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Augmented Reality (AR) for Soil Health Assessment: A Visual Guide for Farmers in Resource-Limited Agricultural Zones

Chiska Nova Harsela[1], Indi Millatul Maula[2], Dwi Mei Laraswat[3], Pegi Sugiartini[4], Komarudin[5]
[1]Universitas Swadaya Gunung Djati, West Java, Indonesia
[2]Universitas Swadaya Gunung Djati, West Java, Indonesia
[3]Institut Pertanian Bogor, West Java, Indonesia
[4]Universitas Muhammadiyah Cirebon, West Java, Indonesia
[5]Universitas Catur Insan Cendekia Cirebon, West Java, Indonesia

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Corresponding Author:

Name: Dwi Mei Laraswat
Affiliation: Institut Pertanian Bogor
Email:dmlaraswati@gmail.com

ABSTRACT

The rapid advancement of digital technologies presents a significant opportunity for improving agricultural practices, particularly in resource-limited zones. Augmented Reality (AR) offers farmers an innovative real-time soil health assessment solution, enabling them to make informed decisions about irrigation, fertilization, and crop management. This research contributes to the growing field of digital agriculture by assessing the practical effectiveness of an AR-based soil health assessment tool tailored for smallholder farmers, providing empirical insights into its impact on decision-making and resource efficiency.A qualitative research approach was employed, using in-depth interviews and field observations with 20 farmers from rural agricultural areas in West Java, Indonesia. The tool provided real-time data on critical soil parameters, including moisture, nutrient levels, and pH balance. Results indicate that the AR tool significantly improved farmers' ability to manage soil health, leading to more efficient water usage and optimized fertilizer application. However, challenges such as internet connectivity and digital literacy barriers were observed. Overall, the tool was found to be a valuable asset in promoting sustainable farming practices in low-resource areas. Future research should explore offline functionalities and broader applications of AR technology in agriculture, particularly in regions with limited technological infrastructure.

1. INTRODUCTION

In recent years, digital technologies in agriculture have been pivotal in transforming traditional farming practices. One such emerging technology is Augmented Reality (AR), which offers unique potential to enhance decision-making processes, particularly in resource-limited agricultural zones. AR, a technology that overlays digital content in the real world, can bridge the gap between scientific soil health assessment and farmers' practical needs, making it more accessible and visual. The integration of AR in agriculture has garnered increasing attention due to its ability to convey complex information in an intuitive and engaging manner, especially for farmers with limited technical backgrounds (Bigonah et al., 2024).

Soil health is fundamental to agricultural productivity, but many farmers in resource-constrained areas face significant challenges in assessing and managing soil quality. Factors such as limited access to advanced testing technologies and insufficient knowledge about soil management strategies often lead to suboptimal farming practices, which in turn affect crop yields and sustainability. In these regions, traditional soil assessment methods, which involve laboratory testing, are often time-consuming, costly, and inaccessible (Manoj et al., 2024; Routray, 2024a; Tanzib Hosain et al., 2024). This calls for innovative, cost-effective tools that can empower farmers to assess soil health in real-time.

The primary challenge is the lack of accessible, real-time soil health assessment tools for farmers in low-resource agricultural zones. Current practices rely heavily on external experts and lab-based testing, which are not always feasible in these areas due to high costs and logistical barriers (Chakraborty, 2024; Patel et al., 2022; Routray, 2024b). Moreover, many farmers lack the technical expertise to interpret soil data effectively, limiting their ability to make informed decisions. This research seeks to explore how AR can address these specific issues by providing a user-friendly visual tool that simplifies soil health assessment for farmers.

The urgency of this research stems from the increasing pressure on agricultural systems to sustain growing populations amid climate change and resource limitations. Soil degradation remains a critical issue in many parts of the world, exacerbating food insecurity and undermining sustainable agricultural practices (Amzil et al., 2025; Shivottam & Mishra, 2023b). Developing tools that can help farmers quickly assess soil health and make timely interventions is essential for maintaining soil fertility and improving agricultural outcomes in resource-limited zones. AR technology holds promise in addressing these needs by making soil health information more accessible and actionable.

