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Geospatial Approaches for Sustainable Wastewater Treatment and Reuse in Agriculture under Climate Change Scenarios

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Abstract: *The growing challenges of climate change, rapid urbanization, and water scarcity have intensified the global demand for sustainable wastewater management and reuse, particularly in agriculture. Geospatial technologies comprising Remote Sensing (RS), Geographic Information Systems (GIS), Geo-Artificial Intelligence (Geo-AI), and Internet of Things (IoT) integration offer innovative, cost-effective, and data-driven tools to optimize wastewater treatment, reclamation, and safe agricultural reuse. These technologies enable precise spatial mapping of wastewater treatment plants, pollution hotspots, and irrigation networks, improving decision-making for water allocation and environmental protection. Climate-adjusted geospatial models support the identification of optimal reuse sites, water demand assessments, and impact evaluations, ensuring adaptive responses to hydrological variability. The integration of geospatial intelligence with advanced treatment methods, such as electrochemical systems and constructed wetlands, enhances wastewater quality while minimizing ecological and health risks. However, challenges persist in data heterogeneity, policy alignment, and limited stakeholder awareness. Future advancements in Geo-AI, machine learning, and climate-smart GIS promise to strengthen wastewater reuse efficiency, promote precision agriculture, and build resilience against climate-induced water stress. This review underscores the transformative potential of geospatial approaches as a cornerstone for sustainable water resource management and circular economy practices in agriculture under changing climatic conditions.*

Keywords: *Geospatial technologies; Remote sensing (RS); Geographic Information System (GIS); Wastewater treatment; Agricultural water reuse; Climate change adaptation; Geo-Artificial Intelligence (Geo-AI); Sustainable water management; Precision agriculture; Water scarcity; Environmental sustainability; Smart irrigation; Circular economy.*

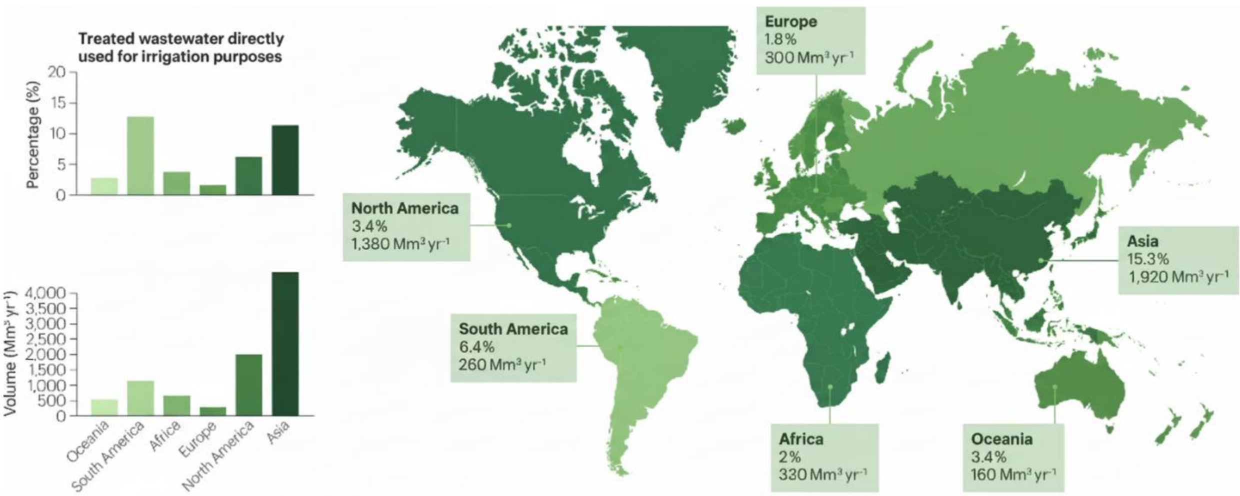
1. Introduction

There are many reasons geospatial techniques are innovative solutions for the sustainable management of waste waters in agriculture. Compared to on-the-ground surveys, these techniques are cheaper, less labor intensive, and provide uniform information across extensive regions (Penserini et al., 2024) With the technological advancements in remote sensing (RS) and Geographic Information Systems (GIS), the monitoring and management of water resources has become more precise, timely, and accurate for assessments of agricultural and hydrological conditions (Tarate et al., 2024). The combination of RS and GIS technologies improves the accuracy of agricultural monitoring, which enhances decision-making for the management of water in agriculture (Mancuso et al., 2022). It also aids the agriculture sector in the safe and effective reclamation of waste water by operating within the standards for water quality. This is vital for the management of the agricultural waste water asymmetries which provide positive nutrient potential, but also have negative pollutant potential (Jeong et al., 2016; Trotta et al., 2024).

