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Delving Into Geospatial Data Services: Monitoring Earth For Covid-19 Impact Measure And Decision Making

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Abstract – Abstract: Geospatial technologies are crucial for many applications and can facilitate decision-making to benefit society. When the Covid-19 pandemic restricted most of the services, geospatial technologies like satellite remote sensing, geographical information systems, and other allied technologies were found essential. They speed up many critical decision-making processes in the fight against the pandemic. This paper explores the significant contributions from the geospatial aspects throughout the pandemic in various research domains. The potential applications of geospatial technology to assist humanity during the pandemic are thoroughly examined. We categorized the entire study into i) environmental monitoring services, ii) disease control and management services, and iii) forecasting and decision-making services. Many valuable findings are derived based on the systematic review of some remarkable works. The outcome helps us understand how decision-making and forecasting are essential in the fight against the pandemic, with profound implications for future multidisciplinary research using geospatial technology.

Keywords – Covid-19, Satellite Remote Sensing, Environmental Monitoring, Location-Based Services, Disease Control and Monitoring, Geospatial Technology, Big Data.

I. INTRODUCTION

The coronavirus 2019 (Covid-19), which emerged in December 2019, spread rapidly, created a public health emergency, and restricted many essential services like environmental monitoring services and healthcare surveillance. During such public emergencies, geospatial technologies with new technological advancements provide a broad spectrum of services like environmental monitoring, hazard assessments, disease control, natural resource management, etc. Many organizations utilize the Earth Observations (EO) data to assist the response-recovery strategies associated with Covid-19 *lockdowns*. In addition, Satellite Remote Sensing (SRS) and Geographic Information Systems (GIS) support analysts' and policymakers' decision-making by providing various outlooks on the unfolding environmental changes, helping control transmitting the disease.

Over the years, there has been extensive progress in technology for capturing geospatial data through photogrammetry using i) Unmanned Aerial Vehicles (UAV), ii) Terrestrial Vehicle-Mounted Mobile Mapping (TV-MMM) systems, iii) Light Detection And Ranging (LiDAR), iv) RADAR interferometry, v) Satellite-based Remote Sensing (SRS), and other techniques. All these data have a broad spectrum of applications. The satellites can see and utilize certain important *proxy* indicators from the Earth in modelling, monitoring, responding to, and recovering from numerous infectious disease outbreaks. Also, they help plan and manage land, water, and other natural resources. This work mainly concentrates on the contributions from the geospatial data services provided by SRS, GIS, GPS, and other allied data during the pandemic. The entire work has been categorized into three, i) environmental monitoring services, ii) disease control and management services, and iii) forecasting and decision-making

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services provided by geospatial data throughout the pandemic for analyzing the various impacts caused by the proliferation of the Covid-19 pandemic on Earth.

The new frontier combines geospatial data with Machine Learning (ML), Artificial Intelligence (AI), Deep Learning (DL), and big data techniques to help humanity tackle the pandemic situation. Especially the SRS data are beneficial for the spatial study of human diseases. As communities worldwide have changed their behaviour in view of the elevated spreading of Covid-19, satellite data provided by several organizations are utilized to observe changes in atmospheric and environmental factors. Moreover, using the EO data, the changes in land cover are investigated by which the impacts of the disease transmission are studied.

A. Organization Support for Covid-19 Allied Research

Several organizations support the research, decision-making, and real-time forecasting of the spread of Covid-19 with their geospatial data and specialized dashboard applications. The National Aeronautics and Space Administration (NASA) has contributed plenty of resources to Covid-19-related responses by using its supercomputing capabilities to accelerate the research areas, including satellite-based health care for the treatment and vaccine-related studies. Moreover, AI expertise is further used in developing new techniques for answering the high-priority scientific queries pertinent to Covid-19. The Indian Space Research Organization (ISRO) supports various states by providing geospatial tools and location-based solutions like the national-level Covid-19 Tracker to fight against Covid-19. European Space Agency (ESA), together with NASA/USGS, provides weekly monitored of Earth regularly.

Researchers from several organizations conducted numerous investigations and discovered changes in environmental factors as a result of the epidemic. The investigations found a low deforestation incidence, lower Air Pollution (AP) levels, better water quality, and more reflecting snow. The primary data sources utilized are the EO satellites, Synthetic Aperture Radar (SAR), 3D LiDAR, Nighttime Light (NTL) emission, Thermal InfraRed (TIR) systems, Global Navigation Satellite System (GNSS) satellites, Wide Area Augmentation System (WAAS), etc.

B. Real-time Disease Monitoring using Geospatial Data

Geospatial technologies are essential in Covid-19 disease management and control activities, and they facilitate real-time decision-making and forecasting in the fight against the pandemic. The LiDAR is deployed in airports to monitor passenger flow in real-time and supply-chains by the manufacturers. During the Covid-19 outbreak, the NTL data helped to track variations in energy use, migration, and *social distance* maintained in transportation and *lockdown* policies in a specific location. Images of Earth at night give an extraordinary view of human activity over time. The nighttime environment illuminates the Earth's features, including city infrastructure, lightning flashes, fishing boat navigation, gas flares, aurora, and natural hazards. Paired with the moonlight, researchers can also spot snow, ice, and other reflective surfaces that allow nighttime land and ocean analysis.

Thermal InfraRed (TIR) remotely sensed imagery to identify hotspots in the urban landscape is essential during the pandemic. Daytime and nighttime TIR images are captured to identify high Land Surface Temperature (LST) locations. The LST measurement can be utilized for urban planning and greening decision-making. GIS provide many location-based services amidst the Covid-19 pandemic. Geospatial technology has provided exclusive visualization and analytical tools to healthcare professionals and decision-makers to execute disease control strategies in affected and/or suspected regions.

Furthermore, they help make analysis and forecasts possible that were technologically out-of-reach. With the *lockdown* criteria and restrictions on movement, GIS-based locations became essential for the home delivery of essential services. Kanga et al. [1] evaluated the risk zones in intelligent decision-making regarding Covid-19 risk reduction using appropriate management of resources-related policy consequences using SRS and GIS. The blending of multiple geospatial data sources from SAR, and EO, along with mobility data, have provided distinct insights into different factors, like human life patterns, economic mobility, dislocation, and country-level output.

The technological developments in AI, ML, DL, and big data help to handle the massive, exceptional volume of data obtained from various sources like i) public health surveillance, ii) real-time epidemic outbreak monitoring, iii) forecasting, iv) regular situation briefing, v) updations from governmental institutions and organizations, and vi) health facility utilization information. They also help analyze the news and other information sources to take images of points of interest for various decision-making. This innovative study briefly describes the essential services and applications provided by geospatial data in

many interdisciplinary research domains during the pandemic, as depicted in Figure 1. The main categories of services analyzed fall into i) environmental monitoring services, ii) disease control and management services, and iii) forecasting and decision-making services.

