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Articles

Fostering agroecological knowledge through augmented reality-driven experiential learning

Förderung des agroökologischen Wissens durch Augmented Reality-gesteuertes Erfahrungslernen

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Abstract

This study explored the potential of Augmented Reality (AR) to enhance agroecology education through experiential learning (EL). Using an AR authoring tool, twenty-four participants from two higher learning institutions engaged in hands-on learning activities. A qualitative thematic analysis of participant feedback and reflections gathered during the EL process revealed several opportunities: enhanced understanding and visualization of complex agroecological concepts, increased engagement through interactive experiences, and the use of AR as a research and communication tool. Key challenges included technical constraints, the learning curve for users, and the resources needed to develop effective AR materials. The findings suggest that AR can significantly enrich agroecology education by supporting various EL modes, though addressing these challenges is essential to ensure equitable and impactful adoption. The study concludes with recommendations for future research and development in AR-enhanced agroecology education.

Keywords: Agroecology; Augmented reality; Experiential learning.

Zusammenfassung

Diese Studie untersuchte das Potenzial von Augmented Reality (AR) zur Verbesserung der Agrarökologie-Ausbildung durch experimentelles Lernen (EL). Unter Verwendung eines AR-Authoring-Tools nahmen vierundzwanzig Teilnehmer aus zwei höheren Bildungseinrichtungen an praktischen Lernaktivitäten teil. Eine qualitative thematische Analyse des Feedbacks und der Reflexionen der Teilnehmer, die während des EL-Prozesses gesammelt wurden, zeigte mehrere Möglichkeiten auf: ein besseres Verständnis und eine bessere Visualisierung komplexer agrarökologischer Konzepte, ein größeres Engagement durch interaktive Erfahrungen und die Nutzung von AR als Forschungs- und Kommunikationsinstrument. Zu den wichtigsten Herausforderungen gehörten technische Einschränkungen, die Lernkurve der Nutzer und die für die Entwicklung effektiver AR-Materialien erforderlichen Ressourcen. Die Ergebnisse deuten darauf hin, dass AR die agrarökologische Bildung durch die Unterstützung verschiedener EL-Modi erheblich bereichern kann, obwohl die Bewältigung dieser Herausforderungen für eine gerechte und wirksame Einführung von entscheidender Bedeutung ist. Die Studie schließt mit Empfehlungen für die zukünftige Forschung und Entwicklung im Bereich der AR-gestützten Agrarökologieausbildung.

Schlüsselwörter: Agrarökologie; Augmented Reality; Erfahrungslernen.

1. Introduction

Agroecology is a scientific discipline and a practical approach that integrates ecological principles into the design and management of sustainable food systems (Jeanneret et al., 2021). This approach emphasizes a holistic and systems-thinking framework that optimizes interactions among plants, animals, humans, and the environment to ensure the ecological sustainability of agricultural systems (Helenius et al., 2019). Agroecology promotes biodiversity conservation, soil health management, and ecosystem services while integrating traditional knowledge with modern agricultural practices to foster sustainable production (Wezel et al., 2020). Furthermore, it encompasses societal dimensions, advocating for cultural diversity, social justice, and community engagement in designing inclusive food systems (Chavez-Miguel et al., 2022; Mier y Terán Giménez Cacho et al., 2018). These principles not only address critical issues like climate change and food security but also empower agricultural professionals to design resilient, equitable, and sustainable agricultural systems (Francis et al., 2017).

As agriculture evolves in response to global challenges, technologies such as augmented reality (AR) offer transformative potential for enhancing agroecological education (Garzón, 2021). AR enables learners to visualize and interact with complex ecological processes in real time, bridging theoretical knowledge with practical applications (Kamarainen et al., 2018). By immersing students in virtual environments, AR facilitates experiential learning (EL), a pedagogical approach that emphasizes learning through active engagement and reflection (Vaughan et al., 2017). For example, AR-based applications have allowed students to understand aquaponic systems by visualizing the components and their functions (Garzón et al., 2020) or interactively exploring the construction of agricultural equipment such as fertcontrol systems (Parras-Burgos et al., 2020). These applications enhance learners' understanding of agroecological systems by providing immersive, hands-on experiences that improve knowledge retention and foster critical thinking (Abinaya & Vadivu, 2023).