Geospatial technologies facilitate the management of change brought on by urbanization and climate change on agricultural water usage. They assist the development of sustainable standards and guidelines on the reuse of wastewater that primarily mitigate and balance negative ecological impacts (Jeong et al., 2016; Tarate et al., 2024). Abonyi et al. (2024). argue that geospatial technologies provide other optimization opportunities that eliminate the management of wastewater by chemical treatment and facilitate recovery of wrought resources in a sustainable manner. Within the management of water resources, climate change poses challenges and opportunities on the treatment and reuse of wastewater (Mancuso et al.,2022; Choudhury et al., 2025). The impact of climate change that most directly alters the management of wastewater is the increased water scarcity due to global warming and the growth of populations (Bauer & Wagner, 2022; Fito & Van Hulle, 2020). The growing scarcity of water requires creative and flexible strategies on the reuse and management of wastewater. The improvement of wastewater treatment systems is one of the methods used to adapt. Systems such as electrocatalytic and photo electrocatalytic oxidation systems were singled out as being capable of addressing contaminants of probable concern and minimizing resource waste. The use of these advanced systems helps in decentralized and semi-centralized systems, which enhances their use, reduces resource waste, and helps in dealing with the inefficiencies of climate waste water (Farissi et al., 2023; Choudhury et al., 2025).

Reuse of treated wastewater, especially in agriculture, provides a durable and reliable water source which is critical with the anticipated water scarcity due to climate change in dry regions, particularly Southern Europe and the Middle East (Dare et al., 2017; Kama et al., 2023). The reuse water can also provide some of the nutrients required for the plants which helps reduce the use of chemical fertilizers (Lavrnić et al., 2017). The use of treated wastewater in irrigation does bring problems of soil and plant contamination and this is where the need for the greatest quality control and appropriate infrastructure. Integrated systems need to be developed so that the treated wastewater is guaranteed to not pose a health and environmental risk (Chaïeb et al., 2024; Kama et al., 2023). Consideration of systems of sound policies and alterations of regulations is warranted. The effective implementation of these systems considers not only adopted technologies but is also reliant on governance, social acceptance, and calculated investments. The local context must be evaluated to determine the best use of reclaimed wastewater for addressing water scarcity and environmental sustainability and for deciding whether to employ a centralized or a decentralized systems approach (Fito & Van Hulle, 2020; Tchobanoglous et al., 2021).

Figure 1.1 Global Treated Wastewater Use



2. Basic Concepts

The application of Remote Sensing and Geographic Information Systems cashes numerous advantages pertaining to the monitoring and management of geospatial waste (Choudhury et al., 2025). The assessment and treatment of water quality issues for large-scale studies is of great importance and these technologies has proven to be cost efficient alternatives for these tasks (Ramadas & Samantaray, 2017). The waste zone mapping, at high resolutions, becomes attainable through the combined use of Remote Sensing, GIS technologies and advanced Hydraulic Techniques. Un contaminated zone detection and devising tailored remediation plans becomes attainable (Ramadas & Samantaray, 2017).

In the case of Hydro dominant problems, Remote Sensing, and GIS provide instruments for in-depth water resource analysis to be maintained in wastewater management. The ability to handle and analyze the information improves to convey the data scarcity and rational resource management (Thakur, et al, 2016). The use of geospatial technologies, especially satellite remote sensing, has applications in hydrology and in the management of wastewater in agriculture. This has a positive impact on the management of water resources in agriculture (Tarate et al., 2024). The use of geospatial technologies particularly has a positive impact on the management of water resources at the agriculture site, and the use of water in agriculture is sustainable and environmentally friendly. Decision-making systems for the management of water resources in sustainable agriculture can be enhanced with the use of advanced geospatial technologies, including remote sensing, GIS, and various sensing technologies, all of which help in the optimization of resource management. Tarate et al. (2024) noted the value of remote sensing technologies and GIS systems, which have the ability to provide accurate and timely data on the agricultural and hydrological states of large areas. This technology can substitute on-the-ground data collection and analysis, which is resource intensive in terms of both funds and labor. It is a valuable technology in agriculture for monitoring soil moisture and the water requirements of crops. For example, water resource assessment and monitoring for agricultural water management is possible with satellite imagery and technologies like multispectral and hyperspectral sensors (Tarate et al., 2024; Penserini et al., 2024).