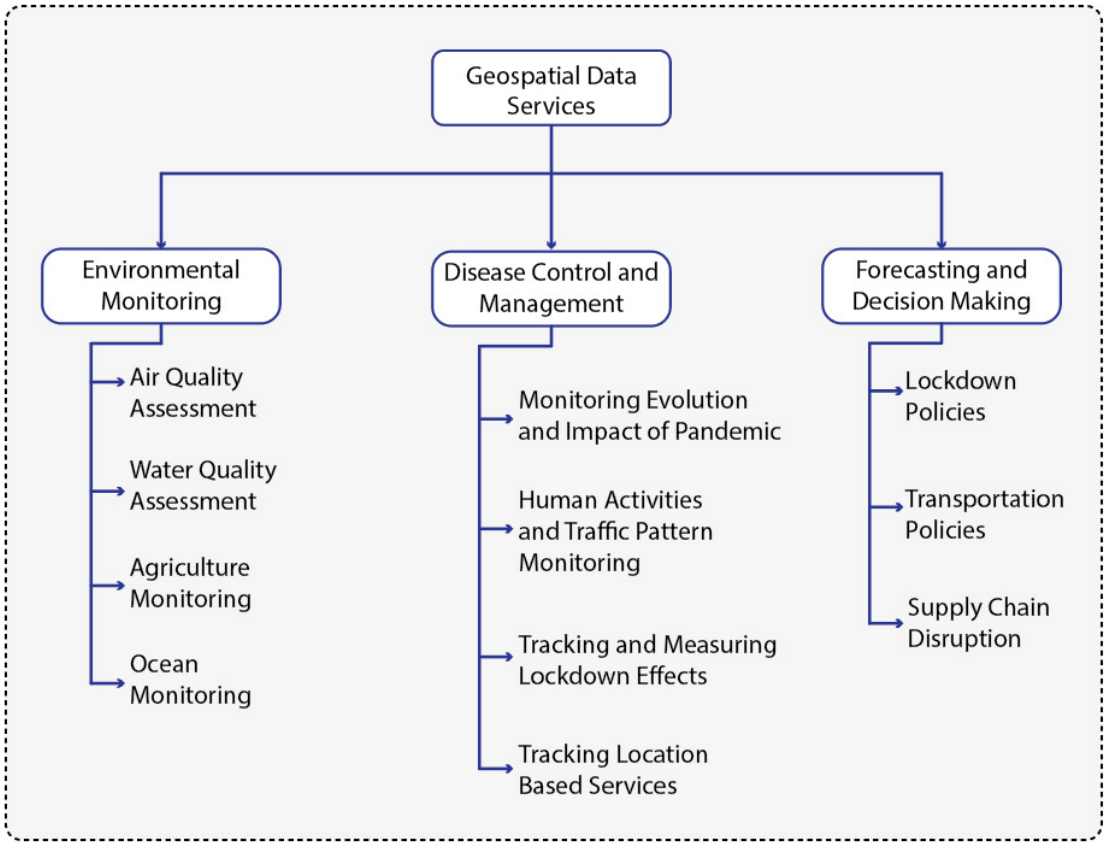

Figure 1: Geospatial Data Services in Various Research Domains during the Pandemic

The significant contributions of this work are briefed as follows:

- Valuable findings are derived through systematic analysis from several interdisciplinary research works incorporating geospatial technology like SRS, GIS, and other allied technologies during the pandemic for various services.
- Introduced many visualization tools and dashboards designed for Covid-19 surveillance, which helps understand and regulate the disease's spread.
- Explained the generalized representation of GIS-based disease modelling and surveillance process.
- Provides an insight into the future research perspectives of using geospatial technology advancements for critical decision-making in the fight against the pandemic.

The remaining sections of this paper are arranged as follows. **Section II** describes diverse types of Earth observation for A) environmental monitoring services that geospatial data offered during the pandemic, B) disease control and management services, and C) forecasting and decision-making services during the pandemic granted by geospatial technologies. **Section III** explores some essential geospatial tools for Covid-19 disease modelling and surveillance. **Section IV** analyses the results and findings from different studies, and a conclusion of the paper is given in **Section V**.

II. Observing The Earth For The Impacts Of Covid-19

The Covid-19 pandemic has very much affected human behaviour in many aspects of living and working. The spread of the virus has slowed economic activities that have significant consequences on environmental activities. Accordingly, it is

essential to delve into the positive and negative environmental impacts due to Covid-19 pandemic. However, the commonly used ground-based environmental monitoring services are also limited due to the contagion. Global and regional environmental monitoring currently rely heavily on SRS and sensors capable of rapidly gathering spatial and spectral information from large-scale entities on Earth's surface. The SRS data obtained during the pandemic are valuable for understanding the Earth's behaviour in fighting against the epidemic in various aspects. The SRS data for environmental surveillance is considered necessary due to its benefits, like more extensive spatial coverage over ground-based data, better temporal resolution, and near-real-time monitoring. Various satellites have been engaged in observing the Earth for different objectives. A few important among them are indexed in Table 1.

Table 1. Major Satellites used for Environmental Monitoring

Satellite	Spectral Range (µm)	Spatial Resolution (m)	Revisit Time (day)	Swath Width (km)
Landsat (1–8)	0.433–1.39 (OLI) 10.6–12.5 (TIR)	15/30/60 (OLI) 100 (TIR)	16	170*180
IKONOS-2	0.45–0.9	0.82/3.28	1–3	11.3
Quickbird	0.45–0.9	0.61/2.44	1–6	16.5
GeoEye	0.45–0.92	0.41/1.65	3	15.2
Envisat	C band	10/30/150/1000	35	5/100/400
SPOT(1–7)	0.45–1.75	1150	26	2250
Rapid Eye	0.4–0.85	5	1	77

The Landsat satellite series are used for environmental monitoring services periodically. Also, they have provided a continuous stream of data about the Earth since 1972 and represent the World's longest continuously acquired space-based moderate-resolution RS data. The Landsat8 carries two important sensors: the Operational Land Imager (OLI) and the TIR sensors for monitoring. The work is grouped based on several environmental application areas where the geospatial data are practised for various services and decision-making.

A. Environmental Monitoring Services

Many environmental factors like changing temperature, humidity, precipitation, air quality, and pollutants are either proven or can potentially influence the spread of disease or the consequences of the pandemic on human health. Hence, it is vital to understand these factors in the fight against the pandemic clearly. Several ecological indexes based on SRS are employed in the research to reflect environmental statuses, such as i) Normalized Difference Vegetation Index (NDVI), ii) Air Quality Index (AQI), iii) Normalized Difference Water Index (NDWI), iv) Soil Adjusted Vegetation Index (SAVI), v) Standardized Precipitation Evapotranspiration Index (SPEI), and vi) LST. These indexes are effective empirical indicators that reflect various environmental factors and describe ecological conditions. The details of the satellites providing the essential atmospheric elements of the spreading trend of Covid-19 are enlisted in Table 2.

Table 2. Information Provided by Satellites for Analyzing the Virus Transmission Rate

Data Sources	Information Provided	Covid-19 Related Studies
MERRA-2 [2]	Temperature, Humidity, & other Environmental Elements	Understanding Virus Spreading Trend, Spread-Range & Rate
IMERG [3]	Precipitation Rate	Spread-Range & Rate
VIIRS/DNB [4]	NTL radiance, Human	Human Activity Impact

	Activity, Community Distributions, Human Gathering Levels	Analysis
Aura-OMI [5]	Air Pollutants Concentration	Mortality Rate, Human Activity Impact Analysis

Some vital research works carried out during the pandemic for environmental monitoring services using geospatial data other than infectious disease-based clinical studies are described below.

