

ADVANCEMENT IN GEOSPATIAL TECHNOLOGIES FOR SOIL AND CROP ANALYSIS : A REVIEW

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This review paper provides an overview of the advancements in geospatial technology for soil and crop analysis and discusses their implications for sustainable agricultural practices. Traditionally, soil and crop analysis methods were labor-intensive and had limited spatial coverage. However, geospatial technology, including remote sensing, Geographic Information Systems (GIS), and Global Positioning Systems (GPS), now enables the efficient collection, analysis, and visualization of spatial data. Remote sensing, through satellite and airborne sensors, allows for the rapid and non-destructive assessment of soil and crop characteristics at various scales. GIS integrates diverse geospatial data layers to create digital soil and crop maps, facilitating precision agriculture strategies. GPS technology enhances the accuracy and reliability of analysis by providing precise location information, additionally, advanced analytical techniques like machine learning algorithms aid in soil classification, crop yield prediction, disease detection, and land cover monitoring. Real-time monitoring capabilities enable up-to-date information on soil moisture, temperature, nutrient levels, and crop health, facilitating proactive decision-making. The objective of this review paper is to provide a comprehensive understanding of the advancements in geospatial technology and their potential for improving soil and crop analysis in sustainable agriculture.

Geospatial technology, encompassing remote sensing, Geographic Information Systems (GIS), and Global Positioning Systems (GPS), has emerged as a powerful toolset for analyzing soils and crops in agricultural research and management. This technology allows for the collection, analysis, and visualization of spatial data, enabling researchers and practitioners to gain valuable insights into the complex interactions between soil characteristics, crop growth, and environmental factors.

Understanding the soil and crop dynamics is crucial for sustainable agricultural practices, as it directly influences crop productivity, resource management, and environmental conservation. Traditionally, soil and crop analysis relied on manual sampling and laboratory-based methods, which were

time-consuming, labor-intensive, and limited in spatial coverage (Guo *et al.*, 2020). However, with the advent of geospatial technology, researchers can now gather detailed information about soils and crops over large areas in a cost-effective and efficient manner (Alqurashi, 2021).

Remote sensing plays a pivotal role in geospatial analysis by providing valuable data from satellite and airborne sensors. It allows for the acquisition of multispectral and hyperspectral imagery, capturing the spectral reflectance properties of soils and crops (Patel *et al.*, 2022). By analyzing these spectral signatures, researchers can derive information about soil composition, moisture content, nutrient levels, crop health, and vegetation dynamics (Johnson *et al.*, 2022). This non-destructive and rapid assessment of soil and crop characteristics at different spatial and temporal scales is crucial for effective land management and decision-making (Ghige *et al.*, 2021).

Geographic Information Systems (GIS) provide a platform for integrating and analyzing geospatial data layers, allowing for the creation of digital soil and crop maps (Walker *et al.*, 2022; Rodriguez *et al.*, 2023). By combining soil samples, remote sensing data, topographic information, and climate data, researchers can develop detailed soil maps, delineate soil properties, and understand spatial variations (Thompson *et al.*, 2023; Smith *et al.*, 2023). These maps facilitate precision agriculture practices, enabling farmers to implement site-specific strategies for irrigation, fertilization, and pest management based on the variability of soil properties within a field (Bennett *et al.*, 2023).

Furthermore, Global Positioning Systems (GPS) technology plays a vital role in geospatial analysis by providing accurate location information for soil and crop sampling points, remote sensing platforms, and agricultural machinery. GPS enables precise spatial referencing; ensuring that data collected from different sources can be accurately integrated and analyzed within a common spatial framework. This integration of GPS with remote sensing and GIS enhances the accuracy and reliability of soil and crop analysis, leading to more informed decision-making in agriculture.

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ADVANCEMENTS IN GEOSPATIAL TECHNOLOGY

Advancements in geospatial technology have also led to the development of advanced analytical techniques for soil and crop analysis. Machine learning algorithms, such as random forests, support vector machines, and neural networks, can be applied to geospatial data to classify soil types, predict crop yields, detect diseases, and monitor changes in land cover (Jadhav *et al.*, 2011). These algorithms learn from large datasets, identifying patterns and relationships that may not be apparent through traditional statistical methods. By leveraging these advanced analytical techniques, researchers can gain deeper insights into the complex interactions between soil properties, crop growth, and environmental factors, ultimately improving agricultural productivity and sustainability.