In addition, flexible and multifaceted geospatial tools have been developed that track, evaluate, and map the spatial dynamics of first order and higher-order geospatial and temporal scales of agricultural crops and variability over time (Mancuso et al., 2022). This facilitates the application of targeted and calibrated amounts of agricultural inputs, namely, water, fertilizers, and other custom inputs, eliminating and mitigating wastage, boosting efficiency, and maximizing profits. In simulating crops' hydrological and other physiological processes and growth in varying agricultural climatic conditions, such tools allow farmers to recognize and forecast adaptive strategies needed to remain both economically and hydrologically sustainable to changing efficiency and sustainable water use in agriculture (Hadeed et al, 2024). In the context of high water-usage crops, such as irrigated rice, geospatial technologies play a critical role in monitoring water consumption and adjusting irrigation practices to enhance water use efficiency and reduce environmental impacts (Niel & Mcvicar, 2004). For example, remote sensing data enable the development of models to predict crop water demand and guide irrigation management practices, reducing water consumption without compromising crop yield (Niel & Mcvicar, 2004; Penserini et al., 2024). Furthermore, enhanced irrigation and crop monitoring with the combination of the Internet of Things (IoT), spatial and non-spatial big data analytics, and other geospatial tools has been proved to be invaluable in reduction irrigation and ensuring sustainable waste in water use in crops. Rational irrigation and real-time crop ET can be adjusted using wireless sensing technologies. Through ET driven irrigation scheduling, diversion of crop ET losses decreases, and the yield and quality of crops increase (Zhao et al, 2023).

3. Geospatial Techniques for Wastewater Treatment

There is an increase in the application of geospatial techniques in the detection and analysis of wastewater sources. Various techniques in the new field of wastewater source monitoring include the use of Geographic Information System (GIS) technologies and spatial modeling methodologies. Geographic Information Systems (GIS) technologies facilitate spatial data analysis, and the management of large volumes of waste data will help in monitoring. Systems Automation of data collection, spatial statistics computation, parameter variable assignment, and automation of statically modeling processes will help in modeling efforts (Watkins et al., 1996). More so, the GIS integration with ground-water models will spatially evaluate GIS data and help decrease the percentage of arbitrary entry in parameter selection (Ross & Tara, 1993; Penserini et al., 2024) Spatial waste treatment systems and their efficacy within geographically defined parameters is an equally important application of spatial modeling. The integration of GIS with specific elements of hydrology permits the GIS user to harness the system in the spatially informed design of wastewater treatment systems (Ross & Tara, 1993). The described method, and the respective work previously defined in function modeling, create a geospatial planning environment in waste treatment that will dramatically improve the use of integrated spatial data systems and reduce the overall use of processing memory (Hogland & Anderson, 2017). Proposed advancements in the use of GIS technology suggest the application of cellular automata for the enhancement of dynamic spatial models and the manipulation of the temporal aspects of such models. The integration of GIS and cellular automata provides more effective dynamic spatial modeling (Wagner, 1997: Penserini et al., 2025). Such advancements reveal the considerable contribution of geospatial techniques, and more so, the cutting-edge spatial models, in improving the evaluation and management of wastewater networks. The operationalization of such techniques promotes evidence-based management of systems, which ultimately contributes to improved and more responsible practices in wastewater management (Shakeri et al., 2021).

