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Transforming the primary sector with XR: A review of applications in agriculture, livestock, and learning environments

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Abstract

The agricultural sector faces pressing challenges such as climate change, freshwater scarcity, overpopulation, energy demands, and workforce aging issues further exacerbated by global disruptions like the COVID-19 pandemic. As a response, emerging technologies such as Extended Reality (XR) which encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) are gaining traction as tools to enhance productivity, sustainability, and education in agriculture and its allied fields. This review aims to explore and synthesize the current applications of XR technologies across agriculture, livestock farming, aquaculture, and agricultural education. By analyzing existing literature, this study categorizes XR use by application areas, device types (e.g., head-mounted displays, gesture recognition tools), and modes of human-machine interaction. In agricultural education, AR/VR technologies have shown significant potential to enrich learning environments, enhance conceptual understanding, and improve student engagement. Despite promising developments, the integration of XR in the primary sector remains at an early stage, with challenges including technical limitations, privacy, health concerns, and accessibility. The paper concludes by identifying current gaps and proposing future research directions to foster more immersive, secure, and effective XR adoption in the agricultural domain.

Keywords: Extended Reality (XR), Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR), agriculture, livestock farming, aquaculture, agricultural education, human-machine interaction, smart farming, immersive learning

Introduction

In recent years, there has been a growing interest among the research community in adopting innovative technologies to enhance educational practices. Among the latest technological advancements making a significant impact in education are Augmented Reality (AR) and Virtual Reality (VR), which fall under the broader umbrella of Extended Reality (XR) technologies (Ghulamani & Zareen, 2018a) [17, 18]. These immersive tools have transformed the classroom experience, shifting the instructional focus toward more interactive and student-centered learning. AR, though not entirely new, has seen a resurgence in demand due to its capacity to blend computer-generated elements with the physical world, thereby enriching the perception of reality in specific contexts. This growing adoption, especially post-COVID-19, is driven by the need for Information and Communication Technologies (ICT) that support remote learning and foster enhanced engagement.

Human civilization has long depended on plants and animals for food, clothing, shelter, medicine, and other essential needs. Agriculture and aquaculture have played pivotal roles in fulfilling these demands and shaping our modern societies. However, these sectors are now facing mounting challenges, including climate change, overpopulation, freshwater scarcity, energy poverty, urbanization, and an aging workforce. These global issues have been further exacerbated by the COVID-19 pandemic, which disrupted labor availability, business operations, and education systems (Anastasiou *et al.*, 2023) [3, 4].

While existing ICT tools like the Internet of Things (IoT), robotics, and remote sensing have made considerable contributions to agricultural and aquatic productivity, they are not sufficient to overcome the limitations intensified by the pandemic. A promising solution lies in Extended Reality (XR), which leverages computer-generated environments to extend human perception and capabilities. XR encompasses three core technologies: Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), (Anastasiou, *et al.*, 2023) [3, 4]. VR creates immersive, entirely virtual environments, AR overlays digital content onto the real world, and MR enables real-time interaction between physical and virtual elements (Anastasiou, *et al.*, 2023) [3, 4].

Although XR concepts date back to the 1960s, meaningful developments began emerging in the 2010s, thanks to advances in computer graphics, electronics, and immersive hardware (Anastasiou E *et al.*, 2023) [3, 4]. XR now employs a variety of tools smartphones, head-mounted displays (HMDs), gesture recognition systems, data gloves, and motion controllers to enable intuitive human-machine interactions across multiple sectors. These technologies have already shown transformative potential in medicine (e.g., pre-procedural planning and 3D anatomical visualization), (Andrews *et al.*, 2019) [5], manufacturing (e.g., gearbox assembly and factory layout planning), (Fast-

Berglund *et al*., 2018) [13], education (e.g., live industry interactions) (Ferreira and Qureshi, 2020), and training (e.g., military and rehabilitation simulations), (Sitompul and Wallmyr, 2019; Doolani *et al*., 2020) [41, 10].

