BioMedpha Volume: 2 Issue:1 6/2025/pp.42-75

A journal of Life, Health, Biomedical, Pharmaceutical and Chemical Sciences

Artificial Intelligence, Geospatial Analytics, and Healthcare Accessibility: Emerging Strategies for Inclusive Pharmaceutical Service Delivery

[1]Irene Omoh Braimoh
[2]Nonso Frederick Chiobi

[1]Fleming College, Peterborough, Canada.
irenebraimoh@gmail.com
[2]University of Jos, Nigeria.
fredchiobi@gmail.com

Abstract

The convergence of artificial intelligence (AI) and geospatial analytics represents a transformative paradigm in pharmaceutical service delivery and healthcare accessibility. This analytical review examines how AI-driven geospatial intelligence addresses systemic inequities in medication access, particularly in resource-constrained and geographically marginalized settings. This paper evaluates the methodological integration of machine learning algorithms with geographic information systems (GIS) to optimize pharmaceutical supply chains, predict accessibility gaps, and inform evidence-based policy interventions. The analysis reveals that hybrid AI-geospatial models demonstrate superior performance in identifying pharmacy deserts, with machine learning-based gravity models achieving 95% population coverage through strategic facility placement (Prabhune et al., 2024). However, critical challenges persist, including algorithmic bias, data heterogeneity, and the digital divide that threatens to exacerbate existing health inequities. The paper synthesizes emerging strategies for inclusive pharmaceutical service delivery, including drone-enabled last-mile distribution, predictive demand forecasting, and equity-centered spatial optimization frameworks. Findings indicate that successful implementation requires addressing data sovereignty concerns, establishing interoperability standards, and embedding equity considerations throughout the AI development lifecycle. This research contributes to the theoretical understanding of how computational intelligence can be leveraged to achieve universal health coverage while highlighting the imperative for context-specific, ethically grounded approaches that prioritize vulnerable populations in pharmaceutical service planning.

Keywords: *Artificial intelligence, geospatial analytics, pharmaceutical service delivery, healthcare accessibility, health equity, GeoAI, machine learning, spatial optimization*

1. Introduction

Healthcare accessibility remains one of the most persistent challenges in global health systems, with pharmaceutical service delivery representing a critical determinant of health outcomes across diverse populations. The spatial distribution of pharmacies and medication access points exhibits profound inequities, creating "pharmacy deserts" where vulnerable populations face insurmountable barriers to essential medications (Wittenauer et al., 2024). These disparities are particularly acute in rural areas, low-income communities, and resource-limited settings where traditional healthcare infrastructure fails to meet population needs. The emergence of artificial intelligence (AI) and geospatial analytics as complementary technologies offers unprecedented opportunities to address these systemic inequities through data-driven optimization, predictive modeling, and evidence-based resource allocation. The integration of AI with geographic information systems (GIS) has catalyzed a paradigm shift in how healthcare planners conceptualize and operationalize pharmaceutical service delivery. Unlike conventional approaches that rely on static demographic data and administrative boundaries, AI-driven geospatial analytics enables dynamic, real-time assessment of accessibility patterns, demand fluctuations, and supply chain vulnerabilities (Chiobi, 2024). Machine learning algorithms can process vast quantities of heterogeneous data, including population density, transportation networks, socioeconomic indicators, disease prevalence, and environmental factors, to generate actionable insights that inform strategic decision-making (Ahmad et al., 2024). This computational intelligence extends beyond descriptive mapping to predictive and prescriptive analytics, enabling proactive interventions that anticipate accessibility gaps before they manifest as health crises.

The theoretical foundation for this convergence rests on spatial accessibility theory, which posits that healthcare utilization is fundamentally shaped by the interaction between geographic proximity, transportation infrastructure, and population characteristics (Kazazi et al., 2022). Traditional spatial accessibility measures, such as the two-step floating catchment area (2SFCA) method, have been enhanced through machine learning techniques that account for distance decay effects, temporal variations, and supply-demand dynamics with greater precision (Hashtarkhani et al., 2024). These methodological advances enable more nuanced understanding of how spatial barriers intersect with social determinants of health to produce differential access patterns across population subgroups. The pharmaceutical sector faces unique challenges that distinguish it from broader healthcare accessibility concerns. Medication supply chains are characterized by complex logistics, stringent regulatory requirements, temperature-sensitive products, and time-critical delivery imperatives that demand sophisticated coordination mechanisms (Bridgelall, 2023). AI-driven geospatial analytics addresses these challenges through multiple pathways: optimizing distribution center locations, predicting demand surges, identifying optimal delivery routes, and enabling alternative delivery modalities such as drone-based pharmaceutical transport (Bridgelall et al., 2024). The COVID-19 pandemic underscored the critical importance of resilient pharmaceutical supply chains, with AI-enabled geospatial frameworks proving instrumental in vaccine allocation strategies for resource-poor settings (Shayegh et al., 2024; Rocha et al., 2021). However, the deployment of AI and geospatial technologies in pharmaceutical service delivery raises fundamental questions about equity, ethics, and implementation feasibility. Algorithmic bias, data privacy concerns, and the potential for technology to exacerbate existing inequalities demand critical examination (Sirmacek et al., 2022). The digital divide, manifested in differential access to technology, data infrastructure, and technical expertise, threatens to create new forms of exclusion even as AI promises to address traditional accessibility barriers (Vaidya et al., 2024). Moreover, the socio-political context of healthcare delivery, including regulatory frameworks, reimbursement structures, and community engagement, shapes the extent to which technological innovations translate into equitable health outcomes. This paper provides a comprehensive analytical examination of how AI and geospatial analytics are reshaping pharmaceutical service delivery with explicit attention to equity and inclusion. The analysis synthesizes evidence from diverse geographic contexts, methodological approaches, and application domains to identify patterns, evaluate effectiveness, and articulate challenges. The research questions guiding this inquiry are: (1) How do AI and geospatial analytics enhance pharmaceutical service delivery and healthcare accessibility? (2) What methodological approaches demonstrate greatest effectiveness in identifying and addressing accessibility gaps? (3) What equity-centered strategies emerge from the literature to ensure inclusive pharmaceutical service delivery? (4) What challenges and limitations constrain the implementation and scaling of AI-geospatial solutions? By addressing these questions, this paper contributes to both theoretical understanding and practical guidance for leveraging computational intelligence to advance universal health coverage and pharmaceutical equity.

2. Literature Review

The scholarly literature on AI, geospatial analytics, and healthcare accessibility has expanded rapidly over the past decade, reflecting growing recognition of technology's potential to address persistent health inequities. Early work in health geography established foundational concepts of spatial accessibility, demonstrating how distance, transportation infrastructure, and facility distribution shape healthcare utilization patterns (Bakimchandra et al., 2020). These studies employed traditional GIS techniques, buffer analysis, network analysis, and nearest neighbor methods, to map healthcare resources and identify underserved areas. However, conventional approaches were limited by static assumptions, inability to account for dynamic demand patterns, and insufficient consideration of supply-side constraints such as facility capacity and service quality.

The integration of AI and machine learning with geospatial methods represents a qualitative advancement in analytical capability. Kazazi et al. (2022) developed a hybrid model combining unsupervised clustering algorithms (K-Means, agglomerative clustering) with supervised learning methods (K-Nearest Neighbors, Support Vector Machines) to map spatial accessibility to healthcare services in Isfahan, Iran. Their analysis revealed that 31% of city blocks exhibited poor spatial accessibility, with marginalized areas experiencing the most severe deficits. Critically, the machine learning approach enabled identification of accessibility patterns that would be obscured by traditional distance-based measures, demonstrating the value of algorithmic sophistication in capturing complex spatial relationships. Subsequent research has extended these methodological innovations to pharmaceutical service delivery specifically. The concept of "pharmacy deserts", geographic areas where residents lack reasonable access to pharmacies, has emerged as a critical focus of inquiry (Wittenauer et al., 2024). Geospatial analysis of pharmacy distribution in Malaysia revealed significant clustering in urban centers with corresponding gaps in rural and remote areas (Tew et al., 2021). Similarly, Xiao et al. (2022) documented spatiotemporal patterns of pharmacy distribution in Chinese cities from 2008 to 2018, finding that while overall pharmacy density improved, regional inequalities persisted. These studies underscore that pharmacy accessibility is not merely a function of absolute numbers but of spatial distribution relative to population needs.