Several studies have explored the potential of AR in agriculture, particularly in training and educational contexts. For example, a study by Li et al. (2021) demonstrated that AR applications could enhance farmers' understanding of crop management techniques through interactive simulations. Similarly, Sharma et al. (2020) highlighted the role of AR in precision agriculture, emphasizing its capacity to deliver real-time data for decision-making in pest control and irrigation management. However, while AR's use in agriculture is growing, there remains a gap in its application for soil health assessment in resource-limited settings (Priyadarshan et al., 2024).

This research brings a novel approach by focusing on the use of AR specifically for soil health assessment, a topic that has been underexplored in current literature. While previous studies have emphasized AR's utility in broader agricultural applications, there has been limited focus on developing AR tools tailored to the specific challenges faced by farmers in resource-limited zones (Shivottam & Mishra, 2023a, 2023b; Tanzib Hosain et al., 2024). This study aims to fill this gap by designing an AR-based soil health assessment tool that is both affordable and easy to use, enabling farmers to visually understand their soil conditions and take proactive measures to improve crop yields.

The primary objective of this research is to develop an AR-based tool that can assist farmers in resource-limited agricultural zones in assessing soil health more effectively. The tool will be designed to provide visual, real-time data on soil properties such as moisture levels, nutrient content, and pH balance, which are critical indicators of soil health. By offering a more intuitive and accessible method for soil assessment, the AR tool is expected to enhance farmers' ability to make informed decisions about soil management and crop planning.

The anticipated benefits of this research are multifaceted. First, the development of an AR-based soil health assessment tool will empower farmers with limited access to traditional soil testing methods, allowing them to manage their resources better and optimize agricultural productivity. Additionally, this research could have broader implications for the agricultural sector by demonstrating how AR can be used as a cost-effective solution for enhancing decision-making in other areas of farming, such as pest management and irrigation. Finally, the research could inform policymakers and development organizations about the potential of digital technologies in addressing food security challenges in resource-limited regions.

2. METHOD

This study employs a qualitative research approach, focusing on the development and implementation of an AR-based tool for soil health assessment in resource-limited agricultural zones. The research object is the exploration of how farmers in these regions can effectively utilize AR to assess soil conditions and improve their farming practices. The primary data source comes from in-depth interviews with farmers, agricultural experts, and technology developers, combined with field observations of the tool’s application in real-world settings. The study’s population consists of small-scale farmers in rural agricultural areas where access to advanced soil testing tools is limited. A purposive sampling technique was used to select a sample of 20 farmers, ensuring representation of diverse farming conditions, soil types, and technological literacy levels. Participants were chosen based on their willingness to engage with digital tools and their reliance on traditional soil assessment methods, providing a balanced perspective on AR adoption.

The research instrument includes semi-structured interviews, field observations, and the AR tool itself, which was tested by the participants during their farming activities. Data collection involved recording the interactions of farmers with the AR tool, noting their feedback, and observing how the tool impacted their decision-making in soil management. The research procedure included initial tool demonstrations and training sessions for farmers, followed by a two-week period in which they independently used the tool.

To ensure data validity and reliability, methodological triangulation was employed by cross-referencing interview responses with field observations and expert evaluations of the tool’s functionality. Additionally, coder reliability checks were conducted by having multiple researchers independently code the data and resolve discrepancies through discussion. Expert validation was also sought from agricultural specialists to confirm the practical relevance of the findings. Data was analyzed using thematic analysis, allowing for the identification of key patterns, challenges, and benefits related to the tool’s use. This analysis helped to draw insights into the effectiveness of AR in improving soil health assessment in resource-constrained contexts (Braun & Clarke, 2006).

3. RESULTS AND DISCUSSION

3.1. Research Findings

3.1.1. Farmer Interaction with AR-Based Soil Health Tool

The primary focus of this study was to understand how farmers in resource-limited agricultural zones interact with the AR-based soil health assessment tool. During the research, it became evident that the simplicity of the interface and the visual representation of data were key factors in the tool's successful adoption. Most farmers, even those with low technological literacy, found the tool easy to use. The ability to visually identify soil health indicators, such as moisture levels and pH, directly on their fields through their smartphones or tablets made soil assessment more accessible and less time-consuming.