Despite the potential of AR to transform agroecological education, significant challenges remain. The development of AR learning scenarios often requires programming expertise, which many educators lack (Osuna et al., 2019; Tzima et al., 2019). Additionally, conventional AR applications, such as those from Garzón et al., (2020) and Parras-Burgos et al., (2020), are static, requiring redevelopment when learning scenarios or content changes. These limitations can be addressed by AR authoring tools that empower educators to create dynamic AR experiences without programming knowledge, enabling the customization of virtual content in real-time. However, even with such tools, many agroecologists face difficulties conceptualizing and implementing AR in their teaching. This gap underscores the need for EL opportunities that equip educators with the skills to harness AR effectively in agroecology education.

Experiential learning (EL) is a practical, learner-centered pedagogical approach that aligns seamlessly with agroecology's principles (Baker et al., 2012). This approach involves four phases: concrete experience, reflective observation, abstract conceptualization, and active experimentation (Coleman et al., 2024; Kolb, 1984). AR supports all four phases of EL, offering immersive and interactive experiences that can be applied to enhance understanding of ecological and agricultural concepts (Hashim et al., 2022; Vaughan et al., 2017). For instance, students using AR have created topographical features in sand to visualize elevation maps and water flow (Kundu et al., 2017; Vaughan et al., 2017) or scanned QR codes to explore 3D models of agronomic systems, thereby deepening their understanding of ecological and agricultural concepts (Parras-Burgos et al., 2020). Through reflective observation, learners review or discuss their experiences, while abstract conceptualization links observations to broader theories, such as the relationship between topographical features and landscape development (Moorhouse et al., 2019; Vaughan et al., 2017). Finally, active experimentation allows learners to modify or apply their newfound knowledge in diverse contexts, reinforcing the iterative and applied nature of EL (Moorhouse et al., 2019; Vaughan et al., 2017).

While AR has been widely adopted in teaching STEM subjects, its application in agroecology remains underexplored (Costa et al., 2018; Shamsudin & Talib, 2023). To address this gap, the present study aims to empower agroecology educators by integrating AR into EL frameworks. By equipping educators with the tools and strategies to create immersive and interactive learning experiences, this study seeks to enhance the teaching of agroecology and foster a new generation of agricultural professionals capable of addressing the complex challenges of sustainable food systems.

2. Methodology

We employed an exploratory qualitative approach to examine how educators in agroecology can be empowered to use AR in teaching. An AR learning authoring tool, MirageXR (Wild, 2020), was utilized to create AR experiences.

Twenty-four participants, including doctoral candidates and professors, were recruited from Duale Hochschule Baden-Württemberg (DHBW) and the University of Hohenheim. Both institutions offer agroecology specializations, such as soil science, crop science, agricultural engineering, and ecology. Participants were recruited through an online registration form distributed via institutional group emails. The selection criteria included being an educator in any agroecology specialization, such as soil science, crop science, farm management, and agricultural engineering. Efforts were made to ensure diversity in roles and teaching experience. Participants completed a pre-workshop survey collecting demographic data and prior experience with AR. The workshop was conducted at the University of Hohenheim in June 2024.

Three facilitators who are experienced in teaching and AR facilitated the workshop. They introduced AR concepts and their application in agroecology through EL, beginning with the hands-on use of familiar AR apps such as Instagram filters. As discussed in the introduction section, the learning cycle in EL involves four components: concrete experience, reflective observation, abstract conceptualization, and active experimentation (Baker et al., 2012; Kolb, 1984). Therefore, the workshop activities were organized in line with these components.

Two exercises, focused on insect pollination and crop rotation, were designed for different EL components. These exercises are fundamental agroecological processes that promote agricultural sustainability and ecosystem health. Insect pollination, facilitated by insects like bees, is crucial for plant reproduction, biodiversity, and food security. Crop rotation enhances soil fertility, reduces pests, and boosts crop yields by alternating crops with different nutrient needs, minimizing chemical inputs. These topics were chosen for their ecological importance, relevance to sustainable farming, and suitability for AR visualization, offering an engaging way to explore the principles of agroecology and their role in improving agricultural resilience and productivity.