The application of AI to pharmaceutical supply chain optimization has generated a distinct stream of literature emphasizing resilience, efficiency, and equity. Chiobi (2024) articulated a framework for AI-driven geospatial analytics that integrates business intelligence, regulatory compliance, and healthcare equity considerations in pharmaceutical supply chain management. This holistic approach recognizes that supply chain optimization must balance multiple objectives: cost efficiency, regulatory adherence, environmental sustainability, and equitable access. Machine learning algorithms enable dynamic route optimization, demand forecasting, and inventory management that respond to real-time conditions rather than static planning assumptions (Chowdhury et al., 2024). Emerging research on advanced air mobility and drone-based pharmaceutical delivery illustrates the potential for technological innovation to overcome geographic barriers. Bridgelall (2023) developed a hybrid machine learning and GIS approach to identify optimal locations for drone-based pharmaceutical transport, demonstrating that drones with 400-mile range could transport over 28% of pharmaceutical weight in metropolitan areas. Subsequent work extended this analysis to rural settings, showing that drone delivery could significantly reduce costs and delivery times compared to traditional truck-based logistics (Bridgelall et al., 2024). These findings suggest that alternative delivery modalities, enabled by AI-driven spatial optimization, may be particularly valuable for serving geographically isolated populations.

The COVID-19 pandemic catalyzed significant advances in AI-geospatial applications for pharmaceutical service delivery, particularly in vaccine allocation and distribution. Shayegh et al. (2024) developed an AI-enabled, geospatial-assisted decision support framework for prioritizing COVID-19 vaccine allocation in resource-poor settings. Their approach combined expert elicitation surveys with scientific literature screening to construct a vulnerability index that weighted multiple factors at the local level, enabling equitable vaccine distribution based on need rather than administrative convenience. Similarly, Rocha et al. (2021) proposed a geospatial artificial intelligence-based framework for microplanning vaccination campaigns in low-resource settings, demonstrating how granular spatial data combined with predictive analytics could optimize campaign design and implementation. A critical dimension of the literature addresses the intersection of AI-geospatial analytics with health equity and social determinants of health. Ahmad et al. (2024) emphasized that GeoAI enables optimization of healthcare facility placement by analyzing population density, socioeconomic data, and social determinants of health, thereby ensuring equitable access. Liu et al. (2023) developed DeepHealth, a geospatial and machine learning-based approach to identify health disparities and determinants during pandemic response, arguing that policymakers should prioritize upstream population health initiatives rather than solely downstream service provision. These equity-centered approaches recognize that technological solutions must be embedded within broader frameworks that address structural determinants of health inequity.

Methodological literature has increasingly focused on enhancing spatial accessibility measurement through AI integration. Prabhune et al. (2024) developed and validated a machine learning-based gravity model for assessing accessibility to primary healthcare centers, classifying villages by accessibility scores and facilities by utilization burden. Their rule-based algorithm recommended specific actions, upgrading, downgrading, or building new facilities, to optimize accessibility and address burden disparities. Hashtarkhani et al. (2024) created a geoprocessing toolbox incorporating enhanced 2SFCA methods with Python script tools for ArcGIS Pro, enabling healthcare planners to measure spatial accessibility with greater precision and identify underserved areas for targeted resource allocation. These methodological contributions provide practical tools that translate theoretical insights into operational decision support. The literature also documents significant geographic variation in AI-geospatial applications, with distinct patterns emerging across high-income, middle-income, and low-income settings. Studies from high-income countries tend to focus on optimizing existing infrastructure and addressing pockets of disadvantage within generally well-resourced systems (Hong et al., 2022; Obeidat et al., 2024). In contrast, research from low- and middle-income countries emphasizes fundamental gaps in infrastructure, workforce shortages, and the need for innovative solutions to overcome resource constraints (Ganasegeran et al., 2024). This geographic heterogeneity underscores the importance of context-specific approaches that account for local conditions, regulatory environments, and community needs.

Theoretical frameworks guiding this research draw from multiple disciplines, including health geography, operations research, computer science, and public health. The concept of spatial justice, the idea that geographic location should not determine health outcomes, provides normative grounding for equity-centered approaches (Lesslie et al., 2023). Complexity theory informs understanding of pharmaceutical supply chains as adaptive systems characterized by nonlinear dynamics, feedback loops, and emergent properties (Adekola et al., 2022). Sociotechnical systems theory emphasizes that technological interventions must account for social, organizational, and political factors that shape implementation and outcomes (Dahiya et al., 2022). These theoretical perspectives collectively suggest that effective deployment of AI-geospatial analytics requires not only technical sophistication but also deep engagement with the social contexts in which technologies are embedded. Despite substantial progress, the literature reveals significant gaps and limitations. Most studies focus on accessibility measurement and facility location optimization, with less attention to implementation processes, stakeholder engagement, and long-term sustainability. There is limited evidence on cost-effectiveness, scalability, and comparative effectiveness of different AI-geospatial approaches. Few studies examine how AI-driven recommendations are translated into policy decisions or how community perspectives shape technology design and deployment. Moreover, the literature exhibits geographic bias, with underrepresentation of studies from sub-Saharan Africa, South Asia, and other regions experiencing the most severe pharmaceutical access challenges. These gaps highlight the need for implementation science research, participatory design approaches, and expanded geographic coverage in future scholarship.

3. AI Applications in Pharmaceutical Service Delivery

Artificial intelligence applications in pharmaceutical service delivery encompass a diverse array of techniques, algorithms, and implementation strategies that collectively enhance efficiency, accessibility, and equity. The analytical examination of these applications reveals three primary domains: supply chain optimization, demand forecasting and predictive analytics, and decision support systems for resource allocation. Each domain leverages distinct AI methodologies while contributing to the overarching goal of ensuring timely, affordable, and equitable access to essential medications.

Supply chain optimization represents the most mature application domain, with machine learning algorithms demonstrating substantial improvements over traditional logistics management approaches. AI-driven systems analyze multiple variables simultaneously, inventory levels, transportation costs, delivery times, demand patterns, regulatory constraints, and environmental conditions, to generate optimal distribution strategies (Chiobi, 2024). These systems employ reinforcement learning algorithms that continuously improve performance through iterative feedback, adapting to changing conditions in real-time rather than relying on static optimization models. For pharmaceutical products requiring cold chain management, AI systems monitor temperature, humidity, and handling conditions throughout the distribution process, triggering alerts when deviations threaten product integrity (Rangavittal, 2024). This capability is particularly critical for biologics, vaccines, and other temperature-sensitive medications where supply chain failures can result in product loss and compromised patient safety. The integration of AI with advanced delivery modalities exemplifies how computational intelligence enables novel service delivery models. Bridgelall (2023) demonstrated that hybrid machine learning and GIS approaches could identify optimal locations for drone-based pharmaceutical transport, with analysis showing that cargo drones could transport over 28% of pharmaceutical weight in metropolitan areas. The AI system evaluated multiple factors, population density, existing pharmacy locations, transportation infrastructure, airspace regulations, and weather patterns, to determine where drone delivery would provide greatest value. Subsequent research extended this framework to rural settings, where geographic isolation and limited transportation infrastructure create severe accessibility barriers (Bridgelall et al., 2024). The analysis revealed that drone delivery could reduce pharmaceutical delivery costs by 60% compared to traditional truck-based logistics while dramatically improving delivery times for time-critical medications. These findings suggest that AI-enabled alternative delivery modalities may be particularly transformative for underserved populations.

Demand forecasting and predictive analytics constitute a second critical application domain, enabling proactive rather than reactive pharmaceutical service delivery. Machine learning algorithms analyze historical utilization patterns, demographic trends, disease prevalence data, seasonal variations, and external factors (e.g., policy changes, economic conditions) to predict future medication demand with increasing accuracy (Adeyemo et al., 2023). These predictive capabilities enable pharmaceutical distributors and pharmacies to optimize inventory levels, reducing both stockouts (which compromise patient access) and excess inventory (which increases costs and waste). During the COVID-19 pandemic, AI-driven demand forecasting proved instrumental in anticipating surges in medication needs, enabling more effective resource allocation and preventing critical shortages (Shayegh et al., 2024). The sophistication of AI-driven demand forecasting extends beyond aggregate predictions to granular, location-specific forecasts that account for local conditions. Prabhune et al. (2024) developed a machine learning-based gravity model that classified villages by accessibility scores and primary healthcare centers by utilization burden, enabling targeted interventions to address specific accessibility gaps. The model incorporated distance decay effects, population characteristics, facility capacity, and service quality indicators to generate nuanced predictions of healthcare utilization patterns. This granular approach enables pharmaceutical planners to anticipate demand at the community level, ensuring that medication supplies are positioned where they are most needed rather than distributed uniformly across geographic areas with heterogeneous needs.

Decision support systems represent a third application domain, leveraging AI to inform strategic decisions about facility location, service expansion, and resource allocation. These systems integrate multiple data sources, demographic data, epidemiological information, transportation networks, existing facility locations, socioeconomic indicators, to evaluate alternative scenarios and recommend optimal strategies (Ramos et al., 2024). Location-allocation algorithms, enhanced through machine learning, identify optimal sites for new pharmacies or distribution centers by balancing multiple objectives: maximizing population coverage, minimizing travel distances, ensuring equitable access across population subgroups, and maintaining financial viability. Lv et al. (2023) demonstrated that particle swarm optimization algorithms could improve healthcare facility accessibility, achieving approximately 95% population coverage by adding 15 strategically located facilities while reducing accessibility standard deviation from 0.06 to 0.04, thereby enhancing both efficiency and equity.

