A Systematic Literature Review for the Development of an Object Detection System for Monitoring Underground Crop (Garlic) Growth Using GPR

Anna Maria Theresa Hermoso[1], *Bea Bianca* Lastimosa[1], *Angel Kathleen* Valdez[2], *Vince Jebryl* Montero[2], and *John* Bacus[1*]

[1]Mapúa Malayan Colleges Mindanao, College of Engineering and Architecture, Computer Engineering Department, Davao City, Philippines
[2]Mapúa Malayan Colleges Mindanao, College of Engineering and Architecture, Electronics Engineering Department, Davao City, Philippines

Abstract. This systematic literature review investigates the development of a Ground-Penetrating Radar (GPR)-based object detection system tailored for under-ground garlic crop monitoring. While garlic-specific GPR applications re-main limited, studies on structurally similar root crops such as potatoes and carrots provide a valuable reference framework. Using a PRISMA-guided methodology, 16 relevant studies were analysed and synthesized, highlighting advancements in GPR signal processing, object reconstruction, and machine learning integration. Results show that mid-frequency GPR (500–800 MHz), especially when paired with deep learning models such as 3D Convolutional Neural Networks (CNNs), offers high accuracy in detecting root structures. Key challenges such as signal attenuation in clay-rich and tropical soils are addressed through electromagnetic induction (EMI) hybridization and antenna optimization. A comparative matrix summarizes the most relevant findings, and actionable recommendations are proposed to guide future research. These include the development of garlic-specific datasets, localized field testing, and AI-enhanced signal classification. GPR, when effectively configured and paired with machine learning, presents a viable solution for real-time, non-invasive garlic crop monitoring in tropical agriculture.

1 Introduction

A critical barrier to optimizing crop yields lies in the lack of effective tools for monitoring subsurface crop development. Traditional methods like manual inspection and destructive sampling are tedious and do not offer real-time information of the crop health, soil conditions, or root growth [1]. Such limitations hinder farmers' ability to implement precision agriculture techniques, adjust irrigation, or detect early signs of disease. Furthermore, challenges like

*Corresponding author: jabacus@mcm.edu.ph

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low-quality planting monitoring, and exploring the integration of object detection systems to enhance its utility.

Ground-penetrating radar (GPR), a non-destructive geophysical technology, has emerged as a promising tool for subsurface imaging in agriculture. By emitting high-frequency electromagnetic waves into the soil, GPR generates detailed profiles of underground structures, enabling the detection of root systems, soil moisture variations, and even crop biomass [2]. Recent advancements in object detection algorithms and machine learning have further enhanced GPR's capability to interpret complex subsurface data [3], transforming it into actionable insights for farmers. For instance, studies have demonstrated GPR's efficacy in monitoring root growth in potatoes [4] and assessing soil compaction in cereal crops [5]. These applications highlight GPR's versatility as a tool for real-time, non-invasive agricultural monitoring.

Despite its potential, the adoption of GPR in agriculture remains limited, particularly in developing regions like the Philippines. Additionally, gaps persist in integrating GPR with automated object detection systems tailored for agricultural contexts, such as real-time crop health assessment or yield prediction. This systematic literature review addresses these gaps by synthesizing current knowledge on GPR's role in agriculture, evaluating its effectiveness in soil and crop monitoring, and exploring the integration of object detection systems to enhance its utility

2 Methodology

This study employs a systematic and comparative review methodology to analyze existing research on ground-penetrating radar (GPR) applications in agriculture, specifically for underground garlic monitoring. By reviewing and synthesizing relevant literature, this methodology as shown in Figure 1 aims to identify key research gaps, refine the proposed system framework, and ensure that the study is built on scientifically validated knowledge.

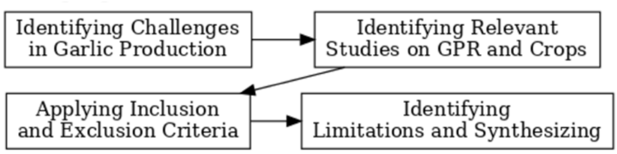

Fig. 1. Methodology

2.1 Formulating the Problem

While ground-penetrating radar (GPR) has been used for underground object detection, its application in agriculture, particularly for garlic, remains underdeveloped. Research on GPR in tropical soil conditions is also limited. This study explores the potential of a real-time, non-invasive GPR-based monitoring system for garlic farming.