1) Air Quality Assessment

The primary air pollution sources in the World are power plant/industrial/automobile combustions, bio-mass burnings, and fossil-fuels used in homes and factories for heating processes, etc. One vital research using the SRS that happened right through the *lockdown* is the measure of air pollutants to assess air quality. Many research works were accomplished to measure the percentage of pollutants present in the air during the *lockdown*. Air Quality Assessment (AQA) using satellite retrievals has been noticed during the pandemic [5-11]. They attempted to estimate the total percentage of crucial pollutant factors, like Carbon Monoxide (CO), Nitrogen Dioxide (NO_2), and Sulfur Dioxide (SO_2), in several regions. Atmospheric emissions using TROPOMI/Sentinel-5p and AOD MAIAC/MODIS, Aqua satellite were studied during the *lockdown* and observed a reduced tropospheric NO_2 to a greater level [12, 13].

Subsequently, the research identified that the large-scale *lockdown* invoked caused an extensive reduction in air pollution percentage. Several satellite products like data from Aura satellite, MODIS, and TERRA are exploited [14] to get distinct perceptions of the consequences of pandemic-related *lockdowns* on the air quality in the United States (US). MERRA2 and AIRS data are used [2] to model air quality conditions in several countries. A cost-effective method of AP exposure assessment has been introduced using multiple ML regression models and big data [15]. It provides a clear picture of the atmospheric changes under powerful government-controlling strategies regarding *lockdowns*. MODIS and AIRS data are used [16] and recommended for a complete *lockdown* for 2 to 3 days at least every 2 or 3 months, on a national or global level, which can significantly enhance the air quality levels and promote the health environment of the entire planet.

2) Water Quality Assessment

Several factors influence water quality, including the quantity of some key atmospheric components, the presence of suspended matter, the sun elevation angle, the time of year, submerged or emerged vegetation, water roughness, turbidity, and water depth [17]. Water quality evaluation is a vital area of research, and the influence of *lockdowns* on quality must be investigated. A spatio-temporal turbidity analysis is performed based on Sentinel-2A/2B remote sensing satellite data [18]. An evidential analysis utilizing the spectral bands has been conducted using a Landsat8 OLI sensor [19]. This analysis authenticated that the turbidity level was reduced amid the *lockdown*. Yunus et al. [20] studied the water quality of Vembanad Lake, Kerala using High-Resolution (HR) Landsat8 OLI data. Muduli et al. [21] analyzed the water quality levels of the Ganges river during the *lockdown*. An RS-based prototype is designed to remodel an existing method for retrieving Total Suspended Solids (TSS) concentrations in China's 'Lower Min' river amidst *lockdown* [22]. The results unveiled that the *lockdown* criterion invoked improved the quality of many water sources with reference to specific water quality indexing parameters. The *lockdown* had significant impacts on the water quality levels of the Yamuna, with an enhanced Water Quality Index (WQI) rating, and exhibited a marked drop in the river's Suspended Particulate Matter (SPM) and turbidity levels [23].

3) Agriculture Monitoring

Monitoring the crop/vegetation growth under the effect of Covid-19 is essential for evaluating the agricultural needs of a specific region. The SRS data helps at distinct scales to assess agricultural systems and productivity. Several studies have been conducted to observe and measure the growth percentage of vegetation using the SRS worldwide. Wang et al. [24] discovered no discernible effects on agricultural growth in China during the pandemic period. Their findings help evaluate the impact of Covid-19 on China's agricultural sector, which is promotive to formulating effective agricultural policy and ensuring food security. Hammad et al. [25] provided empirical evidence of the after-effects of the *lockdown* policy on agricultural land greenness in Bali, Indonesia, using ML and SRS data and resulting in an Enhanced Vegetation Index (EVI) croplands. However, [26] showed that India had a good cropping season during the *lockdown* and post-*lockdown* periods.

4) Ocean Monitoring

The EO satellite data offer a unique view of oceans, seas, and coasts. Ocean or sea monitoring is essential for fisheries to food and nutrition and to monitor the night fishing boat navigation during the *lockdown* for security reasons. The drastic presumption of Covid-19 in small-scale fishing sectors has become obvious in many studies. The suitability of using SRS data in monitoring the impacts of Covid-19 related *lockdowns* on the Indian fisheries sector was narrated [27]. Newly available HR, high-frequency satellite data from April 2017 to December 2020 are used to identify seaweed farming, which maps the seasonal changes in the industry in Indonesia [28]. Okyere et al. [29] employed UAV and GIS tools to assess the risks experienced by fishers during the pandemic time frame using "physical distance" as a proxy. The analysis uses a cumulative distribution function (G-function) of the Nearest-Neighbour Distances (NND), covering the major crowded fish-landing beaches, for identifying the potential "hotspots" for disease transmission.

Many works examined for this systematic study used various ML approaches to improve predictability. In addition, they provide timely analysis to handle the pandemic with better solutions for controlling the disease spread in their respective research areas. Some essential research areas analyzed and the ML techniques used in supporting the SRS and GIS data for visualizing, especially during the *lockdown* period (Jan. 2020 – Apr. 2022), have been given in Table. 3.

Table 3. Various GSD based Inter-disciplinary Research Works Happened during the Pandemic

Author	Objective	Study Area	Type of Satellite Data	Period	Methods
Fan et al. (2020) [5]	Air Quality	China	**1.1.1.1 TROPOMI-Sentinel-5P**	Dec. 2019 - Mar. 2020	MAIAC[6]
Metya et al. (2020) [6]	Air Quality	India & China	**1.1.1.2 Atmospheric Infrared Sounder (AIRS), Polar-Orbiting Aqua Satellite (POAS)**	Jan. 2020 - Apr. 2020	Nonlinear Regression
Gonzalez et al. (2020) [7]	Air Quality	Peru	**1.1.1.3 Sentinel-5P**	Mar. 2020 - May 2020	VISAN[1], DOAS[2], PCA[3]
Naqvi et al. (2021) [9]	Air Quality	India	**1.1.1.4 Sentinel-5P**	Feb. 2020 - Apr. 2020	IDW[4], GCM[5], ArcMap
Sathe et al. (2021) [10]	Air Quality	India	**1.1.1.5 MODIS**	Mar. 2020 - Apr. 2020	MAIAC[6]
Zhao et al. (2022) [13]	Air Quality	City of Toronto	**1.1.1.6 TROPOMI, Pandora Sun Spectrometer**	2020–2021	Wind rotation-based satellite validation technique
Tripathi et al. (2020) [18]	Water Quality	Patna City	Sentinel-2A/2B	Mar. 2020 - Apr. 2020	Water Pixel Extraction, NDWI[7]
Yunus et al. (2020) [20]	Water Quality	Vembanad Lake, Kerala	HR Landsat8 OLI	Apr. 2013 - Apr. 2020	SPM[8]
Muduli et al. (2020) [21]	Water Quality	The Ganges	Sentinel-2	Mar. 2020 - May. 2020	ANOVA[9]
Wang et al. (2020) [24]	Crop Monitoring	China	Sentinel-2, MODIS	Jan. 2020 - Mar. 2020	Cloud Computing, Google Earth Engine
Rabha et al. (2021)[26]	Crop Monitoring	India	ResourceSAT- 2/2A	2019 - 2020	MVC[10]
Avtar et al. (2021) [27]	Fishing Sector	India	HR PlanetScope Imagery	Mar. 2020 - May 2020	SVM[11]
Okyere et al. (2020) [29]	Fishing Sector	Central Region of Ghana	UAV, GIS	10th Apr. - 23rd Apr. 2020	NND[12]

