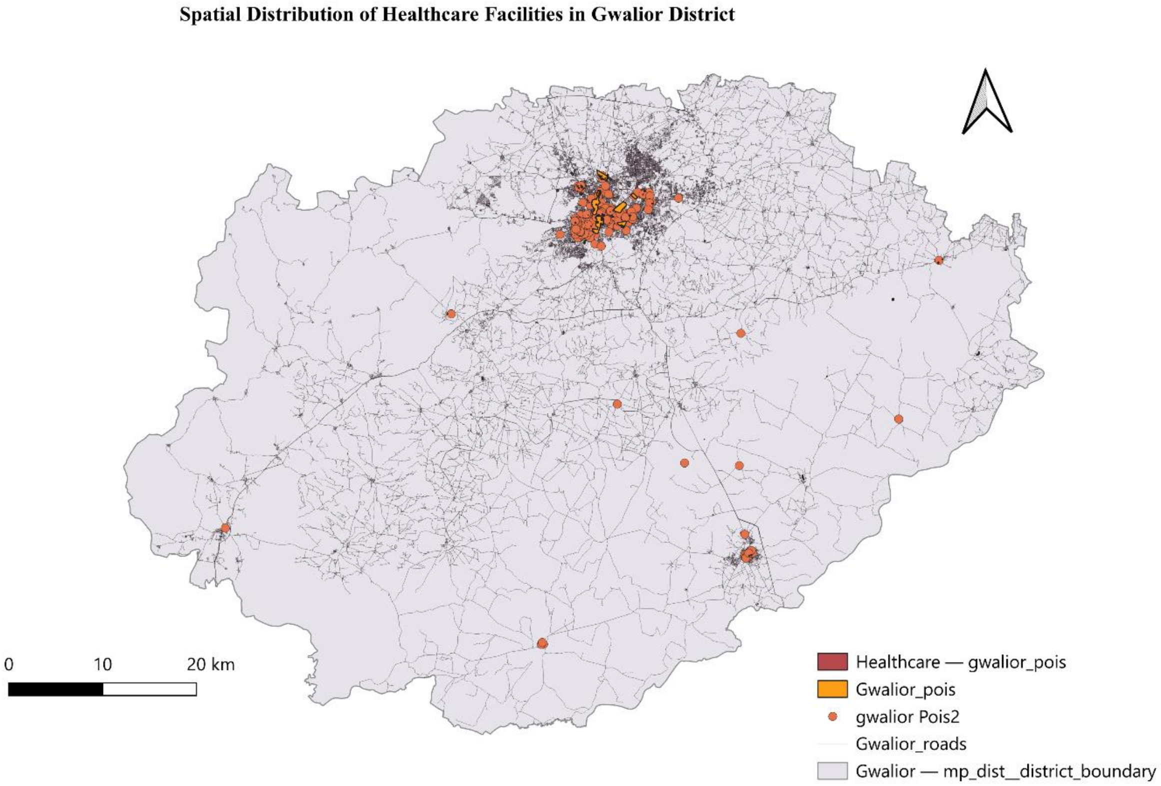

Figure 4: Spatial Distribution of Healthcare Facilities in Gwalior District during Covid19

Table 3. Spatial Distribution Characteristics of Healthcare Facilities in Gwalior District

Distribution Category	**Spatial Characteristics**	**Healthcare Facility Concentration**	**Biomedical Waste Generation Potential**	**Relative Importance**
Highly Clustered Urban Zone	A dense concentration of healthcare facilities within Gwalior city	Very High	Very High	Critical
Moderately Clustered Zone	Facilities concentrated around major towns and semi-urban settlements	High	High	Significant
Dispersed Rural Zone	Facilities distributed across rural areas with moderate spacing	Moderate	Moderate	Moderate
Isolated Healthcare Centers	Individual facilities located far from major clusters	Low	Low	Low
Peripheral Healthcare Facilities	Facilities situated near district boundaries with	Very Low	Very Low	Minimal

	limited surrounding infrastructure			

The spatial distribution of healthcare facilities in Gwalior District is shown in Figure 4. The majority of health facilities are located in the north-central urban area surrounding Gwalior city, representing the main site for providing healthcare services in this district. There are also additional clusters of healthcare facilities spread out in the east and south-east areas of the district; rural and outlying areas have a less clustered distribution. There appears to be an abundance of healthcare facilities for the generation of biomedical waste from the COVID-19 pandemic; therefore, it can be assumed that similar types of waste will have accumulated at urban facilities, resulting in defined areas with high concentrations of waste. The distribution of healthcare facilities in this district will provide the basis for identifying hotspots of biomedical waste and determining where there is an environmental health risk associated with it, using GIS-based methods to analyze environmental data.