To refine the research, the following questions are formulated:

1.How effective is GPR in detecting and reconstructing underground objects, and how can its application be optimized for real-time, non-invasive monitoring of garlic growth in tropical soil conditions?

2. How effective has GPR been in agricultural studies?

3. What are the key challenges in using GPR for underground monitoring in different soil conditions?

4. How have object detection and machine learning techniques improved the accuracy and automation of GPR-based crop monitoring?

5. What research gaps exist in integrating GPR with real-time object detection systems for precision agriculture?

2.2 Research Identification and Data Extraction

To ensure an extensive knowledge of ground-penetrating radar (GPR) applications in agriculture, this study uses a systematic literature review to collect the relevant information. Finding current research, techniques, and technology developments that can support the creation of a GPR-based garlic monitoring system is the objective. Place the figure as close as possible after the point where it is first referenced in the text. If there is a large number of figures and tables, it might be necessary to place some before their text citation.

Data Selection. To ensure reliability, relevant research was sourced from government publications, conference proceedings, and peer-reviewed journals. Engineering, agriculture, and precision farming technologies are the main topics of the databases that were chosen as shown in Table 1.

Table 1. Data Selection Process

Source/Database	Purpose or Coverage
ScienceDirect (Elsevier)	Engineering and Agricultural studies
IEEE Xplore	Sensor-based object detection and GPR research
SpringerLink	Precision farming and soil monitoring
Google Scholar	Open-access research on GPR application
Philippine Statistics Authority (PSA)	Data on garlic production trends
Department of Agriculture (DA)	Agricultural policies and reports

Data Extraction. To extract relevant research, a systematic approach was used. Firstly, Keyword Selection: "Ground-Penetrating Radar in agriculture," "real-time soil object detection," "underground crop monitoring," and "GPR for root crops" were among the search terms used. Next, Initial Search and Screening: Relevance-based selection of the studies ensured that the focus was on current developments (2014–2024). Then, Abstract and Full-Text Review: We concentrated on research that investigated techniques for locating crops that are growing underground. Lastly, Categorization: The research was categorized according to the crops examined (garlic, onions, potatoes, and other root vegetables) and the technologies they employed (such as soil sensors, machine learning, and ground penetrating radar, or GPR).

2.3 Inclusion & Exclusion Criteria

A criterion, as shown in Table 2, was utilized to include or reject research to ensure that the best and most relevant data is found. This assisted in eliminating any study that wasn't relevant. Only the studies that provided with credible information about the use of Ground Penetrating Radar (GPR) to monitor crops growing underground were retained. The research selected showcases the most recent developments in garlic farming and precision agriculture, emphasizing what is technically possible and what has been demonstrated in practical trials.

Table 2. Inclusion-Exclusion Criteria

Criteria	Inclusion	Exclusion
Publication Year	2014–2024 (Recent advancements)	Studies before 2014 (outdated technology)
Topic Relevance	GPR applications in agriculture and soil monitoring	GPR for non-agricultural purposes
Technology Focus	Studies on underground crop detection	Research on above-ground crop monitoring
Methodology	Experimental and theoretical studies with data validation	Studies without experimental results
Crop Type	Research on root and bulb crops (garlic, onion, potato)	Studies on non-bulb crops (corn, wheat, rice)
Access	Open-access and full-text	Abstract-only papers

2.4 Data Evaluation and Analysis

A "Review of Related Literature (RRL) Matrix," which compares all the earlier studies on the application of GPR (ground penetrating radar) for underground crop monitoring, was developed. Table 3 made it simpler for to organize and evaluate the key findings of each study by grouping them based on criteria such the technology used, the procedures used, the level of accuracy, and the applicability. By adopting a wide view of patterns, strengths, and weaknesses, this matrix assisted in refining the pro-posed GPR-based garlic monitoring system and ensuring that it closes the gaps in previous research.