Despite growing adoption in other industries, XR applications in the primary sector including agriculture, livestock farming, and aquaculture are only beginning to gain attention. Agriculture, in particular, is a labor-intensive field where safety, efficiency, and health are paramount. The sector has seen a gradual shift from manual practices to mechanized and precision farming, driven by advances in automation (Lohan *et al*., 2015; Sharma *et al*., 2014; Singh *et al*., 2022) [30, 39, 40]. XR technologies offer further advancement by simulating real-world conditions through immersive virtual environments, thus reducing the need for physical exposure during training or operations (Karkee *et al*., 2011) [25]. For instance, stereoscopic virtual interfaces now allow tractor operators to train in simulated fields (Grandi *et al*., 2018; Karkee and Steward, 2010a, 2010b; Luecke, 2012) [16, 23, 24].

Technologies such as HMDs, portable devices, gesture controllers, and motion sensors enable effective interaction within XR environments, supporting advanced human-machine collaboration (Hurst *et al*., 2021; Liu *et al*., 2020a) [20, 28]. Over the past decade, VR/AR has seen notable use in industries such as medicine, smart manufacturing, communication, surveillance, and education emerging as a powerful tool for training, skill development, and workplace safety (Doolani *et al*., 2020) [10]. In agriculture, XR has been studied for its applications in crop production (Yu *et al*., 2010) [47], livestock management (Anastasiou E, *et al*., 2023 & Anastasiou C, *et al.* 2023) [3, 4], robotic experimentation (Shamshiri *et al*., 2018) [38], and educational tools (De-Oliveira *et al*., 2023; Hurst *et al*., 2021; Javaid *et al*., 2022) [9, 20, 21]. However, there remains a research gap in areas such as machinery operation, farm supervision, and environmental monitoring using XR (Vrochidou *et al*., 2022) [43].

Thus, the objective of this study is twofold: (i) to map and analyze the existing applications of XR technologies in agriculture, livestock farming, and aquaculture, and (ii) to identify current trends, research gaps, and future directions for optimizing XR adoption in the primary sector.

Technology Development and Applications in Agricultural Education

In recent years, Augmented Reality (AR) and Virtual Reality (VR) technologies have gained momentum across various sectors, including education. These immersive technologies are proving to be transformative tools for teaching and learning, allowing users to engage with content in innovative and interactive ways.

Researchers like Dunleavy *et al*. (2009) [11] highlighted the potential of AR/VR in enhancing learning outcomes by promoting deeper engagement and improved understanding. Hsieh & Huang (2016) [19] further illustrated the growing popularity of AR technology with real-world applications such as the release of "Pokémon GO" in Taiwan in 2016, which brought AR into the mainstream and piqued public interest.

According to Milgram & Kishino (2014) [33], AR/VR technologies have broad applications across domains such as medicine, the military, business, education, and entertainment. Ghulamani & Zareen (2018b) [17, 18] emphasized that pairing these technologies with smartphones allows for accessible and engaging educational experiences, while Kencevski & Zhang (2019) [26] pointed out that AR/VR represents a revolutionary shift in educational delivery, particularly as students increasingly rely on ICT tools.

Argued that virtual environments can surpass traditional classroom setups by offering immersive, hands-on learning experiences. Their research supports the growing body of evidence that shows AR/VR can significantly improve the quality and depth of learning. Additionally, Phan & Choo (2010) [35] listed major contributors to the growth of AR/VR, citing companies like ARTool-kit, ARQuake, Google, Inglobe Technologies, Layar, Metaio, and Total Immersion, who have all played pivotal roles in advancing the technology.

As education technology continues to evolve, Tlili *et al*. (2022) [42] suggested that the future lies in the metaverse a new virtual space where immersive learning may become the norm. The interest from major tech companies in building user-friendly, immersive environments indicates a promising shift toward integrating such tools in academic ecosystems.

Augmented Reality (AR) is defined as an interactive experience where real-world environments are enhanced with computer-generated elements such as text, images, videos, audio, and 2D/3D objects. These elements are designed to stimulate various sensory modalities, including visual, auditory, and even olfactory feedback (Cipresso *et al*., 2018) [7]. The term AR was coined in the 1990s by Boeing researchers (Akçayır & Akçayır, 2017) [1], and early developments such as the "Sword of Damocles" system, spearheaded by Sutherland, are considered pioneering efforts in this field. Azuma (1997) [6] provided one of the first widely accepted definitions of AR, describing it as a system that integrates the real and virtual worlds, supports real-time interaction, and incorporates 3D tracking (Wu *et al*., 2013) [45].