Table 3.1. Geospatial Technologies Applied in Wastewater Management

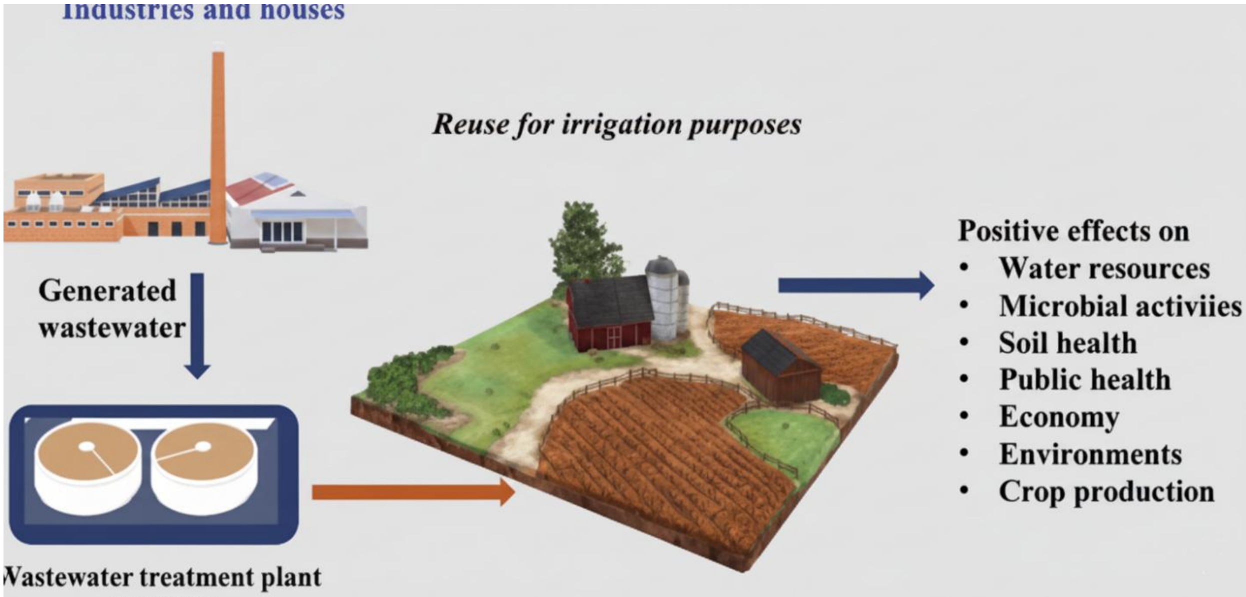
Technology	Main Function	Application Area	Key References
Remote Sensing (RS)	Detects surface water quality and hydrological conditions	Water quality monitoring, irrigation scheduling	Ramadas & Samantaray (2017); Tarate et al. (2024)
Geographic Information System (GIS)	Spatial data integration and mapping	Wastewater source mapping, reuse planning	Watkins et al. (1996); Ross & Tara (1993)
Geo-AI	Predictive analytics and modeling	Groundwater potential mapping, pollution prediction	Ayadi et al. (2025); Xing & Sieber (2023)
IoT and UAVs	Real-time data and precision irrigation	Smart irrigation systems	Zhao et al. (2023)

4. Geospatial Approaches in Wastewater Reuse for Agriculture

Logistics of Wastewater Treatment Plants (WWTPs), Proximity analysis of potential wastewater reuse sites, such as agricultural lands, assists in the planning of the diversion of treated wastewater for irrigation (Friedler & Lahav, 2006). Water Quality Assessment: The determination of the suitable sites for wastewater reuse from geospatial analysis incorporates the assessment of spatial variations of water quality parameters, including contamination levels and treatment efficacy (Berbel et al., 2023; Penserini et al., 2024). Demand Assessment: The geographical distribution of water demand is analyzed to strategically plan wastewater reuse initiatives. This helps prioritize areas that would benefit from supplemental irrigation provided by treated wastewater (Rice et al., 2013: Jan et al., 2025). Environmental Impact Assessment: Geospatial analysis studies the impact of wastewater discharge on the bodies of water and the associated ecosystem (Vaiyapuri et al., 2025). Treated wastewater has potential to resolve issues of water scarcity and ecosystem degradation, thereby contributing to the sustainable management of water resources (Finnerty et al., 2023).

The spatial distribution of wastewater treatment plants (WWTPs), which involves the mapping and the assessment of the treatment and disposal capacities of wastewater treatment facilities; the assessment of the water quality by describing and monitoring the chemical and biological pollutants, nutrients and pathogens contained in the disinfected and treated wastewater (Mancuso et ., 2022) land-use pattern descriptions that delineate the agricultural, industrial, and urban zones, to assess the potential wastewater reclamation and reuse; hydrological analysis that defines and describes the water ways, especially river systems that will receive and transport treated wastewater, and (socioeconomic) demographic and economic characteristics assessments that describe the areas surrounding the treatment and potential reuse sites (Sala & Serra, 2004; Penserini et al., 2024). The use of modern geospatial technologies, including Geographic Information Systems (GIS), offers a more integrated approach to analysis and thereby more effective management of wastewater treatment and disposal systems, and more safe, efficient, and sustainable irrigation systems.