The application of AI to pharmaceutical service delivery also encompasses medication management and clinical decision support. AI-powered systems assist healthcare providers in developing personalized treatment plans based on patient-specific data, medical history, and predictive analytics (Vaidya et al., 2024). These systems analyze drug interactions, contraindications, and patient characteristics to recommend optimal medication regimens, reducing adverse events and improving therapeutic outcomes. In hospital settings, robotic systems enhanced by AI prepare and track oral and injectable medications, improving accuracy and efficiency while reducing medication errors (Vieira et al., 2023). Barcode scanning technology integrated with AI-driven inventory management systems ensures medication safety throughout the storage, preparation, and dispensing process. Natural language processing (NLP) and conversational AI represent emerging applications with significant potential for pharmaceutical service delivery. AI-driven chatbots and large language models provide medication information, answer patient questions, and facilitate medication adherence through personalized reminders and education (Rangavittal, 2024). These systems can operate 24/7, providing accessible support for patients navigating complex medication regimens or experiencing medication-related concerns. For populations with limited health literacy or language barriers, NLP systems can translate medication information into accessible formats and multiple languages, reducing comprehension barriers that compromise medication adherence and safety.

The analytical synthesis of AI applications reveals several patterns. First, successful applications typically integrate multiple AI techniques rather than relying on single algorithms, combining supervised learning, unsupervised learning, reinforcement learning, and optimization algorithms to address multifaceted challenges. Second, effectiveness depends critically on data quality, with AI systems requiring comprehensive, accurate, and timely data to generate reliable insights. Third, AI applications demonstrate greatest value when embedded within broader sociotechnical systems that account for organizational processes, stakeholder needs, and implementation contexts. Fourth, equity considerations must be explicitly incorporated into AI system design, as algorithms optimized solely for efficiency may inadvertently disadvantage vulnerable populations.

Table 1 synthesizes key AI applications, methodologies, and outcomes documented in the literature, illustrating the diversity of approaches and their respective contributions to pharmaceutical service delivery.

Table 1: AI Applications in Pharmaceutical Service Delivery

Application Domain	**AI Methodology**	**Key Outcomes**	**Geographic Context**	**Reference**
Supply Chain Optimization	Machine learning algorithms, spatial analysis	Improved last-mile drug delivery, enhanced resilience	Cross-continental	Chiobi (2024)
Drone-Based Delivery	Hybrid ML and GIS approach	28% pharmaceutical weight transportable, 60% cost reduction	Metropolitan and rural USA	Bridgelall (2023); Bridgelall et al. (2024)
Vaccine Allocation	AI-enabled expert elicitation, geospatial vulnerability index	Equitable vaccine distribution in resource-poor settings	Resource-limited settings	Shayegh et al. (2024)
Demand Forecasting	AI-driven predictive analytics	Optimized inventory, reduced stockouts	Rural and low-income USA	Adeyemo et al. (2023)
Facility Location	Particle swarm optimization	95% population coverage, reduced accessibility inequality	Urban China	Lv et al. (2023)

Accessibility Modeling	ML-based gravity model, K-Nearest Neighbors	Classification of villages by accessibility, targeted interventions	India	Prabhune et al. (2024)
Medication Management	Clinical decision support, robotic systems	Reduced medication errors, improved safety	Hospital settings	Vieira et al. (2023)
Patient Support	Chatbots, large language models	24/7 medication information, adherence support	North America	Rangavittal (2024)

The evidence demonstrates that AI applications in pharmaceutical service delivery are not merely incremental improvements over existing approaches but represent fundamental transformations in how pharmaceutical systems operate. The shift from reactive to predictive, from static to dynamic, and from efficiency-focused to equity-centered approaches reflects the transformative potential of computational intelligence when thoughtfully applied to complex health system challenges.

4. Geospatial Analytics for Healthcare Accessibility

Geospatial analytics provides the spatial intelligence infrastructure upon which AI-driven pharmaceutical service delivery depends. The integration of geographic information systems with advanced analytical techniques enables precise measurement of accessibility, identification of spatial inequities, and evidence-based planning for pharmaceutical service expansion. This section examines the methodological evolution of geospatial analytics, its application to healthcare accessibility assessment, and the synergies created through integration with artificial intelligence. Traditional geospatial approaches to healthcare accessibility relied on relatively simple distance-based measures, such as Euclidean (straight-line) distance or network distance to the nearest facility. While these measures provided initial insights into geographic barriers, they failed to account for critical factors including facility capacity, population demand, transportation mode availability, and temporal variations in accessibility (Jagadeesan et al., 2021). The two-step floating catchment area (2SFCA) method represented a significant methodological advance, incorporating both supply and demand factors by calculating accessibility scores based on the ratio of available services to population within defined catchment areas. However, standard 2SFCA methods assumed uniform accessibility within catchment boundaries and did not account for distance decay effects, the empirical observation that utilization decreases with increasing distance even within accessible ranges.

Enhanced 2SFCA methods address these limitations through multiple refinements. Hashtarkhani et al. (2024) developed a geoprocessing toolbox incorporating both classic and enhanced 2SFCA methods with Python script tools for ArcGIS Pro, enabling healthcare planners to measure spatial accessibility with greater precision. Their case study of hemodialysis services revealed stark disparities, with urban areas demonstrating accessibility scores of 12.9 to 27.7 dialysis machines within 15-mile radius compared to nearly nonexistent availability in rural regions. The enhanced methods incorporated distance decay functions that weighted accessibility based on travel distance or time, providing more realistic representations of how geographic barriers influence healthcare utilization. These methodological refinements enable identification of underserved areas that might appear adequately served under simpler distance-based measures. The integration of machine learning with geospatial analytics represents a qualitative advancement in analytical capability. Kazazi et al. (2022) developed a hybrid model combining unsupervised clustering methods (K-Means, agglomerative clustering, bisecting K-Means) with supervised learning algorithms (K-Nearest Neighbors, Logistic Regression, Support Vector Machines) to map spatial accessibility to healthcare services. The unsupervised methods identified natural groupings of city blocks based on accessibility characteristics, while supervised methods generated predictive models that could classify accessibility levels for new locations. This hybrid approach achieved superior performance compared to traditional methods, with K-Nearest Neighbors demonstrating highest accuracy in predicting accessibility categories. The analysis revealed that 47% of city blocks exhibited rich spatial accessibility, 22% medium accessibility, and 31% poor accessibility, with the poorest accessibility concentrated in marginal areas distant from the historical city center.

Network analysis constitutes a critical component of geospatial analytics for healthcare accessibility, accounting for the actual transportation infrastructure through which populations access pharmaceutical services. Unlike Euclidean distance measures that assume direct-line travel, network analysis calculates travel distance or time along road networks, accounting for road types, speed limits, traffic conditions, and barriers such as rivers or mountains (Bakimchandra et al., 2020). Dijkstra's algorithm and related shortest-path algorithms enable efficient calculation of optimal routes between population locations and service facilities. For pharmaceutical service delivery, network analysis reveals how transportation infrastructure shapes accessibility patterns, identifying areas where poor road connectivity creates accessibility barriers despite relatively close proximity to facilities. The application of geospatial analytics to pharmacy accessibility has documented pervasive spatial inequities across diverse geographic contexts. Xiao et al. (2022) analyzed spatiotemporal patterns of pharmacy distribution in Chinese cities from 2008 to 2018, constructing a Pharmacy Density Index (PDI) that integrated both population distribution and geographic distribution to assess spatial equity. While the number of pharmacies per 10,000 residents increased from 0.5 to 3 during the study period, with over 85% of cities meeting WHO recommended standards, significant regional inequalities persisted. The PDI revealed that pharmacy distribution was highly uneven, with urban centers exhibiting high density while rural and remote areas remained severely underserved. This pattern reflects broader urbanization trends but also highlights how market-driven pharmacy location decisions may exacerbate geographic health inequities.

Geospatial analysis has proven particularly valuable for identifying and characterizing "pharmacy deserts", areas where residents lack reasonable access to pharmacies. Wittenauer et al. (2024) conducted a comprehensive geospatial study of pharmacy desert locations and characteristics in the United States, revealing that pharmacy deserts disproportionately affect rural areas, low-income communities, and communities of color. The analysis employed buffer analysis and service area analysis to define accessibility thresholds, typically using 1-mile radius in urban areas and 10-mile radius in rural areas as benchmarks for reasonable access. Areas falling outside these thresholds were classified as pharmacy deserts, enabling targeted policy interventions to address these gaps. The geospatial approach revealed that pharmacy deserts were not randomly distributed but systematically concentrated in areas characterized by social vulnerability, highlighting the intersection of geographic and social determinants of health. The integration of geospatial analytics with epidemiological data enables more sophisticated understanding of how accessibility patterns influence health outcomes. Ganasegeran et al. (2024) modeled accessibility to public health facilities in resource-limited settings through GIS and Geo-AI applications, demonstrating how spatial accessibility measures could be linked to disease prevalence, treatment adherence, and health outcomes. Areas with poor accessibility exhibited higher rates of preventable complications, medication non-adherence, and adverse health outcomes, providing empirical evidence for the health consequences of geographic barriers. This evidence strengthens the case for policy interventions to improve pharmaceutical accessibility, moving beyond abstract equity arguments to demonstrate concrete health impacts.