One of the key advantages of geospatial technology for soil and crop analysis is its ability to provide real-time and near-real-time monitoring capabilities (Williams *et al.*, 2021). With the integration of sensor networks, remote sensing platforms, and data processing techniques, researchers and farmers can access up-to-date information on soil moisture, temperature, nutrient levels, and crop health (Singh *et al.*, 2022). This timely information allows for proactive decision-making, such as adjusting irrigation schedules, optimizing fertilizer applications, and implementing early pest and disease detection strategies (Ali *et al.*, 2023). By monitoring soil and crop conditions in real time, stakeholders can respond more effectively to dynamic agricultural challenges and mitigate potential risks (Johnson *et al.*, 2023).

Moreover, geospatial technology enables the modelling and simulation of soil and crop processes. Through the integration of Geostatistics, machine learning algorithms, and mathematical models, researchers can predict soil properties, crop yields, and environmental impacts (Smith *et al.*, 2021). These models assist in optimizing resource allocation, improving crop management practices, and mitigating the adverse effects of climate change on agriculture (Barnes *et al.*, 2022; Gonzalez *et al.*, 2023).

1. **High-Resolution Remote Sensing:** The availability of high-resolution satellite imagery, such as from sensors like Worldview and Sentinel, has enabled more detailed and accurate mapping of soil properties and crop characteristics. These advancements in remote sensing technology have improved the spatial resolution and spectral capabilities for soil and crop analysis.

2. **Unmanned Aerial Vehicles (UAVs) and Drones:** UAVs equipped with advanced sensors have become increasingly popular for collecting high-resolution imagery and generating precise 3D models of agricultural fields. UAVs offer flexibility in capturing near real-time data for various applications, including monitoring crop health, detecting nutrient deficiencies, and mapping soil variability.

3. **Hyperspectral Imaging:** Hyperspectral sensors capture data across a wide range of wavelengths, allowing for more detailed analysis of soil and crop

properties. By analyzing the spectral signatures of vegetation and soil, hyperspectral imaging can provide valuable information on plant stress, nutrient content, and soil composition.

4. **Machine Learning and Artificial Intelligence:** Advancements in machine learning and AI algorithms have facilitated automated analysis of geospatial data for soil and crop analysis. These techniques can process large datasets and extract meaningful patterns and relationships, enabling more accurate predictions of crop yield, nutrient requirements, and disease detection.

5. **Integration of Multi-Source Data:** The integration of data from multiple sources, such as satellite imagery, ground-based sensors, weather data, and historical records, has improved the understanding of soil and crop dynamics. Combining different data types allows for more comprehensive analysis and decision-making in precision agriculture. This literature review aims to provide a comprehensive overview of the applications of geospatial technology in soil and crop analysis. By examining existing studies, we will explore the advancements, challenges, and potential future directions in this rapidly evolving field. In the context of soils and crop analysis, geospatial technology plays a crucial role in understanding the spatial variability of soil properties, crop growth, and agricultural practices. It allows researchers, agronomists, and farmers to gain insights into the relationships between soil characteristics, crop performance, and environmental factors on a spatial and temporal scale (Tripathi *et al.*, 2023).

APPLICATIONS OF GEOSPATIAL TECHNOLOGY FOR SOILS AND CROPS

The concept of geospatial technology for soil and crop analysis is based on the understanding that soil and crop conditions vary across landscapes due to natural and human-induced factors (Anderson *et al.*, 2021). These variations impact crop productivity, nutrient availability, water management, and overall agricultural sustainability. By integrating geospatial data, such as satellite imagery, aerial photographs, and ground-based measurements, with geospatial tools and techniques, researchers and stakeholders can gain valuable information to support decision-making in agriculture (Jiang *et al.*, 2022). Geospatial analysis enables the identification of spatial patterns, the assessment of soil fertility and health, the monitoring of crop growth and health, the evaluation of land suitability, and the optimization of resource allocation (Kumar *et al.*, 2023; Lopez *et al.*, 2023).

1. **Remote Sensing for Soil and Crop Analysis:** Remote sensing techniques offer a non-destructive and cost-effective means of assessing soil and crop characteristics over large areas. Studies have utilized multispectral and hyperspectral remote sensing data to estimate soil properties such as moisture content, organic carbon content, and nutrient levels. Additionally, remote sensing has been employed to monitor crop growth, identify stress conditions, and predict yield potentials. Integration

of remote sensing with machine learning algorithms has shown promising results in mapping and monitoring soil and crop parameters at different scales.

2. GIS-Based Soil Mapping and Modelling: Geographic Information Systems (GIS) provide a powerful platform for soil mapping and modelling. Numerous studies have utilized GIS to create digital soil maps by integrating soil data with topographic, climatic, and vegetation information. These maps enable researchers and land managers to better understand soil variability, identify suitable land use practices, and develop precision agriculture strategies. Furthermore, GIS-based soil modelling techniques, such as Geostatistics and soil fertility modelling, allow for accurate prediction and spatial analysis of soil properties and their relationships with crop growth.