Figure 4.1: Wastewater Treatment and Reuse Process Flow



5. Impact of Climate Change Scenarios

Scenarios relating to climate change will worsen water scarcity and affect the availability of wastewater and its potential for reuse. Consequently, the need for alternative water sources will grow. As climate change advances, especially for more water-stressed regions, the pressures on available freshwater resources will likely worsen. In these situations, the climate-adjusted safe strategy would involve the reuse of treated wastewater. With every cycle of wastewater, more pressure on available freshwater resources shrinks. Reusing water becomes critical to serve as a dependable alternative water supply for agriculture, industry, and urban uses, especially for climate-affected uses (Bauer & Wagner, 2022; Gholami-Shabani & Nematpour, 2024). Reusing wastewater with changing climate extremes not only mitigates water scarcity but also enhanced sustainable water resource management aligned with the Sustainable Development Goals, primarily Goal 6(Bauer & Wagner, 2022).

The reuse of wastewater allows for safe irrigation, particularly in agriculture, which consumes a significant proportion of freshwater. As the nutrient value of some treated wastewater contributes to plant growth, the use of synthetic fertilizers can be minimized, saving even more water (Lavrnić et al., 2017). Nevertheless, to avoid contaminating the environment and posing health threats through pathogens and heavy metals, treated wastewater must be of the appropriate quality (Jeong et al., 2016; Ungureanu et al., 2020). Advances in the treatment of wastewater through the application of constructed wetlands and electrochemical systems, amongst other novel tactics, enhances the quality of treated wastewater to a desirable standard for agricultural reuse (Farissi et al, 2023; Lavrnić & Mancini, 2016). Such systems improve the removal of toxic pollutants to the extent that reclaimed water can be considered safe for reuse.

The use of reclaimed wastewater in the management of water resources enhances productivity of water systems, and the potential to develop inter-sectoral water swaps and climate adaptability (Drechsel et al., 2022). Nevertheless, the use of reclaimed wastewater in water systems is a complex endeavor and requires the appropriate infrastructure and policies to motivated public advocacy, which is required to solve behavioral obstacles to its use, such as negative perception and public regulation (Bauer & Wagner, 2022; Jeong et al., 2016). Utilizing wastewater management and overseeing changes for climate adaption and climate mitigation is where the maximum benefit of geospatial approaches, GIS, and remote sensing data come in. For pinpoint geospatial mapping, monitoring, and management is valuable because of the growing climate change challenges in the environment (Singh & Malik, 2025).

Gained insight from integrated geospatial technologies facilitates the management assessment of scope and quality of wastewater. Predicting and planning for geospatial technologies is aimed for climate changes the worsen drought and flooding scenarios mapping of groundwater, precipitation analysis, and water demand simulation (Hadeed et al., 2024). When it comes to geospatial technologies that are practical in wastewater management and control, it has great importance for geospatial data in the analysis of environmental impacts assessment, and for water supply systems enhancements and the development of more efficient systems of wastewater treatment (Lako & Çomo, 2024). For instance, these technologies are appropriate to model and predict the consequences of climate change on variable water resources and provide the frameworks for environmental mitigating and unsustainable management practices to be removed. In addition, remote sensing and GIS technologies advance the spatial analysis of water-related risks and resources potentially available. They assist in identifying groundwater potential zones, which is key in determining the adequate water supply for the treatment systems of wastewater (Ayadi et al., 2025).