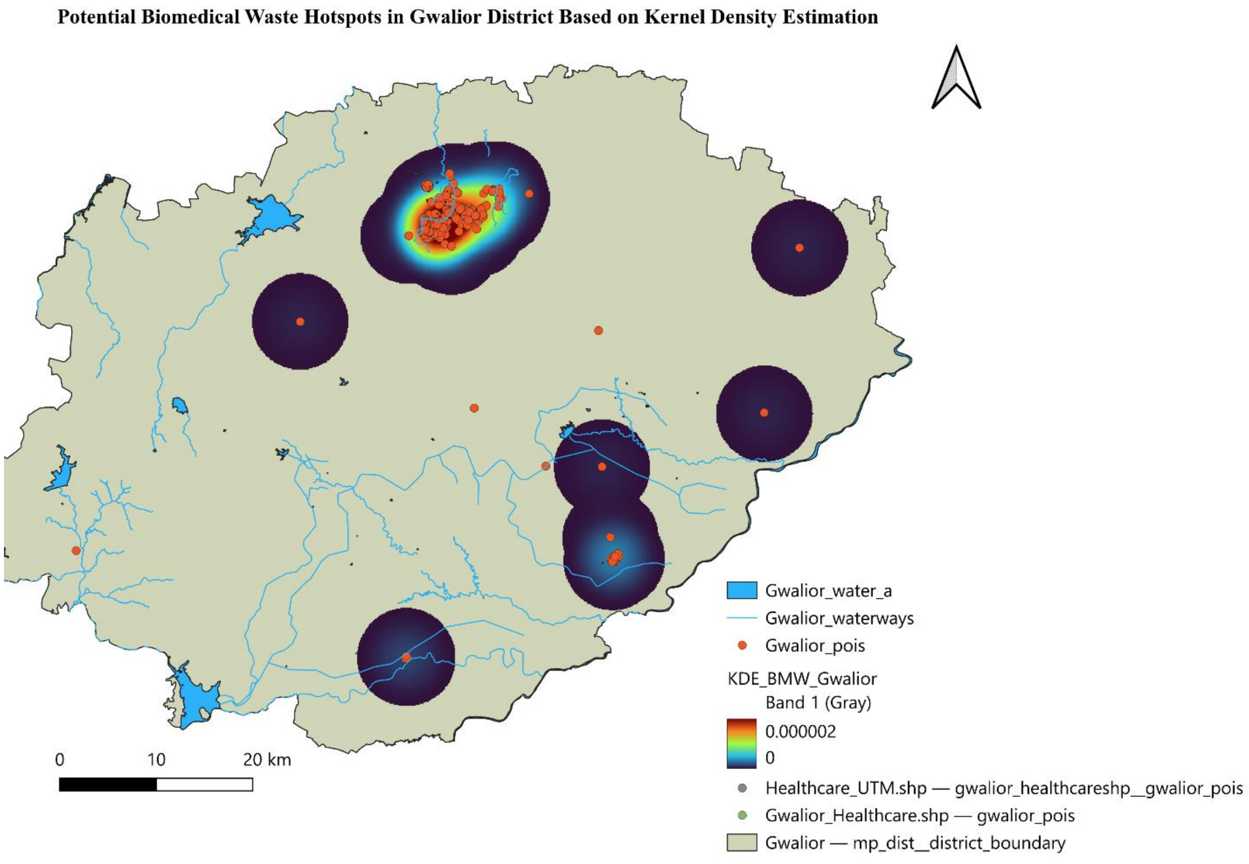

Figure 5: Potential Biomedical Waste Hotspots (KDE) during Covid19

Table 4: Classification of Potential Biomedical Waste Hotspots Based on Kernel Density Estimation

KDE Density Range	Hotspot Class	Spatial Interpretation	Biomedical Waste Concentration	Environmental Health Risk

0.000000 – 0.0000004	Very Low Density	Isolated healthcare facilities with limited clustering	Minimal biomedical waste generation	Very Low
0.0000004 – 0.0000008	Low Density	Small localized clusters of healthcare facilities	Low biomedical waste accumulation	Low
0.0000008 – 0.0000012	Moderate Density	Moderate concentration of healthcare facilities	Moderate biomedical waste generation	Moderate
0.0000012 – 0.0000016	High Density	Significant clustering of healthcare facilities	High biomedical waste generation potential	High
0.0000016 – 0.0000020	Very High Density	Major biomedical waste hotspot zones are concentrated around urban healthcare centers.	Very high biomedical waste generation and accumulation potential	Very High

Figure 5 shows where biomedically disposed hazardous material may occur by putting together all of this information into one geographic surface of biomedically hazardous materials using the KDE method; the results reveal an area of intense concentration of biomedically hazardous materials located in the northern part of Gwalior City where there are many health care (i.e. Medial) facilities and an area developing as biomedically hazardous material hot spots in the west along with the eastern and southern sections of the District near the areas containing primary health care facilities. The KDE analysis has shown that there is a significant amount of nuisance biohazardous material disposed of in and around urban health care facilities as compared with rural health care facilities, which could result in environmental pollution and the potential to create public health hazards in the future due to increased density of biomedical waste generated during the COVID-19 pandemic. The results also show highly clustered clusters of biomedically hazardous materials, indicating areas that have a higher need for improved disposal, management, and regulation of biomedically hazardous materials.