Geospatial collective intelligence approaches represent an innovative methodological direction, combining expert knowledge with spatial data to inform healthcare planning. Vélez et al. (2017) developed a geospatial collective intelligence approach for health planning in Esmeraldas, Ecuador, employing a spatial version of the Delphi method to elicit expert judgments about optimal locations for screening test services. The approach integrated group decision support system (GDSS) and spatial decision support system (SDSS) features, enabling structured deliberation about how to expand coverage of HIV screening tests for pregnant women. This participatory approach ensured that local knowledge and community priorities informed spatial planning decisions, addressing a common limitation of purely technical geospatial analyses that may overlook important contextual factors. The application of geospatial analytics to healthcare accessibility faces several methodological challenges. Data availability and quality vary substantially across geographic contexts, with high-income countries typically possessing comprehensive, high-resolution spatial data while low- and middle-income countries often lack basic infrastructure data (Hierink et al., 2022). Temporal dynamics, including seasonal variations in accessibility due to weather conditions, traffic patterns, or facility operating hours, are often inadequately captured in static accessibility measures. The modifiable areal unit problem (MAUP) affects spatial analyses, as results can vary depending on the geographic scale and boundaries used for analysis. Distance decay functions, while theoretically grounded, require empirical calibration for specific contexts and populations, yet such calibration data are often unavailable.

Despite these challenges, geospatial analytics provides indispensable tools for understanding and addressing pharmaceutical accessibility inequities. The ability to visualize spatial patterns, quantify accessibility gaps, and evaluate alternative intervention scenarios enables evidence-based decision-making that would be impossible through non-spatial approaches. The integration of geospatial analytics with AI amplifies these capabilities, enabling more sophisticated pattern recognition, predictive modeling, and optimization than either approach could achieve independently. As data availability improves and analytical methods continue to advance, geospatial analytics will play an increasingly central role in efforts to achieve universal pharmaceutical access and health equity.

5. Inclusive Strategies and Equity Considerations

The deployment of AI and geospatial analytics in pharmaceutical service delivery must be explicitly oriented toward equity and inclusion to avoid replicating or exacerbating existing health disparities. This section examines strategies documented in the literature for ensuring that technological innovations advance rather than undermine health equity, with particular attention to vulnerable populations, resource-limited settings, and the structural determinants of pharmaceutical access inequities. Equity-centered spatial optimization represents a foundational strategy, requiring that facility location and resource allocation decisions explicitly prioritize underserved populations rather than optimizing solely for efficiency or cost-effectiveness. Obeidat et al. (2024) analyzed healthcare facility distribution in Irbid, Jordan, finding significant access challenges in remote areas and healthcare resource distribution falling short of national and international standards. Their recommendations emphasized equitable resource redistribution, tailored allocation to local needs, improved infrastructure in remote areas, and continuous monitoring to ensure alignment with international standards. This approach recognizes that equity requires active intervention to counteract market forces and historical patterns that concentrate resources in affluent, urban areas while neglecting marginalized communities.

The integration of social determinants of health into AI-geospatial analyses ensures that accessibility assessments account for the multidimensional nature of health inequities. Ahmad et al. (2024) emphasized that GeoAI enables optimization of healthcare facility placement by analyzing population density, socioeconomic data, and social determinants of health, thereby ensuring equitable access. This approach moves beyond purely geographic measures of accessibility to incorporate factors such as income, education, employment, housing quality, and social support networks that shape populations' ability to access and utilize pharmaceutical services. By incorporating these social determinants, AI systems can identify populations facing compounded disadvantages, those experiencing both geographic barriers and social vulnerabilities, and prioritize interventions for these groups.

Participatory design and community engagement constitute critical strategies for ensuring that AI-geospatial solutions reflect community needs and priorities rather than imposing externally defined solutions. Saah et al. (2023) conducted a geospatial evaluation of maternal health service areas in Wenchi Municipality, Ghana, revealing that only 34 of 85 analyzed communities enjoyed easy access to maternal healthcare. Their recommendations emphasized targeted infrastructure development, community engagement programs, and integration of technology to enhance accessibility, recognizing that technological solutions must be embedded within broader community development initiatives. This participatory approach ensures that vulnerable populations are not merely passive recipients of technological interventions but active participants in shaping how technologies are designed and deployed. The development of vulnerability indices and equity metrics enables systematic identification of populations requiring prioritized attention. Shayegh et al. (2024) developed an AI-enabled vulnerability index for COVID-19 vaccine allocation in resource-poor settings, combining expert elicitation with scientific literature screening to identify and weight vulnerability factors at the local level. The index incorporated multiple dimensions of vulnerability, epidemiological risk, healthcare system capacity, socioeconomic factors, and geographic accessibility, to generate composite scores that informed equitable vaccine distribution. This approach demonstrates how AI can be leveraged to operationalize equity principles, translating abstract commitments to fairness into concrete allocation decisions that prioritize those most in need.

Addressing the digital divide represents an essential equity consideration, as AI-geospatial solutions risk creating new forms of exclusion if access to technology, data, and technical expertise is unevenly distributed. Sirmacek et al. (2022) highlighted concerns that AI deployment in healthcare could increase inequalities, particularly among populations with lower AI literacy or access to digital technologies. Strategies to address this challenge include investing in digital infrastructure in underserved areas, providing training and capacity building for healthcare workers and community members, and designing user interfaces that are accessible to individuals with varying levels of technical sophistication. The goal is to ensure that technological innovations enhance rather than constrain pharmaceutical access for digitally marginalized populations.

The integration of equity considerations throughout the AI development lifecycle, from problem definition through algorithm design, validation, and deployment, is essential for preventing algorithmic bias. Vaidya et al. (2024) identified algorithm bias as a major challenge in AI healthcare applications, noting that biased datasets can lead to disparities in healthcare outcomes. Strategies to address algorithmic bias include ensuring training datasets are representative of diverse populations, employing fairness-aware machine learning techniques that explicitly optimize for equity metrics, conducting bias audits to identify and mitigate discriminatory patterns, and establishing accountability mechanisms for algorithmic decisions. These technical strategies must be complemented by governance frameworks that ensure diverse stakeholder participation in AI system design and oversight. Context-specific approaches that account for local conditions, cultural factors, and health system characteristics are essential for effective and equitable pharmaceutical service delivery. Saah et al. (2023) emphasized the importance of context-specific approaches in maternal healthcare planning, recognizing that standardized solutions may fail to address unique challenges faced by specific communities. This principle applies broadly to AI-geospatial applications, requiring that algorithms and interventions be adapted to local contexts rather than assuming universal applicability. For example, accessibility thresholds appropriate for urban areas with dense transportation networks may be entirely inadequate for rural areas with limited infrastructure, necessitating context-specific calibration of accessibility measures and intervention strategies.

Adekola et al. (2022) articulated a comprehensive framework for equitable pharmaceutical access through convergence of AI, blockchain, and pharmacoeconomics in building adaptive pharmaceutical supply chains. Their framework emphasized equitable distribution of essential medications, especially in underserved regions, addressing systemic challenges including logistical inefficiencies, pricing disparities, and regulatory compliance to promote affordability. This holistic approach recognizes that pharmaceutical access inequities stem from multiple interacting factors, supply chain inefficiencies, pricing structures, regulatory barriers, and geographic isolation, requiring integrated solutions that address these factors simultaneously rather than in isolation.

The literature also highlights the importance of upstream approaches that address structural determinants of health inequities rather than solely focusing on downstream service provision. Liu et al. (2023) argued that policymakers should prioritize initiatives protecting population health through upstream interventions rather than solely providing health and social services. This perspective suggests that while AI-geospatial analytics can optimize pharmaceutical service delivery within existing systems, achieving health equity ultimately requires addressing the social, economic, and political structures that produce health inequities in the first place. Technological solutions should be viewed as complements to, rather than substitutes for, structural reforms that address poverty, discrimination, and systemic marginalization.

Table 2 synthesizes equity-centered strategies documented in the literature, illustrating the multidimensional nature of inclusive pharmaceutical service delivery.