(1)VISAN is a cross-platform library for analysis and visualization applications for atmospheric data. (2) Differential Optical Absorption Spectroscopy. (3) Principal Component Analysis. (4) Inverse Distance Weighting. (5) Graduated Color Map (6) Multi-Angle Implementation of Atmospheric Correction. (7) Normalized Difference Water Index. (8) Suspended particulate matter. (9) ANalysis Of VAriance. (10) Maximum Value Compositing. (11) Support Vector Machine, (12) Nearest-Neighbor Distance.

Most of the listed works are supported by ML and DL techniques to better predict and visualize results. These techniques are essential for Covid-19 disease control and management services and forecasting and decision-making in real-time.

B. Disease Control and Management Services

For preventing and controlling Covid-19, the services provided by geospatial technology are essential. For the study, we have mainly concentrated on the early monitoring of this infectious disease. The inbuilt capability of geospatial technology is well considered to investigate the risk factors incorporated in the spread of the pandemic. The disease control and monitoring using GIS have been facilitated by integrating remote sensing, Database Management Systems (DBMS), computer cartography, and geo-statistics. Moreover, they have been utilized for mapping, monitoring, visualizing, monitoring, retrieving, analyzing, and modelling the pandemic. These powerful technological interventions are heavily relied on for disease control and management due to their ability to store massive data related to demographic patterns. The GIS-based disease mapping depends on identifying a number of prospectives like i) locations of disease occurrence, ii) patterns of disease spread, iii) environmental risk factors leading to disease spread, and iv) socio-economic data for analyzing spatial relationships within the affected area and helping in real-time forecasting services. The important activities performed for better management are listed below.

1) Monitoring Evolution and Impacts of Pandemic

In the fight against Covid-19, the SRS and GIS technologies have played an essential role in many aspects. The various roles include i) rapid aggregation of multi-source data, ii) visualizing epidemic information, iii) spatial tracking of confirmed cases, iv) prediction of regional transmission, v) spatial segmentation of the epidemic risk, and vi) prevention level, which provides spatial information supporting for decision-making, measures formulation, and effective evaluation of epidemic prevention-control activities. Studies used different statistical and spatial analytical techniques to investigate the correlation between Covid-19 cases with the temperature, wind speed, solar radiation, daylight hours, and humidity factors. Another application of GIS data in Covid-19-related studies is to determine whether the meteorological factors are associated with the virus's transmission.

GIS data are not commonly utilized to track or predict the disease's trend of transmission pattern at the initial stages. However, later on, GIS data are used essentially to indicate the number of Covid-19 verified cases, and specific locations of the outbreak, with higher statistical precisions, have been shown [30]. An AI-based method is presented for real-time forecasting of new and cumulative verified Covid-19 cases in total and provinces/ cities across China [31]. In addition, a new hybrid forecasting method using Nearest Neighbours (NN) and multivariate clustering has been proposed for forecasting the outbreak of the epidemic [32]. A simulated forecasting trend of virus spread is employed using a GIS environment and AI [33]. By using AI technologies, appropriate strategic decisions are made in real-time to identify risks for combating Covid-19, which has been declared a natural disaster that caused great harm to humanity. Zhou et al. [34] analyzed the spatial representations of the disease, materials, population, and social psychology at three scales: individual, group, and regional, using GIS and big data technologies.

2) Human Activity and Traffic Pattern Monitoring

Understanding the dynamic nature of human mobility and traffic pattern change is indispensable for evaluating the impacts of non-pharmaceutical conditions like stay-at-home orders, *lockdown*s, and travel regulations during the pandemic. Spatio-temporal analysis employing SRS images as an alternative plays a significant role in comprehending the global impacts of extremely intense occurrences. Chen et al. [35] proposed a method that utilizes the high temporal Planet SRS data to perceive the traffic patterns and their correlation with Covid-19. A road traffic volume analysis in Gliwice before and during the restrictions related to Covid-19 using video RS [36]. A DL-based approach is introduced [37], combining the location sampling with an ensemble of *lightweight* Convolutional Neural Networks (CNN) to compute the economic indicators using the xView satellite images. Many economic indicators were identified that could analyze issues connected with the supply-chain, by counting the number of trucks, trains, or containers. Observing moving vehicles in rural areas helps evaluate the agricultural activity and

vehicle movements in factories aid in measuring industrial activities. The pool of indicators usually differs based on the regional concerns of each city.

Observing the Earth during the night provides perceptions into many human behaviours, from the observation of various religious or cultural events to illegal fishing to decreased city traffic [64]. The Nighttime Light (NTL) imagery shows the Earth's surface and atmosphere with a sensor intended to capture Low Light Emission (LLE) sources under varying illumination conditions, which can aid in understanding how NTL changes due to changes in human behaviours [63]. The NTL data acts as an effective measure for evaluating long-term socio-economic specifications like human population monitoring, electrical power consumption, greenhouse gas emissions, etc. The NTL data is extensively used in monitoring the effects of several unexpected events like war, natural disasters, large-scale power outages, etc. Also, they are employed in tracing fisheries, measuring environmental effects, and evaluating issues like light pollution and animal living habits. The spatio-temporal patterns of Covid-19 impact on human activities are studied using the NTL and air quality data [38].

Lan et al. [4] studied the impact of Covid-19 on humans with the help of NTL extracted from the Visible Infrared Imaging Radiometer Suite (VIIRS). The study shows that Covid-19 had a clear and observable impact on almost all major cities, like changes in human activities, community distributions, and human gathering levels. Christopher et al. [39] explored the effects of dimming lights during a *lockdown* in China and discovered a 3%–24% decrease in illumination brightness. SAR images detect traffic patterns throughout the *lockdown* in Rome - Fiumicino International Airport [40]. The changes in economic activities and environmental impacts are studied using the NTL during the *lockdown* in the US [41]. Yin et al. [42] focused on assessing the rehabilitation of city activity in China's Eastern and Southern areas around the period in early 2020 using NTL data.

3) Tracking and Measuring Lockdown Effects

Together with ground data, SRS imagery provides an outstanding Situation Awareness (SA) mechanism and can track hospital facilities and other public health infrastructures. The satellites precisely monitor the sub-meter resolutions of critical areas, like tourism attractions, cultural points, and public transport hubs. The consequences of the Covid-19 *lockdown* in Spain are well-studied [43]. Pulella and Sica [40] demonstrate the potentiality of existing RS constellations for situational awareness applications. The spatial-temporal variations of LST before and after the lockdown, in response to the spread of Covid-19, for three major Indian cities located in different climate zones (New Delhi, Hyderabad, and Mumbai) are studied [44]. The impact of the Covid-19 lockdown on human mobility trend patterns, air quality, and utility consumption in Sharjah, United Arab Emirates (UAE) is analyzed [45].