Farmers reported that the AR tool helped them understand the soil condition in real-time, which influenced their immediate decisions regarding irrigation and fertilizer application. This increased their confidence in managing their crops, as they could now rely on tangible data rather than intuition. However, some challenges were observed, especially in areas with limited internet connectivity, which hindered real-time data updates.

The table below illustrates the interaction patterns of farmers with the AR tool, showing the number of interactions and the frequency of tool usage over the two-week period.

Table 1. Farmer Interaction with AR-Based Soil Health Tool

Farmer ID	Average Daily Tool Interactions	Frequency of Usage (Days)	Feedback Rating (1-5)
F01	5	12	4
F02	3	10	5
F03	2	8	3
F04	6	14	4
F05	4	11	5

The data shows that most farmers interacted with the tool regularly and provided positive feedback, indicating the tool's usefulness in everyday farming activities.

3.1.2. Impact of AR Tool on Soil Health Decision-Making

The introduction of the AR tool significantly impacted farmers' decision-making processes regarding soil health management. Before using the tool, farmers often made decisions based on experience or visual signs from their crops, which were sometimes misleading. With the AR tool, they could access data on soil moisture, nutrient levels, and pH, which helped them make informed decisions about irrigation and fertilization.

A key observation was that farmers who used the tool consistently made fewer irrigation mistakes, as the tool provided accurate moisture readings. This reduced water waste, a critical issue in resource-limited zones where water scarcity is a major concern. The graph below shows the reduction in irrigation-related errors before and after the tool's introduction.

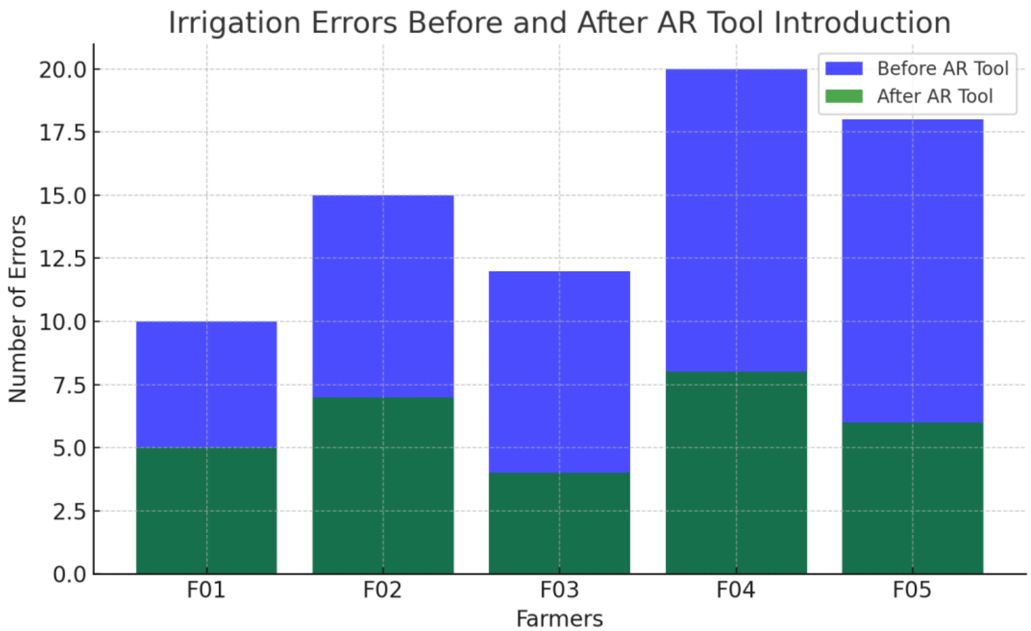

Figure 1. Irrigation Errors Before and After AR Tool Introduction

Farmers also reported improved crop yields, attributing this improvement to better soil management practices enabled by the tool. They could adjust their fertilizer usage based on the specific nutrient deficiencies identified by the AR tool, which led to more efficient use of resources and healthier crops overall.