3. Precision Agriculture and Site-Specific Crop Management: Geospatial technology has played a crucial role in the implementation of precision agriculture techniques. By combining GPS, GIS, and sensor technologies, farmers can make informed decisions regarding optimal planting, irrigation, fertilization, and pest management strategies at a site-specific level. Remote sensing data, in conjunction with ground-based sensors, provide real-time information on crop health, nutrient status, and water stress, facilitating timely interventions and resource optimization. Integration of geospatial technology with decision support systems has shown significant potential in improving crop productivity while minimizing environmental impacts.

4. Climate Change and Adaptation Strategies: Climate change poses significant challenges to agricultural systems, necessitating adaptive strategies. Geospatial technology can help in assessing climate change impacts on soils and crops, identifying vulnerable areas, and developing adaptation measures. Remote sensing and GIS-based analyses provide insights into the changing spatial distribution of suitable agricultural areas, crop suitability modelling under future climate scenarios, and assessing the impacts of extreme weather events on crop yields. These tools assist policymakers and farmers in formulating climate-smart agricultural practices for sustainable food production.

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The background of geospatial technology for soils and crop analysis can be traced back to the emergence of remote sensing and GIS technologies. Over the years, advancements in satellite technology, sensor capabilities, and data processing techniques have greatly enhanced the spatial resolution, spectral sensitivity, and temporal frequency of remote sensing data. This has enabled more detailed and accurate mapping of soil properties, crop characteristics, and their interactions. Additionally, the integration of geospatial technology with other disciplines, such as agronomy, soil science, and computer science, has led to the development of interdisciplinary approaches for analyzing and interpreting spatial data in agriculture. This integration has fostered the adoption of precision agriculture techniques, which aim to optimize agricultural practices at a site-specific level based on the variability observed in soils and crops (Sajan *et al.*, 2023).

The increasing availability of open-source geospatial tools, online data repositories, and mobile applications has democratized the access and utilization of geospatial technology for soil and crop analysis, paving

the way for sustainable land management, precision nutrient application, irrigation scheduling, pest management, and yield forecasting (Li *et al.*, 2021; Park *et al.*, 2022). Numerous scientists and researchers have contributed to advancements in this field, bolstering our understanding of the spatial variability of soils, crops, and agricultural systems (Wilson *et al.*, 2023). Geospatial technology for soil and crop analysis provides a comprehensive framework for informed decision-making, resource management optimization, and the advancement of sustainable and efficient agricultural practices (Nelson *et al.*, 2023).

Guo *et al.* (2020) elucidated the inherent limitations of traditional methods for soil and crop analysis that primarily rely on intensive manual labour and have constrained spatial coverage. The authors incisively underscore the urgent need for innovative, technology-based, and broad-scale approaches to address these burgeoning challenges. They meticulously delineate the transformative role of geospatial technology in navigating these issues and nurturing sustainable, efficient agricultural practices. They shed insightful light on the historical evolution of soil and crop analysis, marked by a steady transition from manual to digital techniques, thereby illustrating the profound potential of technology for agricultural advancement.

Alqurashi *et al.* (2021) explored the multitudinous benefits of geospatial technology in the realm of agricultural science. Their work delves into the comprehensive and precise data collection capabilities of this technology concerning soil properties and crop conditions, proving superior in cost-effectiveness, efficiency, and scalability. They presented a thorough examination of geospatial technology's potential for large-scale soil and crop analysis, painting a promising picture of the technology-driven future of agriculture.

Patel *et al.* (2022) provided an in-depth understanding of remote sensing's role in agriculture. They investigated the efficacy of this technology in capturing the spectral reflectance properties of soils and crops. They elucidate how hyperspectral imagery contributes to analysing intricate soil aspects such as composition, moisture, and nutrient levels. Their work accentuates the potential of remote sensing in facilitating non-destructive, rapid, and broad-scale assessment of agricultural land, further promoting precision agriculture.

Johnson *et al.* (2022) presented a comprehensive study that underscores the importance of spectral signatures in determining vegetation dynamics and crop health. Their work illuminates the benefits of utilizing remote sensing technology for rapid, non-destructive evaluation of soil and crop characteristics at multiple temporal and spatial scales. This capacity plays a crucial role in influencing effective land management and decision-making processes in agriculture, demonstrating the profound potential of geospatial technology in revolutionizing farming practices.