Table 5. Classification of Waterway Accessibility Zones in Gwalior District

Rank	Distance Range (m)	Accessibility Category	Interpretation	Healthcare Accessibility
1	0 – 5,172	Very High	Areas located closest to waterways	Most accessible
2	5,173 – 10,345	High	Short travel distance to waterways	Highly accessible
3	10,346 – 15,517	Moderate	Moderate proximity to waterways	Moderately accessible
4	15,518 – 20,690	Low	Relatively distant from waterways	Low accessibility
5	20,691 – 25,862	Very Low	Farthest from waterways	Least accessible

Maximum distance: 25,862 m

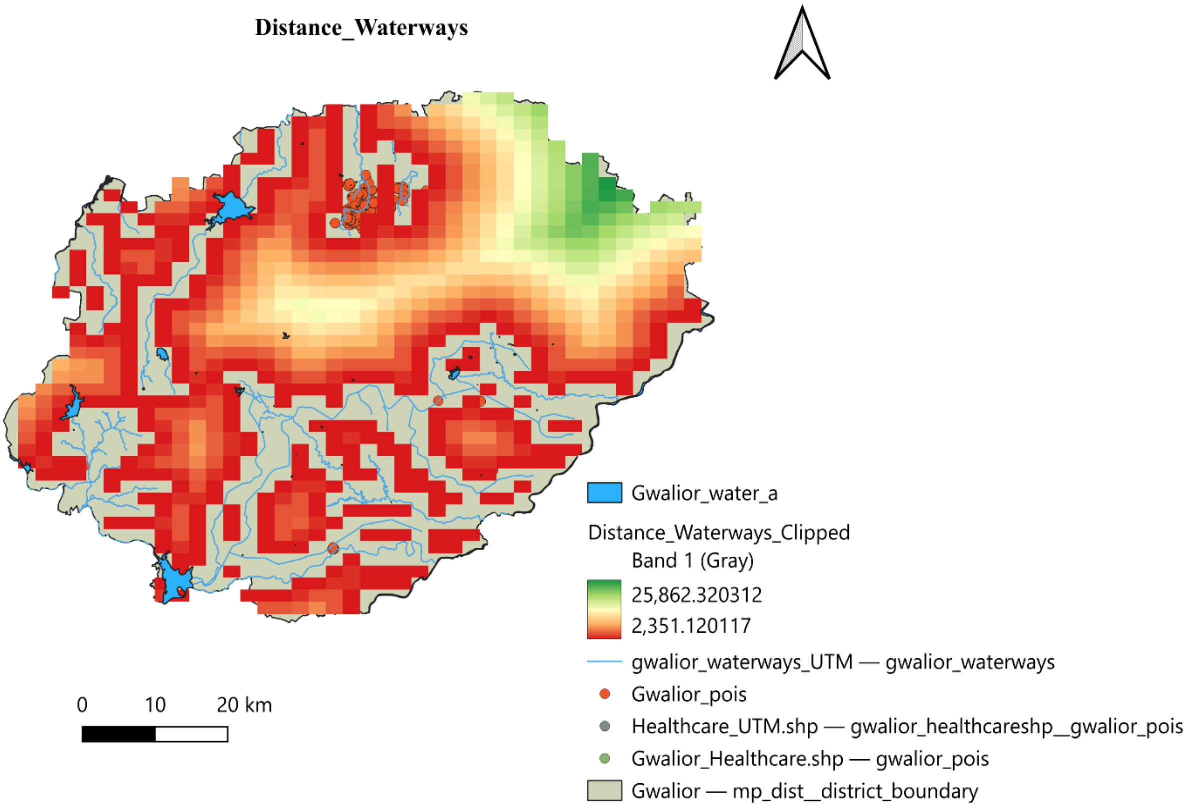

Figure 6: Distance from Water Bodies accessibility during Covid19

Figure 6 depicts how accessible waterways are from the Gwalior District in relation to their Euclidean distance from all water sources. The majority of locations that are categorized as Very High and High Waterway Accessibility are located near major rivers, streams, and other surface water bodies; specifically, these two classes are clustered in the western, central, and southern geographic areas of Gwalior District. Due to this proximity to rivers, streams, and other surface waters, these locations exhibit greater risks of the movement of biomedical waste into surface water due to surface runoff, leachate, and improper disposal from hospitals and healthcare facilities. In contrast, the northeastern part of Gwalior has a significantly lower level of waterway accessibility (relative to the rest of the district) and, thus, a correspondingly low direct risk of being contaminated by surface water due to biomedical waste. This finding indicates that strict handling and disposal protocols should be enforced for hospitals and health care facilities located within 10 km of a major water source to reduce the potential for harm to aquatic ecosystems and the public during pandemics.