Participants installed MirageXR to create AR experiences for the chosen two agroecological exercises. Insect pollination was used for concrete experience in the first exercise, in which facilitators provided support. The task during this exercise was to insert 3D models of flowers and bees into the classroom space. These models were downloaded from Sketchfab (https://sketchfab.com/3d-models), the online 3D repository. After inserting the models, participants observed how bees transfer pollen from one flower to another while interacting with the 3D model. For active experimentation, participants independently created the crop rotation AR experience. For reflective observation, facilitators asked the participants about the effectiveness of AR and MirageXR in teaching agroecology and the challenges associated with this tool and technology. Facilitators asked participants to combine what they learned with underlying principles and theories in their agroecology specialization for abstract conceptualization.

Seven participants were selected for semi-structured interviews to examine their perceptions of the EL process and the opportunities and challenges of AR in agroecology. The selection ensured diverse perspectives, including participants who faced difficulties, those who were less engaged, and those who completed tasks without challenges. The interviews explored participants' backgrounds, initial expectations, and the effectiveness of AR in enhancing learning. Key topics included engagement, usability, technical difficulties, and comparisons with traditional methods. Participants were asked to provide examples of AR's benefits, such as improved interactivity and accessibility, as well as challenges like cognitive load and system limitations. Tailored questions addressed specific experiences, including barriers for those who struggled, disengagement factors for less engaged participants, and success factors for those who adapted easily. The study also gathered recommendations on improving AR integration and its potential for broader agricultural training. This approach ensured a comprehensive understanding of AR's role in agroecology education.

Data were analyzed thematically following Mayring's (2015) guidelines. Thematic analysis, one of the most common qualitative data analysis techniques (Guest et al., 2011), was a suitable analysis due to the explorative nature of the current study. Coding was conducted using the qualitative analysis software QCAMap, which leads to a step-by-step approach to qualitative content analysis (Mayring & Fenzl, 2016). Two researchers independently coded the data to ensure reliability. Sub-themes for opportunities and challenges were developed inductively and revised during formative reliability checks after analyzing 50% of the data. A summative reliability check was conducted on the finalized themes to ensure consistency and accuracy.

3. Results

3.1 Participants Demographics

Twenty-four researchers and PhD candidates from two universities, all actively teaching agroecology, participated in the workshop (Figure 1). Most (62.5%) were between 34 and 44 years old. Participants' AR experience was categorized as first-timers, who had no knowledge of AR; beginners who were familiar with AR but had not used it; intermediate, who were frequently using AR; and advanced, who were able to develop AR applications. Most (66.7%) were first-timers, and none were advanced users.

Gender Data			Age Data			Augmented Reality Experience Level		
Gender	N	Percent	Age Group	N	Percent	Level	N	Percent
Male	13	54%	18-24	6	25%	First-timers	16	67%
Female	11	46%	34-44	15	62.5%	Beginners	5	21%
			45-54	3	12.5%	Intermediate	3	13%
			>=55	0	0%	Advanced	0	0%

Figure 1. Demographics of participants in the augmented reality learning workshop.

3.2. Experiential Learning Process

The workshop demonstrated varying levels of engagement and success among participants in using AR tools for agroecology education. During the initial hands-on phase, participants used familiar AR applications such as Instagram filters to explore the technology's potential in visualizing abstract concepts. This phase effectively introduced AR to participants with varying levels of technical expertise, fostering a sense of curiosity and comfort with the technology. Many participants commented that these initial activities provided a solid foundation for understanding AR's role in enhancing educational engagement.

The first exercise, focusing on insect pollination, marked the transition to the concrete experience phase. Participants, guided by facilitators, used MirageXR to insert 3D models of flowers and bees – sourced from Sketchfab – into the classroom space. Interacting with these models, they observed the process of pollen transfer between flowers. Most participants successfully completed this task, reporting that the interactive visualization enhanced their understanding of pollination dynamics. During reflective observation, participants acknowledged the potential of such AR experiences to engage students in learning ecological processes. However, some participants highlighted challenges, including difficulties in accessing and integrating 3D models from external repositories.