Table 2: Equity-Centered Strategies for Inclusive Pharmaceutical Service Delivery

Strategy Domain	Specific Approaches	Target Populations	Implementation Mechanisms	Reference
Spatial Optimization	Equitable resource redistribution, tailored local allocation	Remote and underserved areas	GIS-based facility planning, continuous monitoring	Obeidat et al. (2024)
Social Determinants Integration	Incorporate socioeconomic data, analyze vulnerability factors	Socially disadvantaged populations	GeoAI analysis of population characteristics	Ahmad et al. (2024); Liu et al. (2023)
Participatory Design	Community engagement, local knowledge integration	Vulnerable communities	Community consultation, co-design processes	Saah et al. (2023)
Vulnerability Indexing	Multi-dimensional vulnerability assessment	Resource-poor settings	AI-enabled expert elicitation, composite scoring	Shayegh et al. (2024)
Digital Inclusion	Infrastructure investment, capacity building, accessible interfaces	Digitally marginalized populations	Training programs, user-centered design	Sirmacek et al. (2022)
Algorithmic Fairness	Representative datasets, bias audits, fairness metrics	Under-represented groups	Fairness-aware ML, accountability mechanisms	Vaidya et al. (2024)
Context Adaptation	Local calibration, cultural sensitivity	Diverse geographic and cultural contexts	Context-specific thresholds, community validation	Saah et al. (2023)
Supply Chain Equity	Address pricing disparities, ensure affordability	Underserved regions	AI-blockchain integration, pharmacoeconomic analysis	Adekola et al. (2022)

The synthesis of equity-centered strategies reveals several overarching principles. First, equity must be explicitly operationalized through measurable metrics and accountability mechanisms rather than treated as an abstract aspiration. Second, technological solutions must be embedded within broader social and political strategies that address structural determinants of health inequities. Third, vulnerable populations must be centered in problem definition, solution design, and evaluation rather than treated as afterthoughts. Fourth, equity considerations must be integrated throughout the AI development lifecycle rather than addressed only at the deployment stage. Fifth, context-specific adaptation is essential, as standardized solutions may fail to address unique challenges faced by diverse communities. These principles provide guidance for researchers, policymakers, and practitioners seeking to leverage AI and geospatial analytics to advance pharmaceutical access equity.

6. Challenges and Limitations

Despite the transformative potential of AI and geospatial analytics for pharmaceutical service delivery, significant challenges and limitations constrain implementation, effectiveness, and equity. This section provides critical analysis of technical, ethical, organizational, and systemic barriers documented in the literature, examining how these challenges shape the translation of technological innovations into equitable health outcomes. Data quality and availability represent fundamental technical challenges. AI algorithms require comprehensive, accurate, and timely data to generate reliable insights, yet such data are often unavailable, particularly in resource-limited settings where pharmaceutical access challenges are most acute (Boutayeb et al., 2024). Geospatial data heterogeneity, arising from multiple data sources with varying formats, resolutions, and quality standards, complicates integration and analysis. Jagadeesan et al. (2021) noted that only 14 of 20 pharmacy mapping studies reported distance to pharmacies, and most represented distance as Euclidean rather than network distance, highlighting data limitations that compromise analytical validity. The lack of labeled training data for supervised machine learning algorithms, particularly for specialized healthcare applications, constrains algorithm development and validation (Boulos et al., 2019). These data challenges are not merely technical inconveniences but fundamental barriers that limit the applicability of AI-geospatial solutions in contexts where they are most needed.

Algorithmic bias and fairness concerns pose critical ethical challenges. AI algorithms trained on biased or unrepresentative datasets may perpetuate or amplify existing health inequities, producing discriminatory outcomes that disadvantage already marginalized populations (Vaidya et al., 2024). Sirmacek et al. (2022) documented that lack of diversity in gender, ethnicity, and socioeconomic background among AI developers contributes to biased results, as algorithms reflect the perspectives and priorities of their creators. Under-representation of certain population groups in training datasets leads to algorithms that perform poorly for these groups, potentially resulting in misdiagnosis, inappropriate treatment recommendations, or inequitable resource allocation. The "black box" nature of complex AI models, particularly deep learning algorithms, raises transparency and accountability concerns, as stakeholders may be unable to understand or challenge algorithmic decisions that affect pharmaceutical access (Vieira et al., 2023).

Interoperability and integration challenges constrain the practical deployment of AI-geospatial solutions within existing healthcare systems. Vaidya et al. (2024) identified integration with existing systems as a major challenge, noting interoperability issues, data standardization problems, and compatibility with legacy systems. Healthcare organizations typically operate multiple information systems, electronic health records, pharmacy management systems, supply chain management systems, billing systems, that were not designed to communicate with each other or with AI-geospatial analytics platforms. Achieving seamless data exchange across these systems requires substantial technical investment, organizational coordination, and adherence to data standards that may not exist or may not be widely adopted. In low- and middle-income countries, where healthcare information infrastructure is often fragmented or underdeveloped, these integration challenges are particularly acute (Vieira et al., 2023).

Privacy and security concerns represent significant barriers to data sharing and system implementation. AI-geospatial analytics requires access to sensitive data, patient health information, location data, demographic characteristics, raising concerns about data breaches, unauthorized access, and misuse (Amjad et al., 2023). The collection and storage of geospatial health data create particular privacy risks, as location information can be used to identify individuals even when other identifying information is removed. Sirmacek et al. (2022) highlighted concerns about patient data being used for unrelated applications by corporations or governments, threatening user trust and potentially deterring participation in data collection efforts. Regulatory frameworks such as HIPAA in the United States and GDPR in Europe impose strict requirements for data protection, but compliance is complex and costly, particularly for resource-constrained organizations. The tension between data sharing necessary for AI-geospatial analytics and privacy protection remains unresolved, requiring careful navigation of ethical and legal considerations.

Clinical adoption and user acceptance pose organizational challenges. Healthcare providers may exhibit resistance or skepticism toward AI technologies due to concerns about job displacement, changes in clinical workflows, perceived reliability of AI-driven decision support systems, and loss of professional autonomy (Vaidya et al., 2024). Kuang (2019) noted that people tend to trust doctors more than "a cold machine" when it comes to health problems, highlighting the essential role of human interaction in healthcare. Alert fatigue, where continuous notifications from AI systems desensitize users to important information, can reduce system effectiveness and increase error rates (Vieira et al., 2023). Successful implementation requires not only technical functionality but also careful attention to user experience, workflow integration, training, and change management processes that address provider concerns and build trust in AI systems. Cost and resource constraints limit accessibility of AI-geospatial solutions, particularly for resource-limited settings. Bhattamisra et al. (2023) documented that AI technologies can be expensive and dependent on specific hardware or computational facilities, creating barriers for organizations with limited budgets. The development, deployment, and maintenance of AI systems require specialized expertise that may be scarce in low- and middle-income countries, necessitating substantial investment in capacity building and technical training. Amjad et al. (2023) identified the expense of implementing telemedicine programs and equipment as a significant obstacle, with similar concerns applying to AI-geospatial pharmaceutical service delivery systems. These cost barriers risk creating a two-tiered system where wealthy organizations and countries benefit from AI innovations while resource-constrained settings are left behind, potentially exacerbating global health inequities.

Methodological limitations constrain the validity and generalizability of AI-geospatial analyses. Kazazi et al. (2022) identified several limitations in spatial accessibility studies, including fixed impedance thresholds that may not reflect actual population willingness to travel, lack of reliable information to confirm method results, uncertainty from diverse sources including measurement error, and simplified representations of healthcare services and population locations. The modifiable areal unit problem affects spatial analyses, as results vary depending on geographic scale and boundaries used. Temporal dynamics, including seasonal variations, time-of-day effects, and changes over time, are often inadequately captured in static accessibility measures. These methodological limitations suggest that AI-geospatial analyses should be interpreted cautiously, with explicit acknowledgment of uncertainty and limitations rather than presenting results as definitive truths.

Regulatory and governance challenges complicate AI deployment in healthcare. Vaidya et al. (2024) noted that the regulatory landscape for AI in healthcare is still evolving, requiring clear guidelines and frameworks for responsible and ethical use of AI technologies. Unclear or outdated regulations may hinder innovation or fail to adequately address risks. The global nature of pharmaceutical supply chains and the cross-border flow of health data create jurisdictional complexities, as different countries have varying regulatory requirements for data protection, algorithm validation, and clinical decision support systems. Establishing governance frameworks that balance innovation with safety, privacy, and equity requires ongoing dialogue among regulators, technology developers, healthcare providers, and patient advocates. Sustainability and scalability concerns affect long-term viability of AI-geospatial solutions. Pilot projects may demonstrate technical feasibility and short-term effectiveness but fail to achieve sustained implementation or scaling to broader populations. Factors affecting sustainability include ongoing costs for system maintenance and updates, dependence on external technical support, changes in organizational priorities or leadership, and lack of integration into routine workflows. Scalability challenges include adapting solutions developed for specific contexts to different settings, maintaining performance as systems scale to larger populations or geographic areas, and ensuring that solutions remain effective as conditions change over time. Addressing these sustainability and scalability challenges requires attention to implementation science, organizational capacity building, and adaptive management approaches that enable continuous improvement.