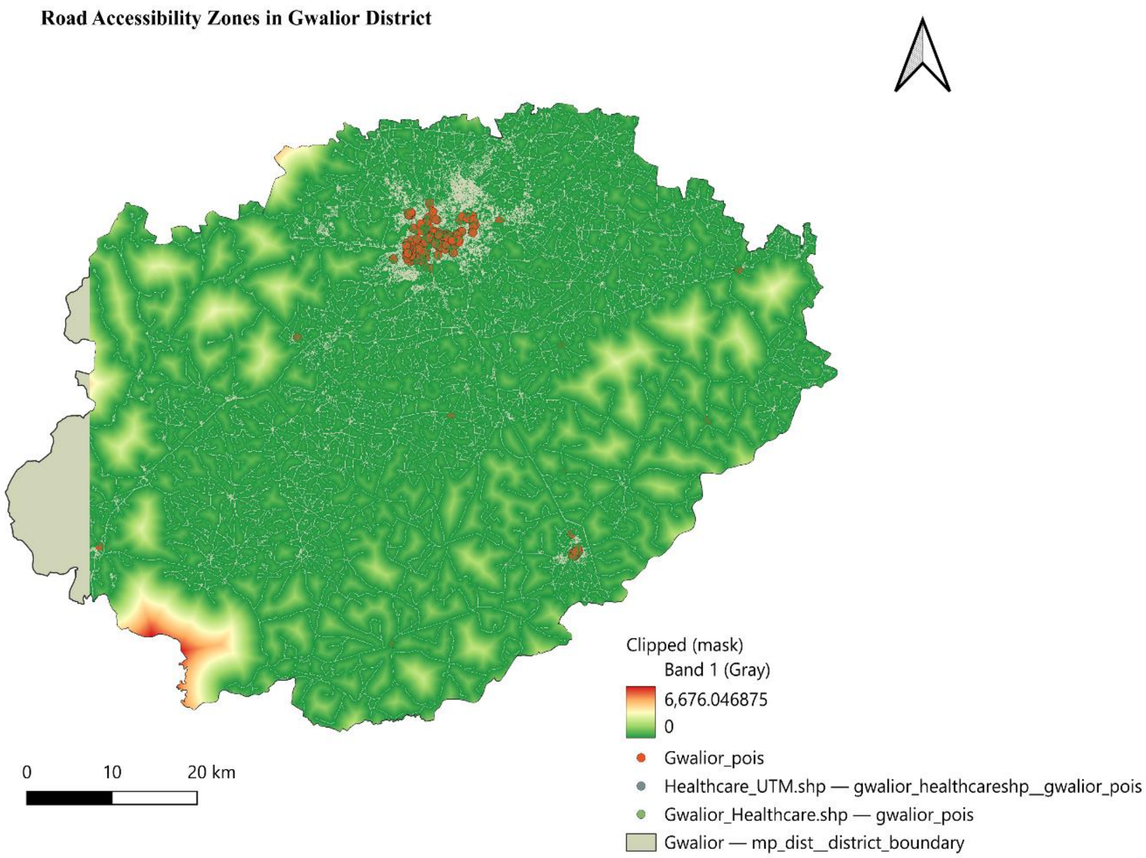

Figure 7: Road Accessibility Zones in Gwalior District during Covid19

Table 6. Classification of Road Accessibility Zones in Gwalior District

Rank	Distance Range (m)	Accessibility Category	Interpretation	Healthcare Accessibility
1	0 – 1,669	Very High Accessibility	Immediate access to the road network	Most accessible
2	1,670 – 3,338	High Accessibility	Proximity to roads	Highly accessible
3	3,339 – 5,007	Moderate Accessibility	Moderate road access	Moderately accessible
4	5,008 – 6,676	Low Accessibility	Limited road accessibility	Low accessibility
5	> 6,676*	Very Low Accessibility	Remote from roads	Least accessible

*Practically represented by the highest class within the study area.

Figure 7 shows the road access throughout the Gwalior District based on an analysis of the Euclidean distance measurements. The vast majority of the Gwalior District has been classified into categories of "Very High" or "High", representing an extensive road network that connects urban and peri-urban areas to rural areas. There is high transportation access throughout the district due primarily to the fact that there is a high density of health care facilities in the northern-central portion of the district. This accessibility provides an excellent opportunity to facilitate the collection and transfer of biomedical waste in an efficient manner. However, there are some remote and/or peripheral areas of the Gwalior District that have comparatively lower levels of accessibility. Waste collected from these lower-access areas may create logistical difficulties in transferring the biomedical waste to appropriate disposal sites and providing emergency medical services in the event of an emergency. The efficient connectivity of the road system is especially significant during public health emergencies like COVID-19, where the timely collection, transportation, treatment, and disposal of biomedical waste is made possible. In areas that are classified as having lower access, future infrastructure initiatives and decentralized waste management programs will be needed in order to minimize health risks associated with the environment.