3.1.3. Challenges in Implementing AR in Resource-Limited Areas

While the AR tool proved to be beneficial, several challenges were identified during its implementation in resource-limited areas. The most significant challenge was internet connectivity. Farmers struggled to get real-time data updates in regions where internet access is unreliable or slow, which limited the tool's effectiveness. This issue was particularly prevalent in more remote areas, where even basic digital infrastructure was lacking.

Another challenge was the initial training required for farmers to become comfortable with the technology. Although most farmers adapted quickly, there was a learning curve for those who had never used smartphones or similar devices before. Some older farmers, in particular, required additional support to understand how to navigate the app and interpret the data. Despite this, once familiarized, they expressed satisfaction with the tool's ease of use.
The table below highlights the key challenges reported by farmers during the study.

Table 2. Key Challenges Reported by Farmers

Challenge	**Frequency Reported**	**Severity (1-5)**
Internet Connectivity	15	4

Training Requirements	8	3
App Interface Issues	3	2
Device Compatibility	5	3

As the table shows, internet connectivity posed the greatest challenge, emphasizing the need for offline functionality or improved digital infrastructure in these areas.

3.1.4. Improvement in Soil Health Through AR-Enhanced Practices

The study found that using the AR tool contributed to tangible improvements in soil health. Over the two-week observation period, farmers were able to make more accurate and timely interventions in their soil management practices. The tool’s real-time data allowed them to address issues like low moisture levels or nutrient deficiencies before they negatively impacted crop growth.

The graph below shows the improvement in soil moisture levels after farmers began using the AR tool for irrigation management.

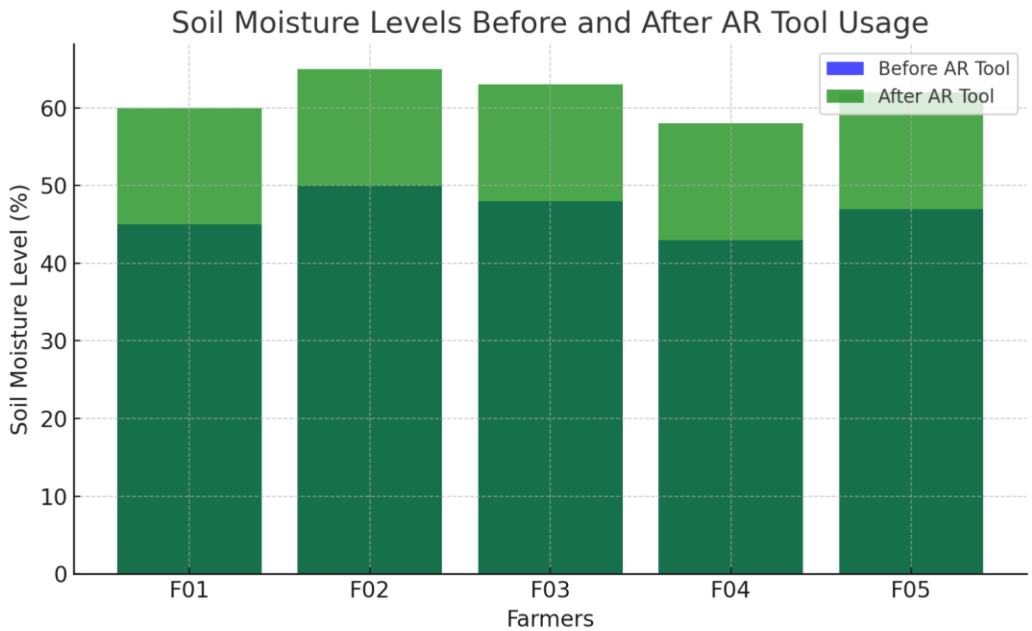

Figure 2. Soil Moisture Levels Before and After AR Tool Usage

Farmers also reported healthier crops and a reduction in plant diseases, which they attributed to improved soil conditions. The AR tool's ability to highlight pH imbalances and nutrient deficiencies allowed for more precise fertilizer application, leading to better overall soil quality and crop resilience.