The environmental impact of AI systems represents an emerging concern. Sirmacek et al. (2022) documented that AI development and training require extensive computational resources, leading to significant carbon footprints and increased energy demand. As AI systems become more complex and data-intensive, their environmental costs increase, raising questions about the sustainability of AI-driven approaches. This concern is particularly salient given the climate crisis and the need for healthcare systems to reduce their environmental footprint. Strategies to address this challenge include developing more energy-efficient algorithms, using renewable energy sources for computational infrastructure, and carefully evaluating whether AI solutions provide sufficient benefits to justify their environmental costs. The synthesis of challenges and limitations reveals that technical sophistication alone is insufficient for successful AI-geospatial implementation in pharmaceutical service delivery. Addressing these challenges requires integrated approaches that combine technical innovation with attention to ethical considerations, organizational dynamics, policy frameworks, and social contexts. The literature suggests that many challenges are not insurmountable but require sustained commitment, adequate resources, and collaborative problem-solving involving diverse stakeholders. Critically, the challenges documented in the literature underscore the importance of proceeding thoughtfully and cautiously, with explicit attention to potential harms and unintended consequences, rather than assuming that technological innovation automatically produces positive outcomes.

7. Future Directions

The convergence of artificial intelligence and geospatial analytics in pharmaceutical service delivery is rapidly evolving, with emerging technologies, methodological innovations, and policy developments creating new opportunities and challenges. This section examines future directions identified in the literature, analyzing how anticipated developments may shape pharmaceutical accessibility and equity in coming years. Methodological advances in AI and geospatial analytics promise enhanced analytical capabilities. The integration of deep learning with geospatial data enables more sophisticated pattern recognition and predictive modeling than traditional machine learning approaches (Özdemir, 2022). Convolutional neural networks (CNNs) can analyze satellite imagery and remote sensing data to identify infrastructure patterns, population settlements, and environmental factors affecting pharmaceutical accessibility. Graph neural networks enable analysis of complex network structures, including transportation networks, supply chain networks, and social networks that shape medication access. Attention mechanisms and transformer architectures allow AI systems to focus on most relevant features in high-dimensional geospatial datasets, improving prediction accuracy and computational efficiency. These methodological advances will enable more nuanced understanding of pharmaceutical accessibility patterns and more effective intervention strategies.

The integration of real-time data streams with AI-geospatial analytics enables dynamic, adaptive pharmaceutical service delivery systems. Internet of Things (IoT) sensors can monitor medication inventory levels, cold chain conditions, and facility utilization in real-time, triggering automated responses when thresholds are exceeded (Boulos et al., 2019). Mobile phone data can provide real-time information about population movements, enabling demand forecasting that accounts for temporal variations and special events. Social media data can identify emerging health concerns or medication shortages, enabling proactive responses. The challenge lies in developing analytical frameworks that can process these diverse, high-velocity data streams while maintaining privacy protections and avoiding information overload. Successful integration of real-time data will enable pharmaceutical systems to shift from reactive to anticipatory, addressing accessibility challenges before they manifest as health crises. Blockchain technology integration with AI-geospatial analytics offers potential for enhanced supply chain transparency, security, and equity. Adekola et al. (2022) articulated a framework for convergence of AI, blockchain, and pharmacoeconomics in building adaptive pharmaceutical supply chains, emphasizing equitable global drug access. Blockchain's distributed ledger technology enables secure, transparent tracking of pharmaceutical products throughout the supply chain, reducing counterfeiting, ensuring product integrity, and enabling verification of ethical sourcing. Smart contracts can automate transactions and enforce compliance with regulatory requirements and equity commitments. The integration of blockchain with AI-geospatial analytics could enable pharmaceutical supply chains that are simultaneously efficient, secure, and equitable, though significant technical and governance challenges must be addressed to realize this potential.

Personalized pharmaceutical service delivery, enabled by AI analysis of individual patient data combined with geospatial context, represents an emerging direction. AI algorithms can analyze patient characteristics, medical history, genetic information, and environmental exposures to recommend personalized medication regimens and delivery modalities (Vaidya et al., 2024). Geospatial context, including proximity to pharmacies, transportation options, environmental exposures, and neighborhood characteristics, can be incorporated into personalized recommendations, ensuring that treatment plans are feasible given patients' geographic circumstances. This personalized approach could improve medication adherence, therapeutic outcomes, and patient satisfaction, though it raises important questions about data privacy, algorithmic fairness, and equitable access to personalized services. The expansion of alternative delivery modalities, including drones, autonomous vehicles, and robotic systems, will reshape pharmaceutical service delivery geography. Bridgelall et al. (2024) demonstrated the potential for advanced air mobility to transform pharmaceutical delivery in rural areas, with drones offering significant cost and time advantages over traditional truck-based logistics. As regulatory frameworks evolve to accommodate these technologies and costs decrease through technological maturation, alternative delivery modalities may become increasingly viable for routine pharmaceutical distribution. This evolution could fundamentally alter accessibility patterns, potentially reducing geographic barriers that have historically constrained pharmaceutical access.

However, ensuring equitable access to these advanced delivery modalities will require proactive policy interventions to prevent concentration of benefits in affluent areas.

The development of global health data infrastructure and standards will enable more effective AI-geospatial applications across diverse contexts. Currently, data heterogeneity and lack of interoperability constrain cross-national learning and scaling of successful interventions (Boutayeb et al., 2024). International efforts to establish common data standards, ontologies, and exchange protocols could enable pharmaceutical systems in different countries to learn from each other's experiences and adapt successful approaches to local contexts. The World Health Organization and other international organizations are developing frameworks for health data governance that balance data sharing benefits with privacy protection and data sovereignty concerns. Progress in this domain will be essential for realizing the full potential of AI-geospatial analytics to address global pharmaceutical access inequities. Participatory AI and community-centered design approaches represent important directions for ensuring that technological innovations serve community needs and priorities. Traditional AI development follows a top-down model where technical experts design systems that are then deployed to end users. Participatory approaches involve communities in problem definition, algorithm design, validation, and governance, ensuring that AI systems reflect community values and address locally identified priorities (Saah et al., 2023). This approach is particularly important for pharmaceutical service delivery in marginalized communities, where externally imposed solutions may fail to address actual barriers or may introduce new problems. Methodological development of participatory AI approaches, including tools and processes for meaningful community engagement, represents an important research frontier.

Policy and regulatory innovation will be essential for realizing the potential of AI-geospatial analytics while protecting against harms. Current regulatory frameworks were developed for traditional healthcare delivery models and may not adequately address AI-specific concerns including algorithmic bias, data privacy, liability for algorithmic decisions, and cross-border data flows (Vaidya et al., 2024). Future regulatory frameworks must balance multiple objectives: promoting innovation, ensuring safety and effectiveness, protecting privacy, advancing equity, and maintaining public trust. Adaptive regulatory approaches that can evolve as technologies and understanding advance will be necessary, as static regulations risk becoming obsolete or counterproductive. International coordination will be important given the global nature of pharmaceutical supply chains and AI development.

Capacity building and workforce development represent critical priorities for ensuring that AI-geospatial innovations benefit resource-limited settings. Currently, technical expertise in AI and geospatial analytics is concentrated in high-income countries and elite institutions, creating barriers for low- and middle-income countries seeking to leverage these technologies (Sirmacek et al., 2022). Investment in education, training, and infrastructure in underserved regions is essential for building local capacity to develop, adapt, and deploy AI-geospatial solutions appropriate for local contexts. This capacity building must extend beyond technical skills to include critical perspectives on ethics, equity, and social implications of AI, ensuring that future practitioners can navigate complex tradeoffs and prioritize equity in their work. Research priorities for advancing the field include implementation science studies examining how AI-geospatial innovations are translated into practice, comparative effectiveness research evaluating different approaches, cost-effectiveness analyses informing resource allocation decisions, and longitudinal studies assessing long-term impacts on pharmaceutical accessibility and health equity. The literature currently emphasizes technical development and proof-of-concept studies, with less attention to implementation processes, sustainability, and real-world effectiveness. Addressing these research gaps will be essential for moving from promising pilot projects to scaled, sustained interventions that meaningfully improve pharmaceutical access for vulnerable populations.

The future of AI and geospatial analytics in pharmaceutical service delivery will be shaped by technological advances, methodological innovations, policy developments, and social movements demanding health equity. The trajectory is not predetermined but will depend on choices made by researchers, policymakers, technology developers, healthcare organizations, and communities. The challenge is to harness the transformative potential of these technologies while ensuring that benefits are equitably distributed and that vulnerable populations are not left behind or harmed by technological change. This requires sustained commitment to equity, ongoing critical reflection on the social implications of technological innovation, and willingness to adapt approaches based on evidence and community feedback.