Ghige *et al.* (2021) emphasized the crucial role of

geospatial analysis in land management and decision-making. Their research focuses on the importance of assessing soil and crop characteristics across various spatial and temporal scales, employing technological advancements to overcome conventional limitations. By highlighting the significance of these assessments for sustainable and effective land management practices, they showed how geospatial technology can contribute to optimizing agricultural productivity.

Walker *et al.* (2022) brought to light the untapped potential of Geographic Information Systems (GIS) in integrating and analyzing diverse geospatial data sets. Their study underscores the importance of creating digital soil and crop maps to facilitate a deeper understanding and effective management of agricultural lands. The authors highlight how the amalgamation of different data types, such as soil samples, remote sensing data, and topographic and climate data, can lead to the creation of comprehensive soil maps, thereby enhancing our understanding of spatial variations in soil properties.

Rodriguez *et al.* (2023) delved deeper into the role of GIS in creating digital soil and crop maps. They emphasized the integration of diverse data sets, including soil samples, remote sensing data, topographic, and climate data, leading to a more comprehensive understanding of soil properties and their spatial variations. This enriched understanding, the authors suggest, plays a critical role in enabling precision agriculture practices, making this technology indispensable for sustainable farming.

Olsen *et al.* (2023) studied on the incorporation of Internet of Things (IoT) technology in modern farming practices. Their work highlighted the role of IoT in gathering real-time data from the fields through sensor networks, enabling farmers to monitor various parameters including soil moisture, nutrient levels, and crop health continuously. They underscore the impact of IoT on improving decision-making and enhancing efficiency, leading to optimized use of resources and improved crop yields. The study contributed significantly to our understanding of IoT as a game-changer in the agricultural sector, driving its transformation towards sustainability and precision.

Chen *et al.* (2023) explored the effectiveness of using satellite imagery combined with machine learning algorithms to predict crop yields accurately. They presented a novel approach to analyzing large-scale data using convolutional neural networks and deep learning algorithms, which had proven successful in identifying intricate patterns in satellite images that correlate with crop yields. Their research holds promise in using technology to tackle food security issues and shape the future of agriculture by making it more data-driven and efficient.

Meyer *et al.* (2023) delved into the possibilities of using LiDAR (Light Detection and Ranging) technology in agricultural applications. Their study highlighted how LiDAR, by generating high-resolution 3D maps of agricultural fields, can provide accurate information about

the topography, crop height, and biomass. The insights from this technology are instrumental in irrigation management, crop health monitoring, and yield prediction. Their research underlines the potential of LiDAR technology in improving precision and efficiency in farming operations.

Castillo *et al.* (2023) explored the use of blockchain technology in traceability and supply chain management within agriculture. They highlighted how block chain can ensure transparency, accountability, and security, thereby adding credibility to the farm-to-table journey of food products. Their work significantly broadens the horizons of the application of digital technologies in the agricultural sector beyond merely production-focused elements.

Wong *et al.* (2023) studied on the use of Virtual Reality (VR) and Augmented Reality (AR) in the realm of agricultural education and training. They discussed how these immersive technologies can simulate farming scenarios, thereby providing practical knowledge and improving skills of farmers and agricultural professionals. Their research is pivotal in recognizing the importance of digital literacy in the sector, fostering the next generation of tech-savvy farmers.

Roberts *et al.* (2023) conducted a significant study into the employment of artificial intelligence-driven drone technology specifically for crop surveillance and management. They unveiled how drone systems fortified with advanced machine learning and AI capabilities hold the potential to perform meticulous and efficient detection of diseases, nutrient deficiencies, and pests in agricultural fields. The technology harnesses the power of real-time imaging to capture and analyze field data rapidly. This detailed and swift method of crop monitoring showcases potential to revolutionize precision agriculture. According to their findings, such a strategy can optimise farm management strategies and subsequently augment crop yields, marking a significant advancement in agricultural practices. The researchers also touched upon how this technology would drastically reduce the requirement for manual labor, thereby streamlining agricultural processes and leading to cost-effective farming.

Li *et al.* (2023) undertook an exhaustive study on smart greenhouses. Their research revolved around the application of Internet of Things (IoT) devices and AI for the regulation and management of the greenhouse environment. Their comprehensive analysis reveals how these advanced automation systems can astutely manage essential growth parameters like light, temperature, humidity, and nutrient levels. This process is accomplished through real-time monitoring and adjustments based on collected data. The study suggests that such management tactics could lead to the maximization of crop productivity in greenhouses. Moreover, the team proposed that this smart technology could pave the way for a future with minimal human intervention in greenhouse farming, thus reducing human error and ensuring the consistent growth of high-quality produce.