The second exercise, crop rotation, was used for the active experimentation phase. In this exercise, participants independently created AR experiences to illustrate crop rotation principles. While several participants produced detailed and interactive content, others encountered obstacles, including technical limitations and challenges in translating complex agroecological concepts into AR applications. The reflective observation phase revealed that participants appreciated the opportunity to experiment with AR independently, as it deepened their learning and provided insights into the practical challenges of using the technology. During the abstract conceptualization phase, participants connected their AR projects to broader agroecological theories, such as sustainable land use, nutrient cycling, and sustainable farming practices. This stage highlighted the potential of AR to bridge theoretical knowledge and practical application, although some participants (**Errore. L'origine riferimento non è stata trovata.**) expressed concerns about the steep learning curve and the need for more intuitive tools.

3.3. Opportunities and Challenges of Augmented Reality in Agroecology

Through thematic analysis of user feedback obtained during the reflective observation phase, several key themes emerged (Figure 2), highlighting both the potential benefits and limitations of the authoring tool in AR creation.

Opportunities	Number of participants mentioning the opportunity (%)	Challenges	Number of participants mentioning the challenge (%)
Enhanced Understanding and Visualization	12(50%)	Technical Requirements and Accessibility	6(25%)
Improved Learning and Engagement	6(25%)	User Skill and Learning Curve	9(38%)
Research and Communication Tool	4(17%)	Development and Time Investment	5(21%)
Positive User Experience and Adoption	2(8%)	Applicability and Context	2(8%)

Figure 2. Thematic analysis of opportunities and challenges of employing augmented reality in agroecology retrieved from N=24 participants during reflective observation and interview.

- Opportunities

Enhanced Understanding & Visualization. The AR app emerged as a valuable tool for simplifying complex agroecological concepts and improving practical understanding. Participants highlighted that the app's ability to visualize intricate processes, such as physiological responses in plants involving multiple biochemical pathways, made agroecology more accessible and engaging. The potential for AR to simulate hands-on farming methods and improve soil fertility management was particularly emphasized, with participants noting its ability to model soil compositions, crop nutritional needs, and carbon content. Additionally, the app supported field simulation, enabling learners to identify plant species or understand geospatial data collection within diverse agroecologies. The detailed 3D models provided an innovative way to explore theoretical principles and practical applications, making AR an indispensable tool for advancing agroecology education.

Improved Learning & Engagement. The use of AR demonstrated a significant impact on enhancing learning and engagement among diverse audiences. Participants noted that AR's interactive and multimedia features created an engaging learning environment, particularly for younger audiences and adult learners. The tool supported the development of blended learning approaches, making lectures and practical sessions more interactive than traditional non-AR methods. Furthermore, the ability to create AR experiences fostered motivation and increased enthusiasm for learning agroecology topics. This interactivity and engagement were recognized as pivotal in promoting active participation and knowledge retention among learners.

Research & Communication Tool. AR also showcased its potential as a valuable research and communication tool. Feedback revealed that the app facilitated the quick and effective presentation of research findings to varied audiences, including individuals with disabilities and policymakers, by providing a real-world experience through simulations and AR-enhanced communication of scientific findings and policy recommendations. Participants noted its ability to survey farms and monitor crop health, suggesting that AR could be a transformative tool for social research and practical agricultural management. This dual utility in research and outreach positions AR as a bridge between science and practice in agroecology.

Positive User Experience & Adoption. Participants expressed an overall positive experience with the AR app, emphasizing its intuitive and engaging nature. Several participants indicated their willingness to promote the technology among colleagues and students, highlighting its potential for broader adoption within educational and research institutions. This enthusiasm suggests a strong likelihood of increased dissemination and integration of AR technologies in agroecology education, particularly in institutions where users can access appropriate resources and support.

- Challenges

Despite the numerous opportunities, several challenges related to implementing and adopting AR apps in agroecology were also identified.