Rich datasets are generated to help the global public administrations by combining SRS imagery with other open data sources. Thereby increasing crisis monitoring, anticipating public needs, enforcing restrictive measures, and ensuring safety in public spaces. By tracking the goods' movements in ports and on major roads, SRS data are used to model the outbreak's impact and the momentum of ultimate economic recovery. SRS imagery helps track areas where viruses are more likely to appear or where particular risk indicators are prevalent. Satellite images have tremendous potential for transforming disaster management and resettlement planning in many regions of the World.

4) Tracking Location-based Services

Spatial data science and location-based data have become more important than ever during this pandemic. Geospatial and RS abilities are useful in limited human interactions and appropriateness and less time-consuming in visualizing the spreading pattern and the fight against the pandemic. GIS data has always been identified as a tool for managing the response to the pandemic by using Location-Based Service (LBS) technology that helps understand the situation at hand, develop a response, and prepare a road to recovery. Location information plays a critical role in managing and controlling the spreading rate of the virus and protecting our communities. The LBS provides tools required for collecting data, mapping the current crisis, simulating the results from modelling response variables, contact tracing and determining hot spots, managing high-risk locations, and distributing help where it is needed most. The LBS has an influential impact on the lockdown measures and imposing social distancing situations. Several innovative geospatial services have emerged as a result of the pandemic regulations.

Smith and Mennis [46] identified various applications of GIS technology like i) developing spatial data frameworks for data sharing and surveillance, ii) incorporating mobility data for forecasting infectious disease, iii) using geospatial technologies for digital contact tracing, iv) integrating geographic data for Covid-19 modelling, v) investigating geographic, social

vulnerabilities and health disparities, and vi) communicating the status of the disease or facilities for returning to a regular operation, etc.

Digital Contact Tracing

With the Covid-19 pandemic, Location Awareness Technologies (LAT) using GIS and GPS have renewed interest in contact tracking facilities [62]. Massive volumes of user data collected are transferred into the GIS frameworks for analysis, and visualization maps are generated for various decision-making. GIS and GPS data of travel routes are mapped to determine the paths of infected individuals and modes of transportation used for contact tracing. Ahmed et al. [47] show a detailed survey of different contact tracking applications using geospatial data with timestamps. A powerful strategy for epidemic prevention and control supported by spatio-temporal trajectory data collection, big data compilation from multiple sources, and GeoAI–based real-time data analysis is shown [48].

Transportation of Critical Items

During the epidemic, many places worldwide used GIS and drone technologies [49]. Drones are utilized for many purposes, like monitoring, delivering food and medicine, thermal scanning, ensuring social distancing, and alert systems. Drone technology has been utilized to its full potential for the rapid transportation of i) critical medical supplies, ii) personal protective equipment, and iii) Covid-19 samples to testing centres, resulting in accelerated testing of infected cases and timely management of the critical situation [50-52]. Also, drones are being engaged in disinfection duties in public places and organizations. Sarfo and Karuppannan [53] studied the utilization of geospatial technologies in the fight against Covid-19. In India, many analyses of Covid-19 instances have been conducted using GIS technology during the pre-lockdown, lockdown, and unlock phases [54]. Geospatial technology has come out with several valuable solutions that could address the pandemic scenario involving Covid-19.

C. Forecasting and Decision-Making Services

Forecasting during the pandemic is essential for effective governmental decision-making, managing supply chain resources, and informing very difficult political decisions like imposing a lockdown or curfews [32]. The forecasting and decision-making for disease control and prevention are done based on various forecasting techniques and different data sources. Machine learning and Artificial intelligence (AI) techniques can benefit in handling the massive, extraordinary amount of time-series and SRS data for better forecasting and decision-making. Also, big data analytics presents an indispensable role in building the knowledge required to make decisions and preventive measures. The AI-ML-inspired SRS methods are considered powerful tools for helping public health planning and policymaking. They provide timely interventions to ensure the significant health effects of Covid-19. Every activity listed in the previous section (Disease control and management) provides essential information for timely forecasting and decision-making regarding the pandemic outbreak. Some of the areas in which forecasting and decision-making can help prevent the disease's spread are listed below.

1) Forecasting on Lockdown Policies

Forecasting models help the authorities decide where to implement control, preventive, and surveillance measures using the lockdown policies, which are considered a very effective way of controlling the outrage. The decisions regarding the lockdown policies can be made from several aspects of data related to the pandemic spread. The environmental monitoring services also provide great decision-making strategies regarding the lockdown criteria. In the decision-making process, a massive volume of past data is analyzed to get a clear perspective of the current scenario of a specific region. However, data availability in huge volumes provided by GIS-based applications is essential for effectively modelling forecasting services.

2) Forecasting Transportation Policies

For formulating the travel and transportation policies, the Panchromatic images provided by the WorldView-3 satellite with a ground sample distance of 0.3m around the Globe are considered valuable assets to measure the impacts of Covid-19 on society. Understanding the dynamics of human mobility change at high spatial-temporal resolution is critical for assessing the impacts of policy interventions during the Covid-19 pandemic. Human activity and traffic pattern monitoring provide timely forecasting measures related to travel and transportation. The SRS and GIS data are employed to facilitate immediate, remote, and real-time assessments for varying human activities and vehicle detection. The aircraft count in many airports and the number

of rental cars in a parking lot before and after the outbreak for a similar period illustrate a decrease in travelling provoked by the epidemic and its consequences on aviation and car rental businesses [37].

Although a decreased number of daily flights are seen at many airports due to the pandemic, the NTL patterns of many airports were seen as brighter than they were before the outbreak of Covid-19. This pattern is due to the increase in the brightness of high pole lights established to facilitate epidemic prevention and control measures. Modelling the changes in travel behaviour is also vital for forecasting future demands for different transport modes and timely operational decisions. The transport policy measures are an essential part of the big picture of the fight against Covid-19.

3) Forecasting Supply-chain Disruptions

During this pandemic, the vital human-to-human interactions that kept humans together to enjoy food are digitized. The travel restriction policies and *lockdown* situations imposed by various governments worldwide further affected the supply-demand balance. The *lockdown* criterion has initiated a considerable disturbance among migrant labourers who participate in seasonal harvesting activities. The reduced agricultural activity significantly affected the overall agricultural production and imposing transportation restrictions further disturbed the supply-chain management. With these disruptions, short-term and real-time forecasts regarding the impacts of the pandemic on the supply chain have become a critical managerial and policymaking imperative. For example, [27] reported using satellite data forecasting that the policymakers made informed decisions in the fishing industry during Covid-19. An investigation of how the recent technological advances in RS and AI improved agricultural systems' adaptability for food production and supply systems has been explained [55]. Many economic indicators were identified that could identify issues with various supply-chain processes [37].