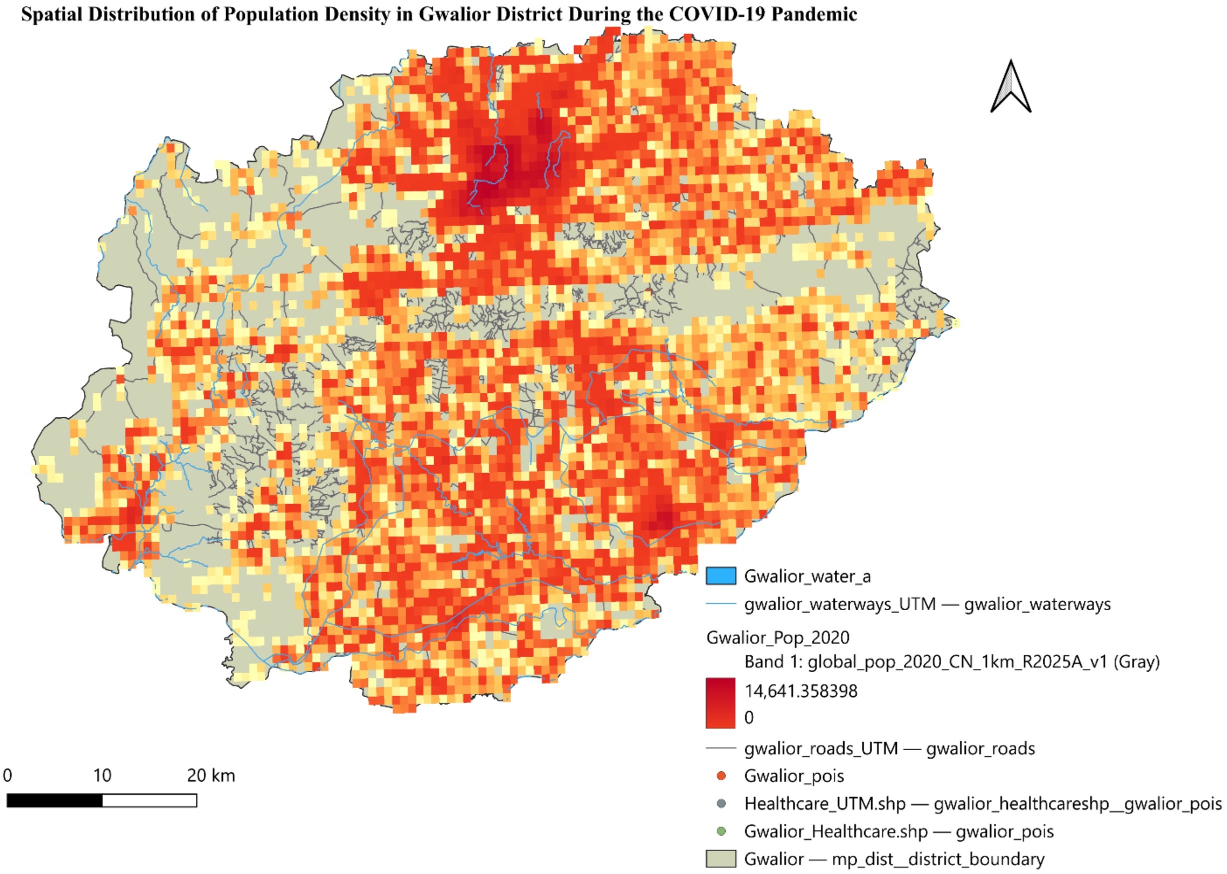

Figure 8: Spatial Distribution of Population Density in Gwalior District During the COVID-19 Pandemic

Table 7. Population Density Classification Used for Exposure Assessment

Rank	Population Density Range	Density Category	Exposure Level	Interpretation
1	0 – 3,660.34	Very Low	Very Low	Sparse population; minimal human exposure potential
2	3,660.34 – 7,320.68	Low	Low	Limited population concentration
3	7,320.68 – 10,981.02	Moderate	Moderate	Moderate human exposure potential
4	10,981.02 – 14,641.36	High	High	Elevated exposure and BMW generation potential

5	Highest observed pixels	Very High	Very High	Maximum population concentration and environmental vulnerability

In the Gwalior district, the population's uneven distribution is clearly seen on the population density map. Most of Gwalior's populated areas are located within Gwalior City's urban center. Outside of that urban area, rural populations tend to have lower concentrations of people. Areas of high and very high population density during COVID-19 will produce more biomedical waste because of greater utilization of healthcare systems and human activity than rural areas. Consequently, densely populated areas are considered as priority zones for environmental health risk assessments and biomedical waste management action.