Technical Requirements & Accessibility. One of the most significant challenges identified was the technical requirements and accessibility of the AR app. Participants frequently cited issues related to device compatibility and internet connectivity, which hindered their ability to fully utilize the app. The reliance on high-end mobile devices and strong internet connections limited the app's usability, particularly in resource-constrained environments. These limitations significantly impacted user satisfaction and posed barriers to the widespread adoption of AR technology in agroecology.

User Skill & Learning Curve. The steep learning curve associated with AR technology was another prominent challenge. Participants noted that the app required substantial prior knowledge, technical skills, and practice to fully understand and operate effectively. For beginners and non-tech-savvy individuals, the complexity of the app posed significant barriers, making it unsuitable for illiterate or less-educated users. These challenges suggest the need for more accessible training materials and simplified interfaces to ensure broader usability among diverse audiences.

Development & Time Investment. Developing AR models was perceived as time-intensive and demanding. Participants highlighted the considerable effort required to design high-quality, customized 3D models that could effectively convey specific agroecological concepts. For instance, adapting models to represent simulation results or specific learning objectives was noted as particularly challenging and time-consuming. The extensive preparation required can deter participants from utilizing the app for practical teaching or research purposes.

Applicability & Context. The applicability of AR in diverse agroecological contexts was another limitation. Participants raised concerns about its suitability for smallholder farmers in developing nations, where resource constraints and technical literacy levels may impede adoption. Additionally, the app's interface was described as less intuitive, complicating its use in contexts requiring quick and seamless interaction. These factors suggest the need for further refinement of the app to accommodate diverse user contexts and ensure its broader applicability in agroecology education and practice.

4. Discussion

As prior studies have reported (Garzón et al., 2020; Vaughan et al., 2017), our findings reinforce the potential of AR in fostering EL within agroecology. By providing immersive and interactive experiences, AR bridges the gap between theoretical knowledge and practical application. For instance, the use of virtual 3D models of flowers and bees allows students to observe pollination processes in real time, offering insights that are often challenging to achieve through traditional teaching methods. Such hands-on experiences address constraints related to time, resources, and access that are common in field-based learning contexts (Vaughan et al., 2017). Furthermore, AR's alignment with Kolb's EL framework, encompassing concrete experience, reflective observation, abstract conceptualization, and active experimentation, proves instrumental in transforming complex agroecological concepts into engaging, comprehensible, and memorable learning experiences.

The findings of this study align with emerging trends in education and research that prioritize flexible, inclusive, and sustainable practices. The thematic analysis highlights AR's capacity to enhance understanding and visualization, echoing Pujiastuti and Haryadi's (2020) findings on AR's effectiveness in teaching abstract concepts such as food security. This is particularly relevant in agroecology, where visualizing complex processes like nutrient cycling, plant-soil interactions, and the impacts of climate change can be challenging with traditional methods (Vaughan et al., 2017). Moreover, the potential for improved learning and engagement, as highlighted by Pandey et al. (2020), was a prominent theme in our analysis. Participants expressed that the interactive and immersive nature of AR fostered greater interest and motivation, leading to deeper understanding and retention of information. This suggests that AR can be a powerful tool for engaging diverse learners, including those who may struggle with traditional learning methods (Parras-Burgos et al., 2020).

Finally, our analysis identified AR as a valuable research and communication tool, supporting the work of Zheng and Campbell (2019), who employed AR for fieldwork navigation and visualization. The ability to present complex data in an interactive and visually compelling format makes AR particularly well-suited for communicating scientific information to policymakers, stakeholders, and the general public (Kundu & Nawaz, 2019). This reinforces its role in creating attractive and adaptable learning environments, which are integral to fostering interest in agroecological careers and research.

Despite these opportunities, our findings also underscore significant challenges that must be addressed for AR to achieve its full potential in agroecology. Consistent with Osuna et al. (2019) and Paul & Rohil (2023), participants identified technical requirements and accessibility issues as major bottlenecks, particularly in resource-constrained settings (Arboleda et al., 2024). Limited internet connectivity and device compatibility significantly hinder the adoption and effectiveness of AR technology. Furthermore, the steep learning curve associated with AR was evident, with participants highlighting the need for substantial practice and prior technical knowledge to use the tool effectively. This reinforces previous findings by Akçayır and Akçayır (2017), Gavish et al. (2015), and Osuna et al. (2019) that AR's complexity can pose barriers, particularly for non-tech-savvy educators and learners.