Virtual Reality (VR), by contrast, offers a completely immersive experience that simulates real-world or imaginary settings using 3D near-eye displays and pose tracking. Unlike AR, which overlays content on the physical world, VR immerses users fully into a virtual environment. The concept of VR dates back to 1963 with the invention of the “Telesphere Mask” and was further popularized by early pioneers such as Greenback and Lanier (1992), who envisioned VR as a transformative medium for interaction and exploration.

As part of the larger "met averse" movement, these technologies are increasingly being deployed across multiple industries. While gaming has been one of the earliest and most commercially successful use cases exemplified by games like Pokémon GO, The Walking Dead: Our World, Ingress, and Harry Potter: Wizards Unite AR/VR is also finding its place in sectors such as e-commerce and retail. Applications like IKEA Place, GAP Virtual Dressing Room, Lowe’s Vision, and Home Depot AR tools allow customers to experience products virtually before purchase, making shopping more interactive and personalized.

Application of AR/VR in Agricultural Education

The agriculture sector, traditionally reliant on hands-on training, has started exploring AR/VR to bridge the gap between theoretical learning and field practice. These technologies allow for the development of virtual training environments where users can simulate machinery operations, crop management techniques, and livestock handling without the risks and resource demands of real-world scenarios. By integrating AR/VR into agricultural education, institutions can offer scalable, safe, and immersive learning experiences that prepare students for the demands of modern precision farming.