III. Geospatial Tools For Covid-19 Modeling And Surveillance

Geospatial technology has emerged as an influential tool for early detection and timely response-recovery process to the Covid-19 disease outbreak. It provides many tools for Covid-19 disease modelling and surveillance other than the mentioned services. They are considered essential for the spatial study of diseases. GIS technology gained popularity in public health [56] and is utilized in many decision-making. GIS provides many visualizations, analytical tools, and dynamic maps to understand the geographical spreading pattern of diseases, which help analyze i) frequent cases, ii) disease mapping and visualization, iii) spatial clustering of regions, iv) the impact of environmental factors on the disease, etc. Geospatial dashboards and service frameworks for infectious disease surveillance are developed using web-based mapping of GIS with real-time infectious disease-related information. With the technological advancements in big data and AI, the Geospatial services for Covid-19 disease surveillance illuminate the path for decision-makers and public health personnel for implementing web-based, spatio-temporal health information systems and epidemiological modelling tools for predictions.

A doppler radar-based physiological sensing technology has been described for the fight against Covid-19, including remote breathing monitoring, continuous identity authentication, occupancy sensing, and hand gesture recognition [57]. Time-series analysis is performed using several RS indicators to identify remotely sensed products that may contribute to Covid-19 disease transmission [58]. Bhattacharjee et al. [59] reviewed the prospect of using SRS and GIS using various cases. GIS and big data technologies have rendered an essential role, which includes i) rapid aggregation of a massive volume of multi-sourced big data, ii) quick visualization of epidemic information, iii) spatial tracking of confirmed cases, iv) prediction of regional transmission, v) epidemic risk and prevention level, vi) balancing and managing the supply and demand of material resources, and vii) social-emotional guidance and panic elimination [34]. It also provided solid spatial information support for decision-making, measures formulation, and effectiveness assessment of Covid-19 prevention and control. Pardo et al. [60] reviewed 63 research articles on geospatial and spatio-statistical analysis of the geographical dimension of the pandemic, with several themes for disease mapping like spatiotemporal analysis, health-social geography, environmental factors, data mining, and web-based mapping.

The Covid-19 pandemic is full of unknowns with spatial dimensions, which needs to be understandable the phenomenon as a geographical and potentially mappable entity. Thus, the Covid-19 study requires a variety of approaches to explain the phenomena, including spatio-temporal analysis, geographical influence on decision-making, and prediction modelling of disease evolution. For the above-discussed reasons, the use of geospatial tools has become particularly relevant. Geospatial technology provides many visualizations and analytical tools to public health professionals and decision-makers to execute disease control programs.

A. GIS-based Disease Surveillance System

The disease surveillance system needs a powerful main geospatial server that automatically stores and processes data. A lot of disease-related data are collected and analyzed to prevent or control the occurrence of an outbreak. The infection-related outcome help to undertake forecasting measures quickly to reduce disease spreading. Several geospatial tools and visualization techniques were utilized for the decision-making process with the support of ML and AI techniques. A generalized graphical representation of the GIS-based disease modelling and surveillance system is given in Figure 2.

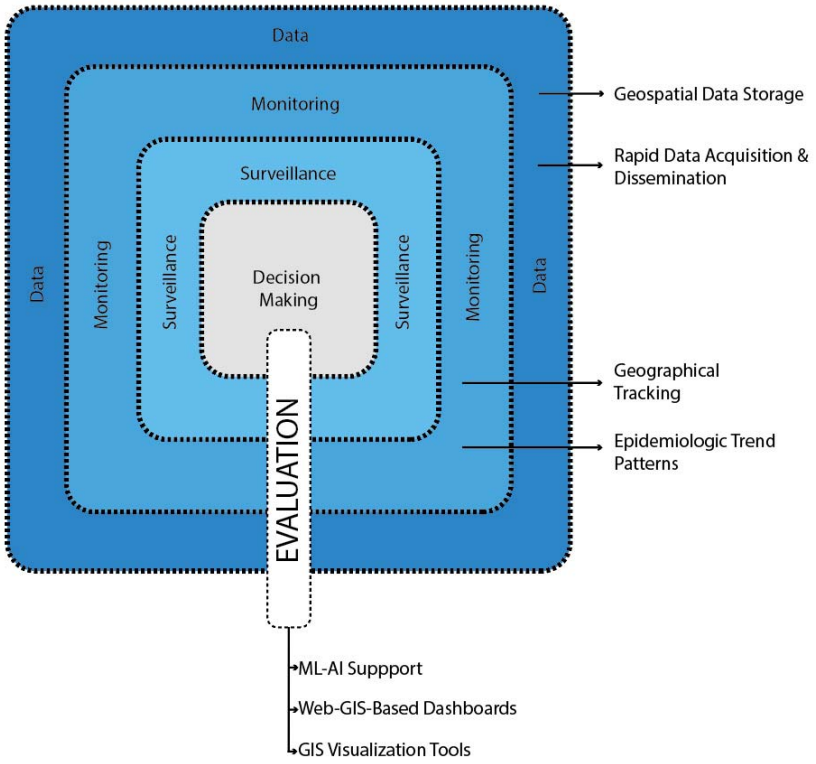

Figure: 2 Generalized Representation of GIS-based Disease Modelling & Surveillance Process

Some GIS tools used for data cataloguing, mapping, visualization, and analysis are ArcMap [9], Google Earth Engine [48], VISAN [7], Graduated Color Map [9], etc. Other than the listed GIS tools, many popular tools, like ArcGIS, QGIS, Kosmo, GIS Cloud, Google Maps, etc., visualize spatial patterns efficiently. Many GIS-based dashboards and application platforms were designed for disease surveillance. Some of the essential applications are listed below:

- *Johns Hopkins University Dashboard*

  It is the best example of a web-based near-realtime Covid dashboard created by Johns Hopkins University [61]. The dashboard's interactive map locates and tallies confirmed infections, fatalities, and recoveries, utilizing authoritative data sources from the i) World Health Organization (WHO), ii) US Centers for Disease Control and Prevention, iii) National Health Commission of the People's Republic of China, iv) European Centre for Disease Prevention and Control, and v) the Chinese online medical resource DXY.cn.

- *ArcGIS Operations Dashboard*

  The WHO provides the ArcGIS operations dashboard for mapping and listing Covid-19 infected cases and the total number of deaths. The visualization of official daily counts of confirmed cases and deaths with time stamps using Esri ArcGIS Online service. The dashboard is automatically updated using the ArcGIS GeoEvent Server.

- *BHUVAN Covid-19 Geospatial Solution*

This dashboard is an initiative of ISRO for the time-series visualization of active, recovered, and deceased cases. It provides a graphical analysis of the state-wise spread trend of the pandemic.

- *DHIS2 Maps*

  DHIS2 is designed by the Health Information Systems Programme (HISP) at the University of Oslo (UiO) as an open and distributed process with developers from India, Vietnam, Tanzania, Ireland, and Norway. It provides standardized tools to support Covid-19 surveillance. The DHIS2 Maps App offers a more intuitive and user-friendly interface mapping engine based on WebGL technology, capable of simultaneously showing thousands of features on a map. Thematic maps of areas and points can be generated with multiple layers using the App.