Geospatial technologies serve immediate analytical requirements, but also contribute to long-term strategic planning. They promote integrated approaches that combine policy adaptation to environmental changes, aided by the monitoring features of the technologies, and management of resources for the sustainable adaptation (Tsatsaris et al., 2021). In closing, the use of geospatial technologies to analyze the hydrological processes, improve monitoring, and develop sustainable resource management help adapt wastewater management systems to the new challenges of climate change (Chang et al., 2023; Lako & Çomo, 2024). Geospatial technologies for GIS and remote sensing, in particular, help in adapting wastewater management to the new climate challenges. They assist in the strategic planning needed to improve the environmental challenges that climate change poses, by helping to accurately identify, assess, and manage water resources (Singh & Malik, 2025). Employing geospatial technology is one of the most effective tools for showering for the water quality and the quantity assessment and management required for treating and managing wastewater for a given period of time. With the growing challenge of climate change, which is extended the magnitude of problems like drought and flooding, geospatial technology, by calculating water demand, modeling precipitation trends, and mapping water storage, can be used to predict and plan for the problem (Hadeed et al., 2024). In the context of practical use of geospatial technology in wastewater management, one can mention the role of geospatial technology in the assessments of water supply improvement, the effect of system changes on the environment, and the plans for the more efficient wastewater management systems (Lako & Çomo, 2024). Geospatial technology and modeling water climate change impacts on the water ecosystem helps in planning of sustainable resource management and best practice mitigation to climate change. Remote sensing and GIS technology improvement offer tools to enhance spatial analysis of water resources and related risks in resource management. This technology helps to delineate aquifers and plan for resources needed for wastewater systems (Ayadi et al., 2025).

In addition to responding to analytical needs, geospatial technologies provide an important resource for strategic planning. The sustained application of geospatial technologies to understand environmental shifts encourages the formulation of integrated policies for resource management and sustainable adaptive strategies (Tsatsaris et al., 2021). In closing, geospatial techniques enhance the comprehension of hydrological processes, as well as monitoring and resource management, which help in the development of sustainable strategies and in the adaptation of wastewater management systems to the impacts of climate change (Chang et al., 2023; Lako & Çomo, 2024).

6. Challenges and Limitations

There exist both technical and policy-related hurdles to the utilization of geospatial methods to wastewater reuse. On the technical side, the challenges of assimilating various geospatial data stems from problems of semantic heterogeneity, differences in data projections and differences in accuracy levels. These issues all complicate the data fusion necessary for a complete geospatial analysis. Semantic issues are the most serious and require ontology for data integration and sharing construction to be effective (Sun et al 2019). For GIS applications in wastewater management, data availability and analysis reproducibility are key, and constant data availability makes data maintenance a challenge (Breunig et al 2020). There are also policy challenges in strategically incorporating geospatial integration into local and global frameworks, especially in relation to the nationally agreed sustainable development goals (SDGs). Policymakers' lack of understanding of the value of geospatial data, or for that matter, data in general, often results in poorly waste reuse strategies (Scott & Rajabifard, 2017). Reducing the uncertainties associated with geospatial data and climate models requires the use of explanatory artificial intelligence (XAI) with geospatial AI (GeoAI) systems. Open geospatial datasets can pose challenges to the precision of spatially diverse datasets (Xing & Sieber, 2023). The use of comprehensive statistical frameworks and spatially correlated machine learning techniques can improve predictive accuracy and mitigate errors caused by spatial autocorrelation (Islam et al.; 2022). The combination of these technical and policy approaches can improve the effectiveness and dependability of geospatial technology with wastewater reuse, thus enhancing environmental sustainability and responsible water management (Vaiyapuri et al., 2025).

7. Future Perspectives

Recent developments in geospatial technology will likely increase the sustainable reuse of wastewater in agriculture. Technology such as Geographic Information Systems (GIS), remote sensing (RS), and the new Geospatial Artificial Intelligence (Geo-AI) tools begin to solve agriculture water management issues (Ayadi et al. 2025; Niel & Mcvicar, 2004; Tarate et al. 2024). In particular, remote sensing gathers timely, reliable, and precise information over wide areas. For monitoring and managing water, and other numerous resources in agriculture, this information is vital. For example, effective management of water resources requires knowledge of water and hydrological conditions. The combination of RS and GIS technologies also improves crop monitoring and mapping to assist in the management of water resources in drylands (Tarate et al. 2024). In addition, assessing the water quality and the groundwater potential zones has geospatial technology improved determining the safe use of treated wastewater in agriculture. For instance, the delineation of groundwater potential zones, a sustainably managing water resources practice, has been improved by the use of Geo-AI technology (Ayadi et al., 2025).