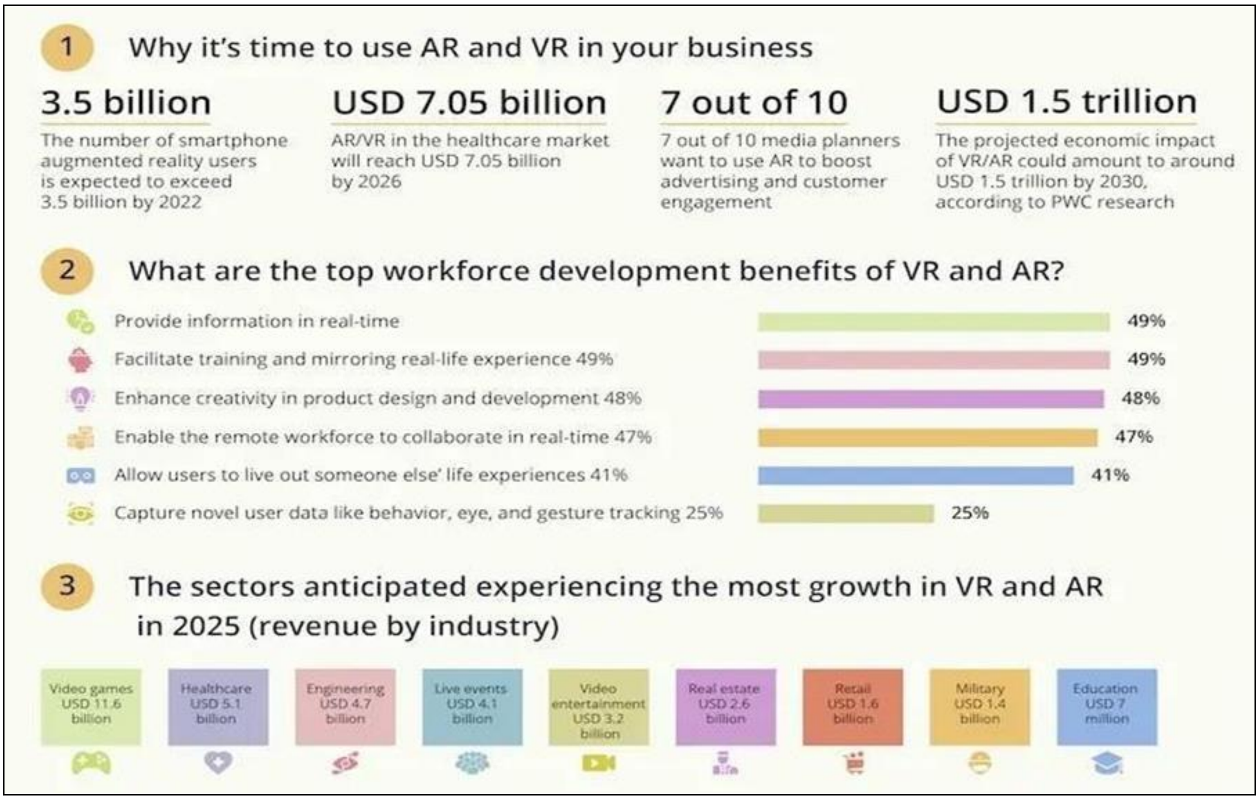

Fig 1: Future-generated revenue forecast to use AR and VR in business (Alsop, 2019) [2]

As discussed earlier, AR/VR technologies are widely applied across multiple domains, including gaming, e-commerce, retail, interior design, real estate, tourism, healthcare, and education. In the context of agricultural education, these immersive technologies offer transformative possibilities for students, researchers, and farmers alike (Joshi, 2020) [10].

Given the rising global demand for food and agricultural products, driven by population growth and the essential role of agriculture during crises like the COVID-19 pandemic, the importance of agricultural education has never been more evident. Unlike many academic disciplines, agricultural education requires a significant amount of fieldwork approximately 70% of students' time is spent outdoors, collecting and analyzing real-time data.

In such a scenario, AR/VR provides a practical and scalable solution. Students can simulate real-world conditions such as soil types, crop growth stages, and weather patterns, all from a remote location. These technologies can bridge the gap between theory and practice, especially during emergencies like pandemics, by offering safe and socially distanced learning experiences.

With AR/VR-enabled dashboards, students and researchers can:

- Virtually inspect farms and monitor crop health.
- Analyze soil fertility to select suitable crops for trial plots.
- Detect pests and diseases visually in real time (Liu *et al.*, 2013) [29].
- Learn the operation of complex farm equipment in a risk-free virtual environment (Cupiał, 2011) [8].
- Engage in remote training by experts on using advanced agricultural tools and machinery (Nigam *et al.*, 2011) [34].

Furthermore, AR-based modules can be used to introduce novice students to traditional farming practices in an interactive and immersive manner, helping them gain foundational knowledge early in their curriculum.

In a broader research context, recent reviews have categorized XR (Extended Reality, including AR/VR) applications in agriculture under five key sub-topics. These include:

1. **Focus Area Type:** The primary objective or domain, such as crop production, livestock management, or auxiliary sectors like farm equipment training.
2. **Application Type:** Categorized as:
3. **Decision:** Tools aiding in management decisions, e.g., monitoring climate data.
4. **Action:** Tools supporting operational tasks, e.g., robot teleoperation or irrigation control.
5. **System Development:** Applications involved in building new XR-integrated agricultural systems.

6. **Education:** Tools designed for training and educational use across focus areas.

The remaining categories focus on human-machine interaction, including: 3. XR Type-Differentiating between AR, VR, and Mixed Reality (MR). 4. XR Viewer Device-The type of display used (e.g., head-mounted displays, smartphones, AR glasses). 5. XR Control Devices-Interaction tools such as controllers, motion sensors, or gesture-recognition systems.

These classifications (summarized in Table 2) help organize the growing body of research on XR applications in agriculture and underscore the educational value of immersive technology in addressing contemporary challenges in the sector

Use Focus Area	Application	XR Type	XR Viewer Device	XR Controller
Agriculture	Decision	Augmented Reality	Portable Device	Handheld
Livestock Farming	Action	Mixed Reality	Monitor	Handheld
Aquaculture	System Development	Virtual Reality	Head Mounted Display	Motion, Hand Tracking
Auxiliary	Education		Wearable, voice, head mounted, portable device, personal computer	Controllers, Equipment