Modern GIS technologies centre around many web-based tools with improved data sharing and real-time information providers to assist in critical decision-making. The incorporation of ML, AI, and big data advancements also support the dashboards and have been essential in sharing data and understanding the spread of the pandemic, and helping authorities remain vigilant. Several countries use these dashboard services for the surveillance of Covid-19. Figure 3 shows the DHIS2 map generated for the surveillance toolkit deployed and tested in different regions of the World.

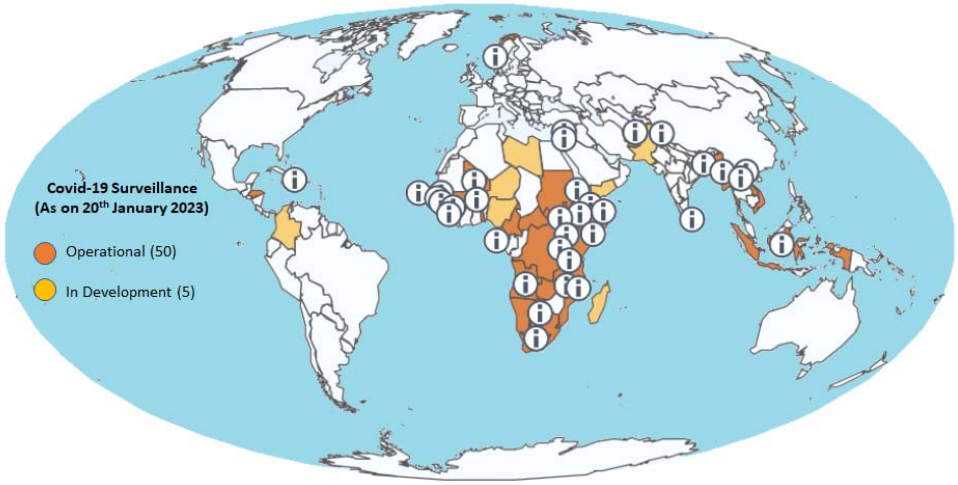

Figure: 3 DHIS2 Deployment Status as on 20th January 2023

IV. Results And Discussion

This integrated review analyzed various interdisciplinary research works that happened using the SRS and geospatial data during the pandemic related to three primary services: i) environmental monitoring services, ii) disease control and monitoring services, and iii) forecasting and decision-making services. This study also mentions the vital GIS tools used in disease modelling and surveillance. The detailed investigative analysis of the works mentioned in this paper contributes valuable knowledge concerning the geospatial data services and their impact during the pandemic. Satellites provide various data types with local, regional, and global coverage and are advantageous for monitoring the areas that are unreachable using ground-based measurements for assessing water quality, precipitation, and other environmental factors. Using the satellite data, assessments are made regarding the air and water quality, land surface, irrigation needs, and crop health human activity monitoring in near real-time. Although many challenges exist in using the SRS depending on the application area, incorporating ML, AI, DL, and big data modelling makes them more robust and integrated forecasting and decision-making systems during the pandemic. Advances in satellite measurements also allow researchers to study large regions with improved accuracy for their respective research areas.

We could find some divergence in the literature concerning the representativeness and the time duration of *lockdown* and base periods for various research. However, from the works analyzed, it is clear that the Covid-19-related *lockdown* restrictions have resulted in a decreased traffic volume and other economic activities in many cities. The air-water pollutants in many parts of the World are very much reduced. In this novel study, several important inter-disciplinary research works carried out throughout the Covid-19 pandemic have been narrated. In the period from Dec. 2019, a major percentage of research has been contributed to

many domain-specific research works using various types of geospatial data services. The volume of research areas and usage percentage of geospatial data are summarised in Figures 4(a) and 4(b).

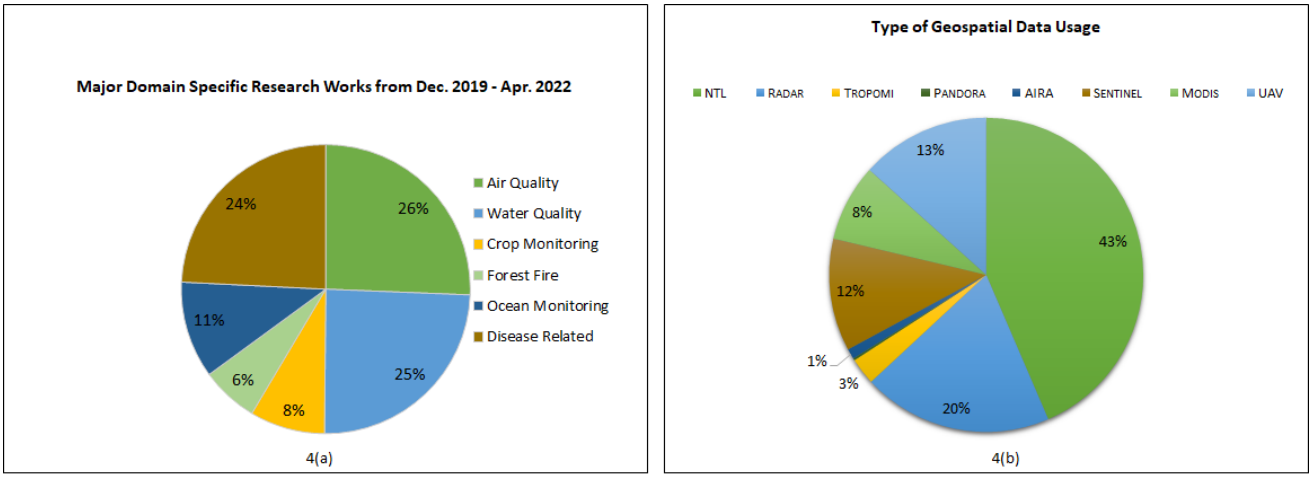

Fig: 4(a) The Percentage of Domain-Specific Research Works, 4(b) Geospatial Data Usage during Covid-19

A.Evaluating Environmental Monitoring Services

Air Quality Measure

All research works mentioned in this systematic review strongly report that the Covid-19 *lockdown* effectively reduced the overall AP throughout India and other countries. Another significant implication of the findings from the studies is that the government policies of restrictions on travelling in several regions due to *lockdown* had a crucial impact on the reduction of air pollution in the respective areas. In many regions, the Ozone Monitoring Instrument (OMI) satellite observations showed a sharp 70–80% decrease in tropospheric NO2 levels between December 2019 and February 2020.

Water Quality Measure

It is seen from many works that the *lockdown* scenario has an improved water quality percentage by the reduced contamination of the up and downstream water sources in many regions.

Area of Boats Detected

The *lockdown* period experienced restrictions in the fishing sectors; hence, the collective number of boats identified in the sea and land has varied much in many coastal regions. The number of boats identified on the sea and land during the pre-*lockdown*, *lockdown*, and unlocking phases shows the *lockdown* effects on fishing sectors.