Moreover, geospatial technologies can promote precision agriculture by optimizing water usage for crops, like in the case of rice irrigation systems. This encompasses the evaluation of crop water consumption through surface energy balances, and remotely sensed vegetation indices, thus improving on-farm efficiency and productivity and reducing adverse effects on the environment (Niel & Mcvicar, 2004). these technologies facilitate the safe reuse of wastewater by enabling risk-sensitive controlled water application and wastewater pollutant containment. Successful wastewater agricultural reuse hinges on risk evaluation and the mitigation of potential soil and plant contamination (Trotta et al., 2024). The integration of geospatial and climate models for agricultural planning addresses the need for improving resilience and providing significant advantages. Transforming agriculture hinges on the application of geospatial technologies such as Geographic Information Systems (GIS) and remote sensing that offer spatial analysis together with real-time data and information for the more efficient, productive, and sustainable environmentally friendly agricultural practices (Toromade & Chiekezie, 2024). Using spatial data, GIS can monitor and manage various farming activities in great detail. For example, GIS can execute, monitor and manage variable rate integration systems to spatially optimize fertilizer and pesticide applications on a field. This prevents excess wastage and mitigates environmental impacts. In addition, GIS can effectively enhance crop management by monitoring and continuously checking crop conditions. This facilitates early identification of crop health issues such as infestations of pests, nutrient deficiencies, and other factors—so that interventions can be made quickly to sustain crop health and yield (Toromade & Chiekezie, 2024).

With regard to modeling potential climate variations, incorporating various climate-models enables the prediction of certain climate impacts and the crafting of adaptation plans. (Vaiyapuri et al., 2025). The use of climate-smart agricultural (CSA) practices urged by various researchers helps improve productivity and resilience, while also reducing greenhouse gas emissions under varying climate conditions. Data-driven precision farming practices which practices data analytics to inform micro-level decisions, emerge as a powerful adaptation to climate change (Alexopoulos et al., 2023; Bhanuwanti et al., 2024). Advanced precision agriculture using geospatial and climate technologies fosters the implementation of sustainable practices such as conservation agriculture, agroforestry, and crop diversification. All of which are important for reducing yield volatility and building system resilience (Eswaran et al., 2024; Safdar et al., 2024). These practices uniquely mitigate climate change by reducing the carbon footprint of agriculture as they facilitate the integration of trees in croplands and land use optimization (Eswaran et al., 2024).

Furthermore, geospatial tools in sustainable farming resource management provide efficient identification and zoning for the allocation of site-specific irrigation, which in turn reduces erosion and water use. This is critical for sustainable farming resource management in drought and erosion prone areas (Toromade & Chiekezie, 2024). The combination of climate and geospatial technologies lays the foundation for resilient agricultural systems by increasing productivity, conserving biodiversity, strengthening adaptive decision-making to climate change, and increasing the adaptive capacity of the systems (Bhanuwanti et al., 2024; Toromade & Chiekezie, 2024).

Table 7.1. Future Prospects of Geospatial Technologies in Sustainable Agriculture

Emerging Technology	**Application in Wastewater Reuse**	**Potential Impact**	**Reference**

Geo-AI and Machine Learning	Predictive mapping of water quality	Improved treatment targeting	Ayadi et al. (2025)
IoT and Big Data Integration	Smart monitoring of irrigation reuse	Enhanced water efficiency	Zhao et al. (2023)
Climate-smart GIS Modeling	Climate-adaptive planning	Increased resilience and productivity	Bhanuwanti et al. (2024); Toromade & Chiekezie (2024)
UAV and Sensor Networks	Precision mapping of soil and crops	Reduced contamination risk	Alexopoulos et al. (2023)

Conclusion

Geospatial technologies are redefining wastewater treatment and reuse by providing spatially intelligent, real-time, and integrative solutions for sustainable water management in agriculture. Through the fusion of RS, GIS, IoT, and Geo-AI, it is now possible to assess water quality, model climate impacts, and optimize wastewater reuse strategies with unprecedented accuracy. These tools not only reduce dependence on freshwater sources but also enhance nutrient recycling and minimize environmental contamination. As climate change intensifies droughts and floods, the reuse of treated wastewater emerges as a critical adaptation strategy. However, realizing the full potential of these technologies requires addressing technical barriers such as data interoperability and model uncertainty and policy challenges, including regulatory harmonization and public acceptance. Moving forward, adopting climate-smart, data-driven wastewater management systems supported by geospatial analytics will be essential for achieving water sustainability, food security, and environmental resilience in the face of global climate change.

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