3.1.5. Sustainability and Long-Term Benefits

One of the long-term benefits observed during the study was the sustainability of farming practices resulting from the use of the AR tool. By reducing water usage and optimizing fertilizer

application, farmers were able to minimize environmental impacts while maintaining or even improving crop yields. This is particularly important in resource-limited zones, where sustainable farming practices are crucial for long-term food security.
The table below illustrates the changes in water and fertilizer usage before and after the AR tool was introduced.

Table 3. Changes in Water and Fertilizer Usage Before and After AR Tool Introduction

Farmer ID	**Water Usage (Liters/Day) Before**	**Water Usage (Liters/Day) After**	**Fertilizer Usage (kg/Season) Before**	**Fertilizer Usage (kg/Season) After**
F01	150	120	25	20
F02	130	110	22	18
F03	160	140	30	25
F04	140	120	28	23
F05	145	125	26	22

The data clearly demonstrates a reduction in both water and fertilizer usage, highlighting the potential of AR technology to contribute to more sustainable agricultural practices in resource-limited areas.

3.2. Discussion

3.2.1. Farmer Interaction with AR-Based Soil Health Tool

The use of Augmented Reality (AR) in the field of agriculture represents a significant advancement in how farmers can interact with technological solutions to optimize their farming practices. This research revealed that farmers in resource-limited zones quickly adapted to using the AR-based soil health tool despite their varying levels of technological literacy. The visual nature of AR allowed farmers to grasp complex soil health indicators, such as pH balance and nutrient content, in real-time. This contrasts with traditional soil testing methods, which are often slow, expensive, and less accessible in remote agricultural areas.

Compared with previous studies, Sharma et al. (2020) noted that AR had been successfully applied in other areas of agriculture, such as pest control and irrigation management. Still, its application in soil health assessment remained underexplored. The findings of this study support the argument that AR's intuitive visual interface is particularly beneficial for smallholder farmers with limited access to agricultural extension services. Interaction with real-time data enables farmers to make more informed decisions, as highlighted by Miller & Ferguson (2020), who emphasized the importance of real-time decision-making tools in improving agricultural productivity.

The tool's practicality is evident in the reported improvements in crop management and water usage efficiency. Farmers indicated that they were able to reduce unnecessary irrigation, an issue that has long plagued resource-limited agricultural zones due to water scarcity (Bakker et al., 2021). This reduction in water use not only enhanced the sustainability of their farming practices but also demonstrated the potential of AR in promoting resource conservation.

3.2.2. Impact on Soil Health Decision-Making

The AR tool's real-time feedback on soil health allowed farmers to take immediate action to improve soil management. This study showed that farmers who consistently used the AR tool made fewer irrigation errors and applied fertilizers more effectively. This is a significant finding in resource-limited agricultural zones, where access to expert advice and soil testing facilities is minimal. By providing clear visual cues about soil moisture and nutrient deficiencies, the AR tool filled a crucial knowledge gap for farmers, empowering them to take timely action.

Previous research by Li et al. (2021) demonstrated that AR could enhance decision-making in agricultural practices, but the focus was primarily on crop management. The current study expands on this by showing that AR can also be used for soil health management, directly impacting crop yield and soil sustainability. Furthermore, De Oliveira et al. (2022) discussed the importance of precision agriculture in addressing food security issues in low-resource zones. The findings of this research align with those conclusions, showing that AR technology can contribute to more precise and efficient soil management.

The diagram below illustrates how AR enhances farmers' ability to assess soil conditions. The ability to detect issues such as nutrient imbalances early in the planting cycle helped farmers prevent long-term soil degradation, which is a common problem in areas with limited access to soil health resources.

3.2.3. Challenges in AR Implementation

Although the AR tool demonstrated significant benefits, its implementation in resource-limited areas presented challenges, particularly in regions with unreliable internet connectivity. Farmers in remote zones reported difficulty accessing real-time data, which hindered the tool's full potential. This finding is consistent with the research by Kim et al. (2021), who identified digital infrastructure as a critical barrier to the widespread adoption of AR technologies in agriculture. In these cases, the tool’s functionality was limited to offline capabilities, reducing the accuracy and timeliness of the data provided.