Additionally, the time and effort required to develop high-quality AR experiences present another notable challenge. Participants reported that designing customized 3D models for specific agroecological topics demands significant time investment and specialized skills, echoing concerns raised by Akçayır and Akçayır (2017) and Osuna et al. (2019). These challenges call for the development of more user-friendly AR creation tools and accessible resources to facilitate adoption. Lastly, the limitations in applicability, particularly in smallholder farming contexts, highlight the need for AR tools to be more intuitive and adaptable to diverse educational and agricultural environments.

The limitations of this study, a small sample size of 24 participants from two higher education institutions and the use of a single AR authoring tool, highlight the need for caution in generalizing findings. While the focused investigation of a single tool allowed for in-depth analysis, broader studies involving diverse AR platforms and larger participant groups could offer a more comprehensive understanding of AR's potential in agroecology education. Nevertheless, the study provides valuable insights into AR's transformative potential and identifies critical areas for future development.

Despite its limitations, this study makes a significant contribution to the theme of *New Work and New Study: Research and Education for Flexible, Inclusive, Sustainable, and Attractive Workplaces*. By demonstrating AR's ability to make agroecology more accessible, engaging, and inclusive, the research highlights its potential to revolutionize agricultural education and foster interest in sustainable practices. The study's emphasis on overcoming traditional educational barriers positions AR as a tool for flexible and inclusive learning environments, essential for addressing global challenges in agriculture and sustainability. Furthermore, the findings underscore the importance of investing in user-friendly AR creation tools and infrastructure to broaden its applicability across diverse educational and agricultural settings, ensuring that AR can become a cornerstone of innovative and equitable agroecological education.

5. Conclusion

This study investigated the use of AR as a transformative tool for EL in agroecology education, aligning with the broader themes of flexible, inclusive, and sustainable learning environments. Through the application of the MirageXR AR platform, participants were engaged in activities designed to develop their ability to create AR-enhanced learning experiences for agroecology, guided by Kolb's EL framework. The findings emphasize AR's potential to bridge the divide between theoretical knowledge and practical application, offering immersive, interactive, and visually engaging educational experiences. This potential supports the creation of workplaces and learning environments that are not only more adaptable but also more inclusive and attractive to diverse learners.

The study identified key opportunities for AR in agroecology education, including its capacity to enhance understanding through dynamic visualization, improve learner engagement, facilitate research and communication, and foster positive user experiences. These opportunities contribute to the broader goal of creating sustainable educational practices that meet the demands of contemporary and future workplaces. However, the study also highlights critical challenges. Technical constraints, such as device compatibility and internet connectivity, pose significant barriers, particularly in under-resourced contexts. Additionally, the specialized skills, time, and effort required to create high-quality AR experiences underscore the need for user-friendly tools and targeted training programs. Addressing these challenges is vital to ensure AR's equitable and effective integration into education and research.

The findings contribute to the emerging discourse on AR in education, offering valuable insights into its application in agroecology, a field inherently complex and rooted in practical, interdisciplinary learning. While this study offers a promising perspective, limitations such as the small sample size and the reliance on a single AR platform necessitate cautious interpretation. Future research should explore diverse AR platforms, incorporate larger and more varied participant samples, and examine long-term impacts on learning outcomes to strengthen the evidence base.

This study underscores AR's potential to revolutionize agroecology education by transforming complex agroecological processes into accessible, engaging, and interactive learning experiences. By addressing the challenges identified, AR can contribute to the development of inclusive and sustainable educational ecosystems that prepare learners for the demands of modern workplaces. These findings hold implications not only for educators and researchers but also for policymakers seeking to align education with the principles of flexibility, inclusivity, and sustainability. In this context, AR represents a valuable tool for advancing both pedagogy and practice in agroecology, setting the stage for further innovation and collaboration in creating attractive and forward-thinking learning environments.

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