8. Conclusion

The integration of artificial intelligence and geospatial analytics represents a paradigm shift in pharmaceutical service delivery, offering unprecedented capabilities for measuring accessibility, optimizing supply chains, predicting demand, and informing evidence-based policy interventions. This analytical review has examined how these technologies are being deployed across diverse geographic contexts, the methodological approaches demonstrating greatest effectiveness, the equity-centered strategies emerging to ensure inclusive pharmaceutical access, and the challenges constraining implementation and scaling. The synthesis reveals both transformative potential and significant limitations that must be carefully navigated to ensure that technological innovations advance rather than undermine health equity. The evidence demonstrates that AI-geospatial applications can substantially improve pharmaceutical accessibility through multiple pathways. Machine learning-based gravity models achieve 95% population coverage through strategic facility placement, reducing accessibility inequality and ensuring more equitable distribution of pharmaceutical services (Prabhune et al., 2024; Lv et al., 2023). Hybrid AI-GIS approaches enable identification of optimal locations for alternative delivery modalities such as drones, potentially reducing delivery costs by 60% while dramatically improving access for geographically isolated populations (Bridgelall, 2023; Bridgelall et al., 2024). AI-enabled vulnerability indices facilitate equitable resource allocation in resource-poor settings, ensuring that those with greatest need receive prioritized attention (Shayegh et al., 2024). Enhanced spatial accessibility measurement tools enable precise identification of underserved areas and pharmacy deserts, providing actionable intelligence for targeted interventions (Hashtarkhani et al., 2024; Wittenauer et al., 2024).

However, the analysis also reveals significant challenges that constrain the translation of technological potential into equitable health outcomes. Data quality and availability limitations, particularly in resource-limited settings where pharmaceutical access challenges are most acute, fundamentally constrain AI-geospatial applications (Boutayeb et al., 2024; Jagadeesan et al., 2021). Algorithmic bias threatens to perpetuate or amplify existing health inequities if training datasets are unrepresentative or if fairness considerations are not explicitly incorporated into algorithm design (Vaidya et al., 2024; Sirmacek et al., 2022). Interoperability challenges, privacy concerns, cost barriers, and clinical adoption resistance create organizational and systemic obstacles to implementation (Vieira et al., 2023; Amjad et al., 2023). These challenges underscore that technical sophistication alone is insufficient; successful deployment requires integrated approaches that address technical, ethical, organizational, and policy dimensions simultaneously.

The equity-centered strategies documented in the literature provide guidance for ensuring that AI-geospatial innovations advance pharmaceutical access equity. Explicit operationalization of equity through measurable metrics and accountability mechanisms, integration of social determinants of health into analytical frameworks, participatory design approaches that center community voices, vulnerability indexing that identifies populations requiring prioritized attention, and context-specific adaptation that accounts for local conditions collectively constitute a framework for inclusive pharmaceutical service delivery (Obeidat et al., 2024; Ahmad et al., 2024; Saah et al., 2023; Shayegh et al., 2024). These strategies recognize that equity is not an automatic outcome of technological innovation but requires intentional design choices, ongoing monitoring, and willingness to adapt approaches based on evidence of impacts on vulnerable populations.

The methodological evolution from traditional distance-based accessibility measures to AI-enhanced geospatial analytics represents substantial progress in analytical capability. The integration of machine learning with enhanced 2SFCA methods, network analysis, and real-time data streams enables more sophisticated understanding of pharmaceutical accessibility patterns than was previously possible (Kazazi et al., 2022; Hashtarkhani et al., 2024). However, methodological limitations, including fixed impedance thresholds, uncertainty from multiple sources, simplified representations of complex realities, and inadequate capture of temporal dynamics, suggest that results should be interpreted cautiously with explicit acknowledgment of limitations (Kazazi et al., 2022). Future methodological development should prioritize validation studies, comparative effectiveness research, and integration of qualitative insights that capture dimensions of accessibility not easily quantified. The geographic heterogeneity documented in the literature underscores the importance of context-specific approaches. Pharmaceutical accessibility challenges, health system characteristics, data availability, regulatory frameworks, and community needs vary substantially across high-income, middle-income, and low-income settings, necessitating adaptation rather than standardization of AI-geospatial solutions (Ganasegeran et al., 2024). Solutions developed for well-resourced urban settings may be entirely inappropriate for resource-limited rural contexts, requiring careful attention to local conditions and community priorities. This geographic specificity suggests that successful scaling of AI-geospatial innovations will require not wholesale replication but thoughtful adaptation guided by implementation science principles and community engagement.

Future directions identified in the analysis, including deep learning integration, real-time data streams, blockchain convergence, personalized pharmaceutical service delivery, alternative delivery modalities, global health data infrastructure, participatory AI approaches, policy innovation, and capacity building, collectively suggest that the field is in early stages of development with substantial potential for continued evolution (Özdemir, 2022; Adekola et al., 2022; Bridgelall et al., 2024). Realizing this potential will require sustained investment in research, infrastructure, capacity building, and policy development, with explicit commitment to ensuring that benefits are equitably distributed and that vulnerable populations are not left behind. The theoretical contribution of this analysis lies in articulating how computational intelligence can be leveraged to address spatial inequities in pharmaceutical access while highlighting the imperative for equity-centered approaches that explicitly counteract market forces and historical patterns that concentrate resources in privileged areas. The integration of spatial accessibility theory with algorithmic fairness principles, social determinants of health frameworks, and implementation science provides a comprehensive conceptual foundation for future research and practice. This integrated framework recognizes that pharmaceutical accessibility is shaped by the interaction of geographic, social, economic, political, and technological factors, requiring multidimensional interventions that address these factors simultaneously.

The practical implications for policymakers, healthcare organizations, and technology developers are clear. First, equity must be explicitly operationalized through measurable metrics and accountability mechanisms rather than treated as an abstract aspiration. Second, community engagement and participatory design should be standard practice rather than optional add-ons. Third, data infrastructure investment, particularly in resource-limited settings, is essential for enabling AI-geospatial applications where they are most needed. Fourth, regulatory frameworks must evolve to address AI-specific concerns while promoting innovation and protecting vulnerable populations. Fifth, capacity building and workforce development are critical for ensuring that technical expertise is broadly distributed rather than concentrated in elite institutions. Sixth, implementation science research examining how innovations are translated into practice should be prioritized alongside technical development.

In conclusion, artificial intelligence and geospatial analytics offer powerful tools for addressing pharmaceutical access inequities, but their deployment must be guided by explicit commitment to equity, ongoing critical reflection on social implications, and willingness to adapt approaches based on evidence and community feedback. The convergence of these technologies with equity-centered design principles, participatory approaches, and comprehensive policy frameworks creates unprecedented opportunities to advance universal pharmaceutical access and health equity. However, realizing this potential requires sustained commitment, adequate resources, and collaborative problem-solving involving diverse stakeholders. The path forward demands not only technical innovation but also ethical grounding, social awareness, and political will to ensure that technological progress serves the goal of health equity for all populations, particularly those who have been historically marginalized and underserved.

References

Adekola, O., Adekunle, A., & Egwuenu, A. (2022). Convergence of AI, blockchain and pharmacoeconomics in building adaptive pharmaceutical supply chains: A novel paradigm shift for equitable global drug access. *International Journal of Scientific Research Updates*, *4*(1), 142-150. https://doi.org/10.53430/ijsru.2022.4.1.0142

Adeyemo, T., Ogunleye, B., & Fashina, A. (2023). Improving access to essential medications in rural and low-income U.S. communities: Supply chain innovations for health equity. *International Journal of Multidisciplinary Research and Growth Evaluation*, *4*(1), 1181-1187. https://doi.org/10.54660/.ijmrge.2023.4.1.1181-1187

Ahmad, S., Khan, M., & Rahman, A. (2024). From data to insights. In *Advances in Computational Intelligence and Robotics Book Series* (Chapter 12). IGI Global. https://doi.org/10.4018/979-8-3693-8557-9.ch012

Amjad, A., Kordel, P., & Fernandes, G. (2023). A review on innovation in healthcare sector (telehealth) through artificial intelligence. *Sustainability*, *15*(8), 6655. https://doi.org/10.3390/su15086655

Bakimchandra, O., Chingangbam, S., & Elangbam, H. (2020). A geospatial approach to assess health coverage and scaling-up of healthcare facilities. *Current Science*, *118*(5), 728-736. https://doi.org/10.18520/CS/V118/I5/728-736

Bhattamisra, S. K., Banerjee, P., Gupta, P., Mayuren, J., Patra, S., & Candasamy, M. (2023). Artificial intelligence in pharmaceutical and healthcare research. *Big Data and Cognitive Computing*, *7*(1), 10. https://doi.org/10.3390/bdcc7010010

Boulos, M. N. K., Peng, G., & VoPham, T. (2019). An overview of GeoAI applications in health and healthcare. *International Journal of Health Geographics*, *18*(1), 7. https://doi.org/10.1186/S12942-019-0171-2

Boutayeb, S., Karra, M., & Moussaoui, O. (2024). A comprehensive GeoAI review: Progress, challenges and outlooks. arXiv preprint. https://doi.org/10.48550/arxiv.2412.11643

Bridgelall, R. (2023). Unlocking drone potential in the pharma supply chain: A hybrid machine learning and GIS approach. *Standards*, *3*(3), 21. https://doi.org/10.3390/standards3030021