Table 3. Summary of Selected Studies

Article Title	Authors and Year	Methodology	Highlights	Results
Efficient Underground Object Detection for Ground Penetrating Radar Signals	Mesecan & Bucak (2016)	Used ANN and SVM to classify GPR signals for object detection.	Improved object detection rate using signal processing techniques.	Increased object detection ratio and classification accuracy.
Underground Object Reconstruction from Ground Penetrating Radar Data	Mahmud et al. (2021)	Investigated feature extraction techniques for GPR data analysis.	Developed a feature extraction method for GPR object classification.	Successfully extracted key features from GPR data for object reconstruction.
Ground Penetrating Radar for Asparagus Detection	Seyfried & Schoebel (2016)	Implemented GPR to determine optimal cutting height for asparagus harvesting.	Demonstrated non-invasive asparagus detection using GPR.	Enabled precision harvesting to maximize crop yield.
3D CNN-based Underground Object Classification using GPR	Khudoyarov et al. (2020)	Used deep learning with 3D CNN to classify underground objects.	Developed a high-accuracy (97%) underground object classification model.	Obtained 97% classification accuracy for underground object detection.
Underground Mapping and Localization Based on GPR	Zhang & Lu (2024)	Used deep learning for 3D mapping and localization with GPR.	Demonstrated deep learning application in underground mapping.	Successfully implemented a deep learning approach for underground mapping.
Simulation of Airborne GPR Model for Detecting Underground Targets	Qi et al. (2019)	Simulated airborne GPR model to detect underground structures.	Showed effectiveness of airborne GPR for detecting buried targets.	Demonstrated feasibility of airborne GPR for underground sensing.
3D Reconstruction of Embedded Object Using GPR	Fadil et al. (2023)	Employed 3D interpolation and SAFT for embedded object reconstruction.	Developed a 3D reconstruction technique for embedded objects.	Successfully reconstructed 3D representations of underground objects.

Classification Size of Underground Object from GPR Image using Machine Learning	Azalan et al. (2023)	Used machine learning (SVM, BPNN) for underground object classification.	Achieved 98% accuracy in underground object size classification.	Achieved more than 98% accuracy in object size classification.
3D Modeling Beneath Ground: Plant Root Detection and Reconstruction Based on GPR	Lu & Lu (2022)	Applied deep learning for plant root detection and reconstruction.	Developed a framework for detecting plant root structures using GPR.	Demonstrated feasibility of GPR in non-invasive root detection.
Model Test Study on Oil Leakage and Underground Pipelines Using GPR	Gao et al. (2020)	Conducted controlled GPR experiments on pipelines and leakage detection.	Provided insights into oil leakage detection using GPR imaging.	Improved detection accuracy for underground pipeline leaks.
Sensing Underground Coal Gasification by Ground Penetrating Radar	Kotyrba & Stańczyk (2017)	Tested radar imaging of underground coal gasification processes.	Demonstrated radar's ability to monitor underground coal gasification.	GPR effectively monitored underground coal gasification, detecting voids, fissures, and structural changes in coal seams.
Integrated ground-penetrating radar and electromagnetic induction offer a non-destructive approach to predict soil bulk density in boreal podzolic soil	Pathirana et al. (2024)	Used GPR and EMI to study the effect of soil compaction on dielectric properties and develop models for predicting soil bulk density.	Integrated GPR and EMI for non-destructive prediction of bulk density in agriculture, proposing a Random Forest model for prediction.	The study identified the dielectric constant and electrical conductivity as good indicators for estimating soil bulk density across different compaction levels.
Assessment of zones prone to sinkhole using ground penetrating radar and soil properties in Central Iran	Amin et al. (2023)	Applied GPR and soil property analysis to detect zones prone to sinkholes in arid and semi-arid regions of Central Iran.	Showed the potential of using GPR combined with soil characteristics for identifying sinkhole-prone areas and avoiding land subsidence.	The GPR results detected subsurface cavities and soil breaks, confirming the potential of GPR to identify sinkhole-prone areas and guide construction decisions.
Phenology, growth, yield, and yield-related traits of Ethiopian garlic genotypes. A review	Galgaye et al. (2023)	Reviewed various studies on the phenology, growth, yield, and yield traits of Ethiopian garlic genotypes.	Provided insights into how genotype affects garlic growth and yield, highlighting the importance of genetic variability for production.	Reviewed how garlic genotypes influence phenology, growth, and yield, suggesting that genotype selection plays a crucial role in increasing garlic yield.
Comparison of soil water content estimation equations using ground penetrating radar	Anbazhagana et al. (2020)	Compared different empirical and dielectric mixing models for converting dielectric permittivity to soil water content using GPR.	Evaluated and compared different models for estimating soil water content from GPR, identifying the Roth et al. (1990) model as the most accurate for various soils.	Found that Roth et al. (1990) dielectric mixing model provided the best estimates for soil water content, particularly for mineral soils, while empirical models were less accurate.
Assessing the Perspectives of Ground Penetrating Radar for Precision Farming.	Lombardi et al.(2022)	Comprehensive review of GPR applications in precision irrigation, analyzing operational and data processing approaches for soil property assessment.	Comprehensive review of GPR applications in precision irrigation, analyzing operational and data processing approaches for soil property assessment.	GPR effectively characterizes soil properties, enhances variable-rate irrigation management, and optimizes water use while maintaining or improving crop yields and quality.