Rasmussen *et al.* (2023) spearheaded research implementation of bioinformatics in the agricultural field. The team focused on how genetic sequencing and genomics data could be leveraged to breed crops with enhanced desirable traits. The authors illuminate that the amalgamation of bioinformatics with contemporary agriculture could quicken the crop breeding process, leading to crops that are more resilient and adaptable to climatic changes. This concept presents a promising future where we could cultivate high-yielding, disease-resistant crops capable of withstanding adverse environmental conditions, thus ensuring food security in the face of potential future challenges.

Suzuki *et al.* (2023) executed an in-depth study on the potential application of 3D printing technology in the agricultural sector. They portrayed how 3D printing technology could revolutionize the way spare parts for farm machinery are created, along with its potential in the construction of intricate micro-irrigation systems and even the prototyping of novel machinery. Their ground breaking research implies that the embracement of such technology could significantly reduce the downtime of agricultural operations and spur innovation in the field. This evolution in technology could also lead to customized and localized solutions for farming equipment, thereby reducing reliance on external vendors for parts and equipment.

De Vries *et al.* (2023) concentrated their research on the crucial role of data analytics and big data in influencing agricultural policies. Their discourse emphasizes how vast data sets pertaining to weather patterns, soil conditions, and crop growth patterns could be crucial in drafting evidence-based agricultural policies. Their insightful study underscores the necessity of a data-driven approach in policy-making to effectively confront and address challenges in the agricultural sector. This work underscores the transformative power of digital technologies in advancing sustainable agriculture, ultimately leading to increased productivity and improved farmer livelihoods.

WAY FORWARD

The field of geospatial technology for soils and crop analysis continues to advance, opening up new possibilities and avenues for improved agricultural practices. Here are some of the key areas that represent the way forward or the future direction for this field:

1. **Precision Agriculture:** Geospatial technology plays a vital role in precision agriculture, which involves site-specific crop management based on spatial and temporal variability. The future will see further integration of geospatial data with real-time monitoring, sensor networks, and automated machinery, enabling precise and optimized agricultural operations. This includes variable rate application of fertilizers, irrigation, and pesticides based on the specific needs of different areas within a field (Bele *et al.*, 2021).

2. **Data Integration and Interoperability:** As more data sources become available, including satellite imagery,

UAVs, ground sensors, and weather stations, the way forward is to integrate and analyze these diverse datasets effectively. Improved data interoperability and advanced data fusion techniques will enable better integration of geospatial information, leading to comprehensive soil and crop analysis.

3. Advanced Remote Sensing Techniques: The future will witness the development of more advanced remote sensing techniques, including hyperspectral, thermal, and LiDAR-based imaging. These technologies will provide more detailed and accurate information about soil properties, crop health, water stress, and nutrient content. Integration of these advanced techniques with machine learning algorithms will enhance the efficiency and precision of soil and crop analysis (Baruah *et al.*, 2021).

4. Big Data and Data Analytics: With the increasing availability of geospatial data, the way forward involves utilizing big data analytics to extract meaningful insights. Advanced data mining, machine learning, and artificial intelligence techniques will enable the analysis of large datasets to identify patterns, predict crop performance, optimize resource allocation, and support decision-making in agriculture.

5. Mobile and Cloud-based Applications: The future of geospatial technology for soils and crop analysis will likely involve the development of user-friendly mobile and cloud-based applications. These applications will provide farmers, agronomists, and other stakeholders with easy access to geospatial information, analysis tools, and decision support systems, empowering them to make informed decisions and manage their agricultural operations more efficiently.

Conclusions

Geospatial technology has emerged as a powerful toolset for soil and crop analysis, enabling researchers and practitioners to better understand the spatial variability of soil properties, monitor crop growth, and implement precision agriculture techniques. Remote sensing, GIS, and GPS technologies provide valuable data and analytical capabilities for mapping, modelling, and decision-making in agricultural systems. However, challenges such as data availability, scale mismatches, and algorithm development persist. Future research should focus on addressing these challenges and exploring emerging technologies like unmanned aerial vehicles (UAVs) and machine learning algorithms to further enhance the accuracy and efficiency of geospatial analysis in soils and crop research. In conclusion, geospatial technology has revolutionized the field of soil and crop analysis, providing researchers and practitioners with advanced tools to understand and manage agricultural systems. The integration of remote sensing, GIS, and GPS technologies has improved our ability to assess soil characteristics, monitor crop growth, and implement precision agriculture techniques. This literature review aims to explore the applications, advancements, challenges, and potential

future directions of geospatial technology in soils and crop analysis, contributing to the advancement of sustainable agriculture practices and food security.

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Rec. on 28.05.2023 & Acc. on 11.06.2023