Bridgelall, R., Huang, Y., Zhang, Z., & Tolliver, D. (2024). Transforming healthcare delivery with advanced air mobility: A rural study with GIS-based optimization. *Sustainability*, *16*(13), 5709. https://doi.org/10.3390/su16135709

Chiobi, E. D. (2024). AI-Driven Geospatial Analytics for Pharmaceutical Supply Chain Resilience: Integrating Business Intelligence, Compliance, and Healthcare Equity. *Algora*, *1*(01), 31–44. https://doi.org/10.63084/algora.v1i01.35

Chowdhury, S., Rahman, M., & Islam, T. (2024). Integrating artificial intelligence and advanced computing models to reduce logistics delays in pharmaceutical distribution. https://doi.org/10.63125/t1kx4448

Dahiya, M., Sharma, M., & Singh, A. (2022). Designing delivery of healthcare services with health management information system, artificial intelligence, big data, and innovative digital technologies. *Journal of Young Pharmacists*, *14*(74), 361-365. https://doi.org/10.5530/jyp.2022.14.74

Ganasegeran, K., Jamil, M. F. A., & Ch'ng, A. S. H. (2024). Modeling accessibility to public health facilities in resource-limited settings through GIS and Geo-AI applications. In *Earth and Environmental Sciences Library* (pp. 315-334). Springer. https://doi.org/10.1007/978-3-031-50848-6_17

Hashtarkhani, S., Kiani, B., Bergquist, R., Bagheri, N., VafaeiNejad, R., & Tara, M. (2024). Enhancing health care accessibility and equity through a geoprocessing toolbox for spatial accessibility analysis: Development and case study. *JMIR Formative Research*, *8*, e51727. https://doi.org/10.2196/51727

Hierink, F., Okiro, E. A., Flahault, A., & Ray, N. (2022). *The winding road to health: Geographic accessibility modelling to support health system optimization and disease estimates in low- and* *middle-income countries* [Doctoral dissertation, University of Geneva]. https://doi.org/10.13097/archive-ouverte/unige:163999

Hong, J., Knapp, S., & McConnell, K. (2022). Challenging terrains: Socio-spatial analysis of primary health care access disparities in West Virginia. *Applied Spatial Analysis and Policy*, *15*(4), 1287-1308. https://doi.org/10.1007/s12061-022-09472-0

Jagadeesan, N., Haque, M., Balakrishnan, P., Haque, S. Z., Ulhaq, I., Islam, S., Irfan, F. B., Akter, F., Kurdi, A., Abubakar, A. R., Godman, B., & Sneddon, J. (2021). Geographical accessibility of medicines: A systematic literature review of pharmacy mapping. *Journal of Pharmaceutical Policy and Practice*, *14*(1), 28. https://doi.org/10.1186/S40545-020-00291-7

Kazazi, L., Nourjou, R., & Aghighi, H. (2022). A new hybrid model for mapping spatial accessibility to healthcare services using machine learning methods. *Sustainability*, *14*(21), 14106. https://doi.org/10.3390/su142114106

Kuang, L. (2019). Insight of artificial intelligence application in healthcare. *International Journal of Sciences*, *8*(9), 1-5. https://doi.org/10.18483/IJSCI.2157

Lesslie, P. T., Reddy, Y. M., & Rao, M. V. (2023). Development of a spatial accessibility index for assessing health infrastructure using AHP approach: A case study of Andhra Pradesh State. *Journal of the Indian Society of Remote Sensing*, *51*(9), 1895-1909. https://doi.org/10.1007/s12524-023-01739-4

Liu, Y., Zhang, H., & Wang, J. (2023). DeepHealth: Geospatial and ML-based approach to identify health disparities and determinants for improving pandemic health care. In *Proceedings of the 2023 International Conference on Computer Communications and Networks* (pp. 1-6). IEEE. https://doi.org/10.1109/icccn58024.2023.10230101

Lv, Z., Wang, L., Han, Z., Zhao, J., & Wang, W. (2023). Optimize the accessibility of healthcare facilities via ACP-based approach. In *Proceedings of the 2023 IEEE International Conference on Systems, Man, and Cybernetics* (pp. 3180-3185). IEEE. https://doi.org/10.1109/smc53992.2023.10394054

Nyakiongora, G. M. (2024). Bridging the health divide: Achieving equitable healthcare access in Kenya through artificial intelligence, Thesis, Massachusetts Institute of Technology. https://hdl.handle.net/1721.1/157182

Obeidat, M., Al-Qudah, H., & Al-Bakri, J. (2024). Healthcare equity in focus: Bridging gaps through a spatial analysis of healthcare facilities in Irbid, Jordan. *International Journal for Equity in Health*, *23*(1), 120. https://doi.org/10.1186/s12939-024-02120-8

Özdemir, V. (2022). Geospatial health data analytics for Society 5.0. In *Geospatial Analytics for Society 5.0* (pp. 23-45). Springer. https://doi.org/10.1007/978-981-16-9476-9_2

Prabhune, A., Sharma, R., & Kulkarni, S. (2024). Enhancing accessibility to primary healthcare centres through the development and validation of a machine learning-based gravity model: Strengthening public health coverage. In *Proceedings of the 2024 International Conference on Intelligent Technologies for Computational Engineering* (pp. 1-6). IEEE. https://doi.org/10.1109/iitcee59897.2024.10467863

Ramos, J., Santos, M., & Cruz, A. (2024). Optimizing healthcare accessibility: An integration of GIS and machine learning for strategic hospital facility location planning. In *Proceedings of the 2024 International Conference on Artificial Intelligence in Information and Communication* (pp. 463-468). IEEE. https://doi.org/10.1109/icaiic60209.2024.10463219

Rangavittal, S. (2024). Harnessing AI for affordable and efficient medication delivery in North America. Zenodo. https://doi.org/10.5281/zenodo.12484119

Rocha, T. A. H., Fachini, L. A., Thumé, E., Silva, N. C., Barbosa, A. C. Q., Carmo, M., Rodrigues, J. M., & Facchini, R. (2021). Microplanning for designing vaccination campaigns in low-resource settings: A geospatial artificial intelligence-based framework. *Vaccine*, *39*(42), 6276-6285. https://doi.org/10.1016/J.VACCINE.2021.09.018

Saah, J. K., Agyemang, S., & Mensah, I. O. (2023). Geospatial evaluation of service areas: Empowering maternal health for ensuring healthy lives and well-being in the Wenchi Municipality of Ghana. *Journal of Nursing Research, Patient Safety and Practice*, *35*, 39-52. https://doi.org/10.55529/jnrpsp.35.39.52

Shayegh, S., Manoussi, V., & Dasgupta, R. (2024). Prioritizing COVID-19 vaccine allocation in resource poor settings: Towards an artificial intelligence-enabled and geospatial-assisted decision support framework. https://doi.org/10.60692/hw2e3-f4p70

Sirmacek, B., Riveiro, M., & Byttner, S. (2022). The potential of artificial intelligence for achieving healthy and sustainable societies. In *Artificial Intelligence for Sustainable Development* (pp. 89-112). Springer. https://doi.org/10.1007/978-3-031-21147-8_5

Tew, M. M., Yong, Y. V., Tan, C. S., Lim, K. H., Yap, K. Y., & Chia, Y. L. (2021). Geospatial analysis of distribution of community pharmacies and other health care facilities providing minor ailments services in Malaysia. *Journal of Pharmaceutical Policy and Practice*, *14*(1), 8. https://doi.org/10.1186/S40545-021-00308-9

Vaidya, R., Sharma, P., & Gupta, A. (2024). Advancing healthcare through artificial intelligence: Opportunities, challenges and future directions. *International Research Journal of Advanced Engineering and Management*, *2*(4), 1234-1245. https://doi.org/10.47392/irjaem.2024.0177

Vélez, X., Ortiz, A., & Sánchez, M. (2017). Geospatial collective intelligence for health planning: A case study for screening tests in the city of Esmeraldas, Ecuador. In *Proceedings of the 2017 International Conference on eDemocracy & eGovernment* (pp. 162-169). IEEE. https://doi.org/10.1109/ICEDEG.2017.7962528

Vieira, A. P. S., Silva, L. M., & Santos, R. B. (2023). O impacto das tecnologias da informação em saúde na atuação do farmacêutico hospitalar na reconciliação medicamentosa. *Revista Eletrônica Acervo Saúde*, *23*(6), e13489. https://doi.org/10.25248/reas.e13489.2023

Wittenauer, R., Bright, T. J., & Duru, O. K. (2024). Locations and characteristics of pharmacy deserts in the United States: A geospatial study. *Health Affairs Scholar*, *2*(3), qxae035. https://doi.org/10.1093/haschl/qxae035

Xiao, Y., Miao, S., Sarkar, C., Geng, H., & Lu, Y. (2022). Uncovering spatiotemporal pattern and geographical equity of pharmacies in Chinese cities from 2008 to 2018. *Health Policy and Technology*, *11*(4), 100691. https://doi.org/10.1016/j.hlpt.2022.100691