3 Results and Discussions

This systematic literature review adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework as shown in Figure 2 to ensure transparent and reproducible reporting of the study selection process. A comprehensive search was conducted across multiple databases (e.g., ScienceDirect, IEEE Xplore, SpringerLink) using keywords such as "Ground Penetrating Radar in Agriculture", "Real-Time Soil Object Detection", "Underground Crop Monitoring", and "GPR for Root Crops".

During title/abstract screening, studies were evaluated against predefined inclusion and exclusion criteria. There was a total of 288 records found from searching. After screening using the inclusion and exclusion criteria a total of 16 papers was included.

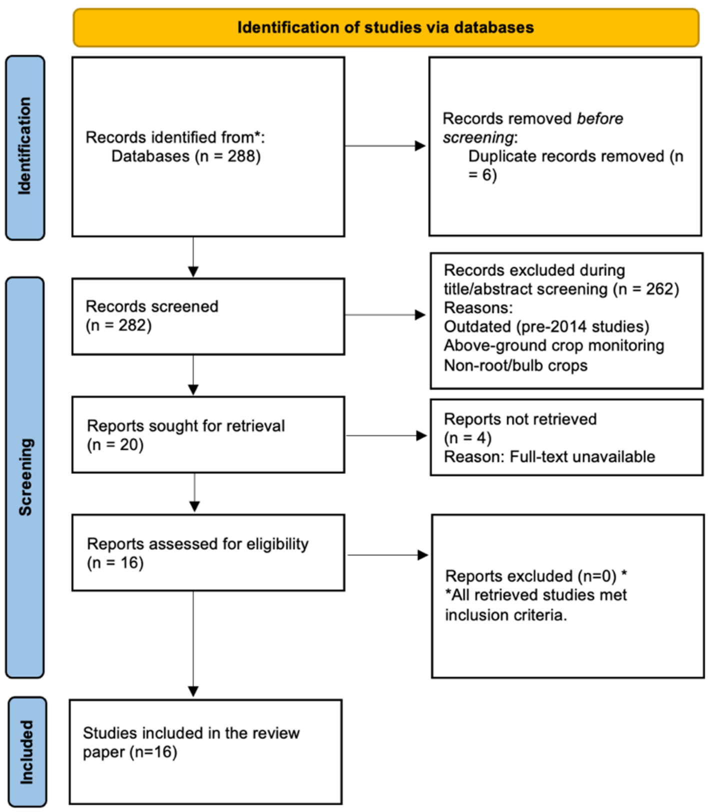

Fig. 2. PRISMA Framework [6]

3.1 Effectiveness of GPR in Detecting and Reconstructing Underground Objects

GPR has shown strong potential in detecting and reconstructing underground objects through subsurface imaging and signal-based interpretation. Study [7] demonstrated the use of GPR for 3D reconstruction of embedded objects, highlighting its capability to generate clearer subsurface visualizations. In a different underground application, study [8] showed that GPR can effectively sense subsurface changes in underground coal gasification, confirming its usefulness in monitoring concealed underground processes. Likewise, study

[9] found that combining GPR data with soil properties improves the detection of subsurface anomalies, particularly in identifying zones prone to sinkholes. In addition, study [10] presented a simulation model of airborne GPR for detecting underground targets, showing how system modelling can support more accurate target detection and signal interpretation.

3.2 GPR in Agricultural Research: Crop Monitoring Case Studies

Although garlic-specific GPR studies remain limited, related agricultural research provides useful guidance for subsurface crop monitoring. Study [11] reviewed the phenology, growth, yield, and root-related traits of garlic and showed that garlic typically has a shallow and fibrous root system, which is important in determining suitable GPR settings for detection. Supporting the feasibility of plant-focused applications, Study [12] demonstrated that GPR can be used for plant root detection and 3D reconstruction, confirming its relevance in agricultural research. Similarly, study [13] applied GPR to asparagus detection and showed that underground crop monitoring is possible, although effectiveness depends on crop structure, depth, and subsurface conditions. Together, these studies suggest that GPR has potential for garlic monitoring, but its configuration must be tailored to garlic's specific root morphology and growth characteristics.