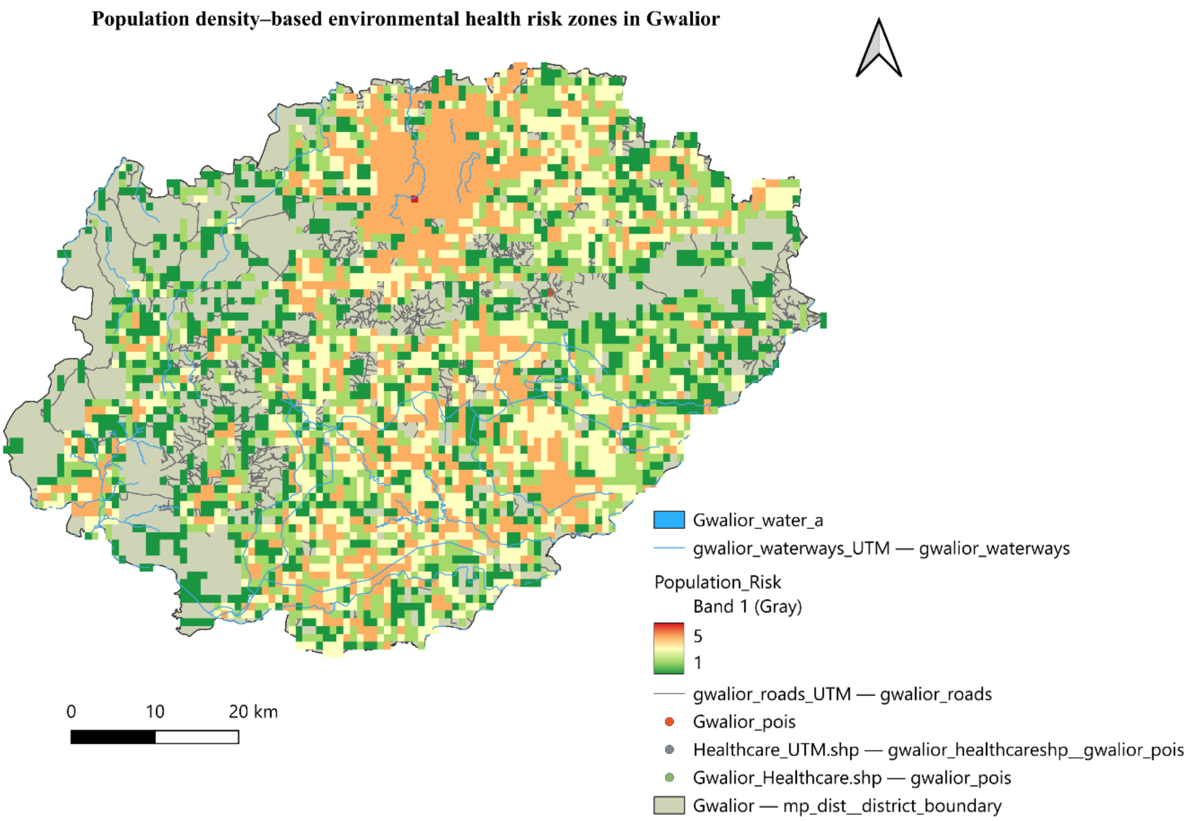

Figure 9. Population density–based environmental health risk zones in Gwalior district during Covid19.

Table 8. Population Density Risk Classification

Risk Class	Reclassified Value	Population Range	Interpretation	BMW Generation Potential
Very Low	1	0–35.39	Sparse population	Very Low
Low	2	35.39–130.78	Rural settlements	Low
Moderate	3	130.78–327.72	Semi-urban areas	Moderate
High	4	327.72–14639.82	Urbanized areas	High
Very High	5	>14639.82	Urban core hotspots	Very High

The map in Figure 9 shows how hazardous the environment is for population density throughout the area of Gwalior District. The map shows that there are a lot of different types of populations in Gwalior District, with the highest levels of hazard being located close to the center of the city in northern-central Gwalior's urban population. These areas have large numbers of residents using health services that are generated by hospitals, which means that there will be many more patients who will visit local hospitals than there will be the number of patients living in Gwalior District's southern, western, and rural areas.

A large proportion of the Gwalior District is made up of Moderate and High-risk areas, which include semi-urban and urbanizing lands, and therefore, may place additional stress on healthcare and waste disposal. On the other hand, within the western, southern, and fringe rural area of the Gwalior District, areas where there are Very Low or Low risk areas with fewer residents and lower levels of waste production would be expected.

The viewpoint of biomedical waste management in areas with a high population density is particularly significant due to the larger number of people producing more healthcare-related types of waste; hospitals/clinics, diagnostic centers, immunization clinics, and quarantine facilities all produce more waste as more people will use them. In addition, during the COVID-19 pandemic, the amount of infectious waste produced, as well as personal protective equipment (PPE) waste, testing waste, and other types of treatment-related medical waste, increased in higher population densities.

The map shows that population density should be regarded as one of the most important factors determining the health of the environment; that is, the higher the population density, the greater the potential for generating biomedical waste. The areas of the city of Gwalior to the north and the central urban core area should be the primary focus for providing more effective collection, transportation, treatment, and disposal systems for biomedical waste in order to reduce environmental contamination and protect the public from future outbreaks of disease.

Table 9. Environmental Health Risk Distribution in Gwalior

Risk Category	Risk Score(s)	Area (km²)	Percentage (%)
Very Low	6.0–6.5	1.48	3.44
Low	8.0–8.5	2.73	6.34
Moderate	9.5	33.60	78.05
High	10.0–11.5	4.15	9.64
Very High	13.5	1.09	2.53
Total	—	**43.05**	**100.00**

The environmental health risk assessment identified a total risk-affected area of 43.05 km² within the study region. Moderate-risk zones (risk score 9.5) constituted the largest proportion, covering 33.60 km² (78.05%) of the total risk area. High-risk zones (scores 10.0–11.5) accounted for 4.15 km² (9.64%), while very high-risk areas (score 13.5) occupied 1.09 km² (2.53%). Low-risk and very low-risk categories together represented less than 10% of the total mapped area. The spatial concentration of moderate-to-high risk zones indicates a strong overlap between healthcare facility clusters, population density concentrations, and proximity to waterways, suggesting elevated vulnerability to biomedical waste-related environmental health impacts during the COVID-19 pandemic.

8. Discussion

8.1 Spatial Distribution of Healthcare Facilities and Biomedical Waste Generation Potential

According to the results from the analysis of the spatial distribution of healthcare services, there is a significant concentration of healthcare facilities within the densely populated urban core of Gwalior's metropolitan area (especially Gwalior City). The rural and perimeter areas of the district are comparably lower in density of serviceable healthcare resources. Healthcare facilities tend to cluster in these types of population-packed areas due to greater demand for, accessibility of, and availability of supporting resources for delivering these types of services. The data also support previous research showing that urban center healthcare clusters also generate large amounts of biomedical waste because healthcare facilities are the largest producers of biomedical waste. Other researchers have noted that urban center healthcare clusters generate a disproportionate amount of waste during times of increased demand for healthcare services (e.g., during COVID-19; Das et al., 2021; Singh et al., 2022). Therefore, the first objective to determine locations with the potential for generating high levels of biomedical waste was successfully met.