B. Evaluating Disease Monitoring

The SRS and GIS technologies are widely used in disease surveillance and early disease warning because of their powerful geospatial data acquisition, management, processing, analysis, and visualization capabilities. Big data analytics is also becoming important for predicting virus transmission, infection control, and emergency response assessments during the disease outbreak. Various mapping techniques have been utilized to track and understand the spatial and temporal distributions of Covid-19, which can predict the disease spread pattern. Several Web-GIS-based dashboards have been developed for Covid-19 data visualization, employing GIS tools to understand the overall outbreak patterns in real-time to identify high-risk populations and intervene accordingly by evaluating existing facilities or creating new healthcare infrastructure.

Moreover, the NTL patterns at the entrances and exits of some expressways also increased during the epidemic, which helped implement the active monitoring and control measures for Covid-19. Therefore, monitoring NTL pattern changes in specific locations helps evaluate the urban planning process and preventive measures against the epidemic [40]. A drastic activity reduction over the apron areas directly connected with the terminal buildings was noticed in the study. The activity monitoring approach can effectively support analysts in many decision-making processes to bridge the gap between data and underlying insights. The changing trend patterns in the daily NTL intensities can reflect the impact of the epidemic in a city and the city's

recovery process. For example, before the pandemic, China's lighting and electricity demand showed an upward trajectory, tracking the expansion in construction and economic activity levels. The NTL patterns showed a reverse trend during the Covid-19 lockdown, resulting in a declined lighting brightness as captured by the satellite [4].

This systematic study ensures that the SRS and GIS technologies could effectively detect the environmental changes and the changing pattern of daily human activities during pandemic lockdowns for timely decision-making. A summary of the evaluations is detailed in Table 4.

Table 4: Summary of Result Evaluation

Domain of Research	Service Category	Effect due to	Observation during Lockdown Period
Environment Monitoring	Air Quality Measure	Tropospheric NO_2, CO & O3 levels	Reduced API
	Water Quality Measure	SPM & Turbidity	Increased WQI
	Crop Monitoring	Travel Restrictions	Less affected
	Fishing Sector	Lockdown	Reduced No. of Boats
Human / Economic Activity Monitoring	Community Gathering	NTL Pattern	Reduced Illumination
	Traffic Activity Monitoring	NTL Pattern	Reduced Traffic
	Supply Chain	Travel & Transportation Restrictions	Limited supply-demand balance
Disease Monitoring	Digital Contact Tracing	Rapid Spreading of Disease	Increased use of Location Awareness Technologies
	Transportation of Critical Items	Travel & Transportation Restrictions	Several Countries Introduced Drone-based Services
	Spreading Pattern of Virus	Environmental Factors	Reduced Spreading

C. Findings from the Study

Based on the systematic analysis, the following vital research findings are derived.

- SRS and GIS data have played an essential role in curbing the spread of the infection, mainly by helping to identify risk zones and facilitating quick response.
- Several environmental studies, such as air and water quality assessments, have been conducted utilizing SRS and GIS data. During the *lockdown*, the quality factor is said to have increased in many regions.
- No correlation was identified between the percentage of dimming lights in February 2020 and the "Covid-19 confirmed case" numbers in the mentioned research work. This finding suggested that the dimming of lights was associated with "stay-at-home" *lockdown* orders implemented to slow down the virus transmission.
- The analysis identifies that the NTL trend's recovery patterns can indicate economic recovery and recovery of affected cities in various regions. Utilizing daily satellite NTL patterns detects dynamic, influential changes in socio-economic activities caused by public health emergencies like Covid-19 promptly and effectively.
- In agreement with the studies, the reduced percentage of air-water pollution contributed significantly to reducing the viral transmission rate and increased the infected persons' survival capability. Policymakers can use these research findings to identify the sources of pollution and take action to enhance the air-water quality.
- It is inferred that the travel restrictions have substantially reduced the percentage of NO_2 and CO pollutants that are directly correlated with the transportation sector in most cases.

- Another group of studies has discussed that the global pandemic has exposed the extreme vulnerability of cities and called for reconsidering the way urban tourism, food, and environment systems are developed and governed.
- Minimized human-to-human contacts are encouraged using drones for autonomous delivery of medical and commercial supplies during the *lockdown* with improved efficiency and speed.
- The GIS-based dashboards are essential in providing real-time information to support critical decision-making against the fighting pandemic with the help of other ML, AI, and big data technologies.

Satellites strikingly capture the immediate effect of change in human behaviour on environmental factors. GIS-driven spatial health information, remote sensing, telemedicine, satellite communication, and global navigation satellite systems play a major role in countering the Covid-19 crisis. Geospatial technology in the form of Geospatial Artificial Intelligence (geoAI) is emerging as a powerful and booming research area with numerous access to health facilities such as monitoring, diagnosis, screening, quarantine, treatment, disinfection operations, and transport. The potential of geospatial technology is relevant to a variety of research and can be a useful tool for different health investigators' decision-making. The study proved that SRS applications combined with ML, AI, and DL technologies had more impact on environmental analysis during the epidemic. SRS and GIS are not merely the tools in our fight against the global pandemic but are proved to be the most important ones that help map, predict, and plan our moves and decision-making policies. Due to various data management strategies, geospatial data capabilities are unlimited and are analyzed in real-time, resulting in a quick recovery from the pandemic.

V. Conclusion

Three primary interdisciplinary services, i) environmental monitoring services, ii) forecasting and decision-making services, and iii) location-based services that happened using the geospatial data during the pandemic, are analyzed in this novel study. The interdisciplinary behaviour of how the geospatial analysis was utilized in Covid-19-related research was evident among the reviewed works. Although the GIS techniques have considerable potential in planning to minimize the disease spread, surveillance, contact tracing, and identifying the trends and hotspots of the outbreak, they are not exploited as much as possible. This interdisciplinary study contributes an overall view of how SRS, GIS, and other GSD were used in various application areas during Covid-19. Moreover, this study provides a clear perception of how the SRS technologies are used in the Covid-19 disease modelling and surveillance and socio-economic modelling approaches together with ML, AI, and DL techniques.

Our investigative study also provides how SRS and GIS techniques are utilized to extract relevant information to provide knowledgeable decision-making to combat the pandemic. Even though satellite technology is beneficial in many aspects, some limitations are specific to using geospatial data in some applications due to their divergence in spatial, spectral, and temporal nature. Researchers have used ML, AI, and DL computational techniques to tackle the complexities in real-time. Despite the limited utilization of SRS and GIS data in determining the spatio-temporal patterns of this enraged pandemic, there are more opportunities to efficiently utilize these techniques in handling the pandemic. The use of geospatial analysis significantly improved the understanding of the pandemic and addressed the underprivileged demographic groups and communities. The outcome of this study not only explores the services provided by geospatial technology during the pandemic but the support of emerging technologies such as ML, AI, and big data techniques incorporated with geospatial data for early decision-making and control of the spread of the pandemic. Also, the findings are valuable for determining the impact of Covid-19 influence on human life and helping decision-making and forecasting in the effort to combat the pandemic and provide profound implications for future multidisciplinary scientific research using the geospatial data.

Data Availability Statement:

The authors confirm that the data supporting the findings of this work are available within the article.

Conflicts Of Interest:

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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