3.3 Challenges in Diverse Soil Conditions

Soil conditions remain one of the major limitations in GPR performance. Study [14] showed that soil water content significantly affects GPR signal behavior because moisture changes the dielectric properties of the soil, which in turn influences signal attenuation and accuracy. In a related study, [15] found that the material surrounding buried objects affects detection performance, with certain materials causing reduced penetration depth and lower image clarity. These findings indicate that soil moisture, texture, and material composition must be considered carefully when designing a GPR system for agricultural applications, especially in tropical environments where moisture variation is high.

3.4 Enhancing GPR Accuracy Through Object Detection and Machine Learning

Recent studies have improved GPR performance through machine learning and intelligent signal interpretation. Study [16] demonstrated that ANN- and SVM-based approaches can improve underground object detection in GPR signals, showing the value of automated classification methods over traditional interpretation alone. Advancing this further, Study [17] used a three-dimensional convolutional neural network for underground object classification from 3D GPR data and reported strong performance in handling volumetric subsurface information. More recently, Study [18] proposed underground mapping and localization methods based on GPR, expanding its use beyond detection toward more integrated spatial analysis. Finally, study [19] demonstrated the effectiveness of YOLOv9 instance segmentation with image augmentation in environmental object detection. Although not directly applied to GPR, this study suggests that lightweight object detection frameworks may be adaptable for real-time subsurface agricultural monitoring when combined with GPR-generated imaging data.

3.5 Summary Matrix of Reviewed Studies

The following matrix as shown in Table 4 includes studies deemed most relevant to garlic GPR applications. These were selected based on their methodological alignment with garlic root morphology, tropical soil conditions, and the use of machine learning in GPR:

Advanced AI techniques significantly enhance GPR signal interpretation. ANN, SVM, and 3D CNNs are commonly employed for signal classification. Among them, 3D CNNs stand out for their capacity to handle volumetric GPR data, achieving superior precision in root detection.

Object detection architectures suited for GPR applications include, YOLO variants (for lightweight, real-time classification), Faster R-CNN (for high accuracy in complex signal environments), 3D CNN architectures (like VoxelNet) for volumetric data analysis.

Table 4. Comparative Summary of Key GPR Studies Relevant to Garlic Crop Monitoring

Crop Type	GPR Frequency	ML Technique	Accuracy	Soil Type	Key Insight
Potato	1 GHz	Random Forest	High	Loam	Real-time yield prediction
Garlic	800 MHz	None	Moderate	Tropical	3D root structure imaging
Garlic	500 MHz	None	—	Sandy	Root growth variability
Carrot	500 MHz	3D CNN	97 %	Sandy	3D object classification

4 Results and Discussions

Based on the comparative and analytical synthesis of current literature, garlic-focused GPR systems should adopt mid-range frequencies (500–800 MHz) and bowtie antennas to ensure optimal performance in tropical soils. Additionally, 3D CNN models are recommended for signal interpretation due to their ability to detect and segment root structures effectively. Multi-sensor integration, particularly the combination of EMI and GPR, is essential to improve accuracy in the diverse and moisture-sensitive soil conditions common in the Philippines. There is a pressing need for the creation of open-access datasets that focus specifically on garlic root imagery under GPR, which would aid in the development and validation of machine learning models. Localized pilot testing in Philippine garlic farms should also be conducted to ensure that the systems are calibrated and adapted to local agricultural environments.

GPR, when enhanced with AI-based object detection and signal optimization, offers a robust framework for non-invasive underground crop monitoring. Despite garlic-specific literature scarcity, insights from related crops and emerging garlic-focused studies offer a viable roadmap for future development. The integration of 3D CNNs, mid-frequency radar, and EMI sensors shows strong promise for real-time, field-deployable monitoring systems in tropical conditions.

Future research should focus on expanding the empirical evidence for garlic-specific GPR applications by developing dedicated datasets, validating antenna configurations in tropical soils, and conducting machine learning-driven detection trials. These ef-forts will contribute significantly to scaling precision agriculture technologies for garlic farming and beyond.

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