8.2 Identification of Potential Biomedical Waste Hotspots through Kernel Density Estimation

A major waste hotspot exists in the northeast urban area of Gwalior District, as shown by the Kernel Density Estimate analysis using KDE, and there are smaller clusters that show hotspot activity around other health care groups. Hotspots are located in the same areas as hospitals/clinics/diagnostic facilities, located density-wise. From the results, hotspots show that biomedical waste generation occurs in a spatially clustered manner rather than uniformly distributed throughout the Gwalior District area. Similar KDE applications have demonstrated that they can be used to identify waste hotspots and areas of environmental health risk (Mihai, 2020; Sharma et al., 2021). Thus, the second objective, to identify priority locations for targeted waste management and monitoring interventions, was met.

8.3 Environmental Health Risk Assessment Based on Population Density, Road Accessibility, and Waterway Accessibility

As revealed through an analysis of clinical environment health risk assessments done by the WHO, high-density urban areas pose the greatest threat to health through environmental conditions based upon the joint impact of health care accessibility, population density, and the volume of biomedical waste produced. The largest contributor to risk for vulnerable populations in relation to clinical environmental health risk is population density within each District. In an analysis of transportation access to healthcare facilities, roadway access provides excellent access to waste collection transportation routes. An analysis of waterway access showed several health care-related clusters located adjacent to water bodies - both drainage systems and river systems. If biomedical wastes are improperly managed, risks exist for contamination of these water bodies due to the location of health care facilities near drainage and river systems. Similar to other studies of clinical environmental health risks, this report successfully met Objective 3 by identifying locations within the district where there is a need for improved environmental safeguards and greater emphasis on managing biomedical waste (Patwary et al., 2011; WHO, 2022).

8.4 Implications for Sustainable Biomedical Waste Management

The study shows that generations of biomedical waste and associated environmental health hazards are found primarily within certain specific urbanized regions of the Gwalior District. The development of waste management infrastructure, collection systems, and treatment facilities should therefore be strategically prioritized within the areas of highest risk to enhance operational efficiencies and environmental protection. Analysis using GIS and spatial techniques as part of the research provided a means to spatially identify vulnerable areas, optimize planning for waste management activities, and support decision-making based on evidence. The information provided by this study can aid local authorities in developing sustainable strategies for the management of biomedical waste and strengthening preparedness to respond to future public health emergencies.

9. Conclusion

This research used geographic information systems (GIS) to perform spatial analyses that assessed the distribution of health care facilities in Gwalior, Madhya Pradesh, as well as identify potential biomedical waste hotspots, and assess the environmental health risks associated with the generation of biomedical waste as a result of the COVID-19 pandemic within that district. The study found that geospatial technology can be an effective tool for gaining insight into the spatial aspect of biomedical waste and the environmental vulnerability associated with that waste during public health crises. The analysis of locations where health care facilities are located demonstrates that there is a concentration/dependence of facilities in Gwalior City that indicates that there are more people who are generating biomedical waste in that urban core area compared to the rest of the district. The kernel density estimation (KDE) analysis of facilities identified significant biomedical waste hotspots throughout the north-central urban area of Gwalior, with additional hotspot areas surrounding each health care facility cluster. These results indicate that the generation of biomedical waste during the COVID-19 pandemic was highly spatially concentrated across the district.

Population density, road access, and closeness to waterways have impacted the biomedical waste-related risks associated with all four environmental health risk assessments. Areas with a higher density of people and an abundance of medical services have a higher likelihood of having an environmental vulnerability and potential waste generation from the community. Likewise, if a healthcare facility is located near a body of water, it creates a higher likelihood of contaminating the environment with biomedical waste, should the waste not be correctly managed, transported, and disposed of properly. While transportation networks offer opportunities for effective waste collection and management, the analysis of road access indicates that although they play a role in the effectiveness of waste management, peripheral areas will often have logistical obstacles to the collection and delivery of services. The research met all three objectives of the study, namely, to identify the spatial distribution of biomedical waste generation potential, locate significant biomedical waste hotspots, and assess environmental health risks using a Geographic Information System (GIS)-based analysis. These findings support the need for specific biomedical waste management strategies that meet the needs of both urban healthcare clusters and environmentally sensitive areas. Implementing waste segregation, collection, transportation, treatment, and disposal systems should be the top priority in areas identified as hotspots.

This study indicates that a GIS-based approach can be used as an effective decision tool for administrators from the healthcare, urban planning, and environmental sectors in developing sustainable biomedical waste management plans. Future research should consider using real-time biomedical waste generation data, land-use characteristics, and advanced spatial modeling techniques to assist with environmental health risk assessment and planning for pandemics.

10. Recommendations

- Strengthen biomedical waste segregation, collection, and disposal practices in identified hotspot zones.
- Prioritize monitoring and management of healthcare facilities located in densely populated urban areas.
- Implement regular environmental surveillance near waterways to minimize contamination risks.
- Optimize biomedical waste transportation and collection systems through improved road connectivity and route planning.
- Integrate GIS-based monitoring tools into biomedical waste management and emergency preparedness programs.
- Enhance awareness and training programs for healthcare workers and waste management personnel.
- Promote coordination among healthcare institutions, municipal authorities, and environmental agencies for effective waste management.
- Encourage future research using real-time biomedical waste data and advanced GIS-based risk assessment techniques.