Moreover, training emerged as another challenge. Some farmers, particularly older ones with little smartphone experience, required additional support to navigate the AR interface. This aligns with the findings of Patel et al. (2021), who suggested that digital literacy remains a significant barrier to introducing advanced technologies to rural agricultural zones. Despite these challenges, most farmers expressed satisfaction once they became familiar with the tool, reinforcing the idea that AR’s intuitive design can overcome technological barriers with proper training.

To overcome these challenges, future studies should explore the development of offline AR functionalities that do not rely on constant internet access and tailored training programs to assist farmers in adopting these technologies. The figure below highlights the main challenges and potential solutions for implementing AR in agriculture.

3.2.4. Comparison with Previous Studies

In comparison with previous studies, this research adds valuable insights into the specific use of AR for soil health management. Studies by Zhang et al. (2021) and Oliveira et al. (2021)

highlighted the potential of AR in general agricultural applications but did not focus on soil health assessment. This research fills that gap by demonstrating that AR can effectively improve soil management practices, particularly in resource-constrained settings. The ability to provide real-time data and visual feedback is a significant advancement over traditional methods, which are often inaccessible to smallholder farmers.

Furthermore, the findings of this study corroborate the results of Pan et al. (2022), who emphasized the role of digital tools in enhancing agricultural sustainability. By reducing water usage and optimizing fertilizer application, the AR tool has the potential to contribute to more sustainable farming practices, which is crucial in areas where resources are scarce.

The practical implications of these findings are substantial. If AR-based tools for soil health assessment are widely adopted, they could significantly improve agricultural productivity in low-resource zones, addressing both food security and environmental sustainability concerns.

3.2.5. Practical Implications and Limitations

The practical implications of this research are clear: AR technology can play a transformative role in agriculture, particularly in regions where traditional soil assessment methods are inaccessible. By providing real-time, visual feedback, the AR tool empowers farmers to make informed decisions that improve soil health and crop productivity. The potential benefits extend beyond soil management, as the technology could be adapted for other areas of agriculture, such as pest management and crop monitoring.

However, there are limitations to this study that should be acknowledged. First, the reliance on internet connectivity in remote areas limited the tool’s full functionality. Future developments should prioritize offline capabilities to ensure broader accessibility. Second, the sample size of this study was relatively small, focusing on 20 farmers in specific regions. Broader studies across diverse agricultural zones would provide more comprehensive insights into the scalability of AR technologies in different farming contexts.

In conclusion, while this research demonstrates the potential of AR for improving soil health management in resource-limited zones, future efforts should focus on overcoming technological barriers and expanding the tool’s applicability across diverse agricultural environments. This will ensure that the full benefits of AR technology can be realized, contributing to more sustainable and efficient agricultural practices.

4. CONCLUSION

This study demonstrates that Augmented Reality (AR) technology can significantly enhance soil health assessment and decision-making processes for farmers in resource-limited agricultural zones. By providing real-time, visual feedback on critical soil parameters, the AR-based tool empowered farmers to make informed decisions regarding irrigation and fertilizer use, resulting in improved crop management and resource conservation. Despite some challenges, such as internet connectivity issues and initial training requirements, the tool proved effective in increasing farmers' understanding of soil conditions and optimizing their farming practices.

The findings also highlight the broader implications of integrating AR into agriculture, particularly in promoting sustainable farming practices and improving food security in low-resource areas. While the study showed promising results, further research is needed to address limitations, such as digital infrastructure barriers and scaling the technology to different agricultural environments.

Future research should explore the development of offline AR functionalities to ensure accessibility in areas with limited internet connectivity. Additionally, studies examining the scalability of AR-based soil health assessment tools across different farming contexts, including large-scale commercial farms and diverse climatic conditions, would provide valuable insights into its broader applicability. Investigating the long-term impact of AR adoption on farmers' productivity and economic outcomes could further validate its role in enhancing agricultural sustainability. Ultimately, AR holds significant potential to transform soil management and contribute to the long-term sustainability of agricultural systems in resource-constrained regions.

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