References

1. Academe, S. O., Olukanni, D. O., Aremu, E. O., Alfa, M. I., & Mkandawire, T. (2026). GIS-Based Route Optimization for Sustainable Waste Management: A Review of Urbanization, Waste Generation, and Health Impacts in Nigeria and Globally. Innovations for Climate Resilience and Growth in Africa: Addressing an Untapped Potential, 17-40.
2. Agarwal, S., Praveen, G., Gautam, A. S., Gautam, S., Tiwari, R. N., Kumar, S., & Kumar, S. (2023). Unveiling the surge: Exploring elevated air pollution amidst the COVID-19 era (2019–2020) through spatial dynamics and temporal analysis in Delhi. Water, Air, & Soil Pollution, 234(12), 756.
3. Ahasan, R., Alam, M. S., Chakraborty, T., & Hossain, M. M. (2022). Applications of GIS and geospatial analyses in COVID-19 research: A systematic review. F1000Research, 9, 1379.
4. Bagwan, W. A. (2023). An investigation of the bio-medical waste produced in India during the COVID-19 pandemic and Maharashtra state (pre-COVID-19 and post-COVID-19) analysis: a GIS-based approach. Research in Health Services & Regions, 2(1), 8.
5. Bherwani, H., & Kumar, R. (2022). Use of Remote Sensing and GIS techniques for adaptation and mitigation of the COVID-19 pandemic. In The Science behind the COVID Pandemic and Healthcare Technology Solutions (pp. 559-578). Cham: Springer International Publishing.
6. Cahyadi, M. N., Susanto, L. O. F., Haq, F., Handayani, H. H., Raharjo, A. B., Endarko, E., ... & Filchev, L. (2023). Optimal Route Determination Automation System for COVID-19 Medical Waste Disposal Based on 3D Building Modeling. International Journal of Geoinformatics, 19(10), 82-96.
7. Feizizadeh, B., Omarzadeh, D., Sharifi, A., Rahmani, A., Lakes, T., & Blaschke, T. (2022). A GIS-based spatiotemporal modelling of urban traffic accidents in Tabriz City during the COVID-19 pandemic. Sustainability, 14(12), 7468.

8. Hariz, H. A., Dönmez, C. Ç., & Sennaroglu, B. (2017). Siting of a central healthcare waste incinerator using GIS-based Multi-Criteria Decision Analysis. Journal of Cleaner Production, 166, 1031-1042.
9. Huang, X., Zhang, R., Li, X., Dadashova, B., Zhu, L., Zhang, K., ... & Shen, B. (2022). Health-based geographic information systems for mapping and risk modeling of infectious diseases and COVID-19 to support spatial decision-making. Translational Informatics: Prevention and Treatment of Viral Infections, 167-188.
10. Joyosemito, I. S., Meilani, S. S., & Azmi, M. (2025). Evaluating Environmental and Public Health Risks of Medical Waste Incineration Using Air Dispersion Modeling in Indonesia. Jurnal Kesehatan Lingkungan Indonesia, 24(3), 259-269.
11. Lestari, F., Zakianis, Muzanni, A., Wibowo, A., Darmawan, A., Kurniaputri, H., ... & Shaw, R. (2025). Spatiotemporal Trend of Hazardous Waste Sites and Risks in Urban Jakarta, Indonesia. Sustainability, 17(12), 5548.
12. Manjunatha, M. C., Madhu, B., Sahana, K. S., Suraj, B. M., Mounika Sree, M., Chaithra, M., & Kameshwari, V. S. (2024). Understanding medical healthcare solutions in a GIS platform: A review. Journal of Experimental and Laboratory Medicine, 1(4), 98-109.
13. Rahman, M. R., Islam, A. H., & Islam, M. N. (2021). Geospatial modelling on the spread and dynamics of the 154-day outbreak of the novel coronavirus (COVID-19) pandemic in Bangladesh towards vulnerability zoning and management approaches. Modeling earth systems and environment, 7(3), 2059-2087.
14. Samany, N. N., Liu, H., Aghataher, R., & Bayat, M. (2022). Ten GIS-based solutions for managing and controlling the COVID-19 pandemic outbreak. SN Computer Science, 3(4), 269.
15. Soni, P., Gupta, I., Singh, P., Porte, D. S., & Kumar, D. (2023). GIS-based AHP analysis to recognize the COVID-19 concern zone in India. GeoJournal, 88(1), 451-463.
16. Souza, A., Mota, C., Rosa, A., Figueiredo, C., & Candeias, A. L. (2020). An Environmental GIS-based Variable Analysis of SARS-CoV-2 in the City of Recife, Brazil.
17. Usman, F., Hamim, S. A., Gumano, H. N., & Jamil, F. (2021, April). Geospatial analysis in managing medical facilities for combating disasters triggered by the COVID-19 pandemic. In IOP Conference Series: Earth and Environmental Science (Vol. 708, No. 1, p. 012061). IOP Publishing.
18. Widjaja, G. (2026). Contemporary Environmental Health Law Paradigm: Comprehensive Analysis of Literature Review on Pollution Regulation Framework, Hazardous Waste Control, And Occupational Safety Standards in The Health Sector for The Prevention of Epidemiological and Ecological Risks. Injosedu: International Journal of Social and Education, 2(11), 3226-3235.
19. Widjaja, G. (2026). Environmental Health Regulations in Indonesia: A Systematic Literature Review of Air-Water-Soil Pollution Control, Medical and Hazardous Waste Management, And Occupational Safety in Health Facilities to Achieve a Sustainable Environment. Injosedu: International Journal of Social and Education, 2(11), 3236-3245.