Trends and Focus Areas in XR Applications within Agriculture

According to the results, over half of the XR-related research studies (64%) were conducted after 2017, indicating a significant surge in interest in recent years compared to the period between 2001 and 2016. Furthermore, the majority of these studies were published as conference papers, rather than in peer-reviewed journals, suggesting that the field is still in an emerging phase and is garnering preliminary academic attention. Notably, between 2001 and 2010, there were no publications in certain years specifically 2002, 2003, 2005, 2006, and 2007 highlighting a period of limited activity. These patterns collectively indicate that XR research in agriculture, livestock farming, and aquaculture remains relatively new and is still in its developmental stages (Figure 2).

Use of XR by Focus Area: As shown in Figure 3, the majority of XR-related research studies were concentrated in the field of agriculture (41.3%), followed by livestock farming (12.7%) and aquaculture (7.9%). Interestingly, auxiliary applications, such as those involving agricultural equipment and tools, accounted for a significant portion 38.3% of the studies, reflecting the growing relevance of XR in supporting activities beyond core farming tasks.

Within the agricultural domain, 25.4% of the studies focused on open field agriculture, while 15.9% addressed covered agriculture, such as greenhouse and indoor farming systems. An annual analysis reveals a clear upward trend in XR research during the past five years, with agriculture and auxiliary domains receiving substantial attention since the early 2000s. On the other hand, XR applications in aquaculture only began to appear from 2018 onwards, further emphasizing the novelty and emerging nature of XR adoption in that sector (Figure 4, 5, 6 & 7), (Evangelos, A. 2023) [12].

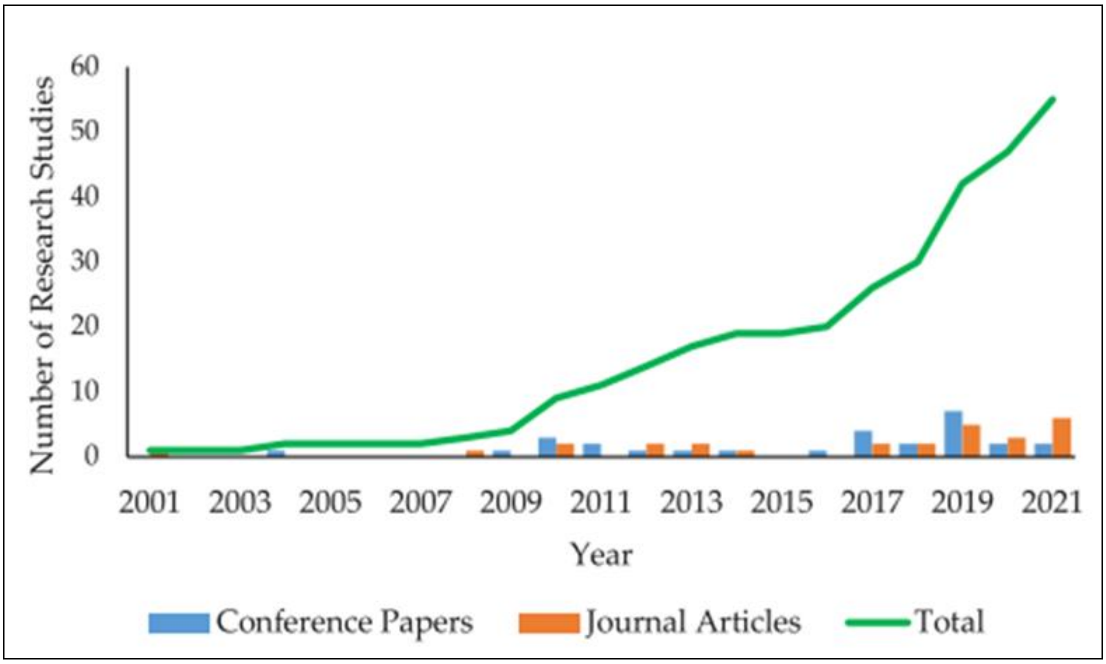

Fig 2: Number of research studies on applications of XR technology for the period 2001-2021 (Anastasiou E, *et al.* 2023) [3, 4]

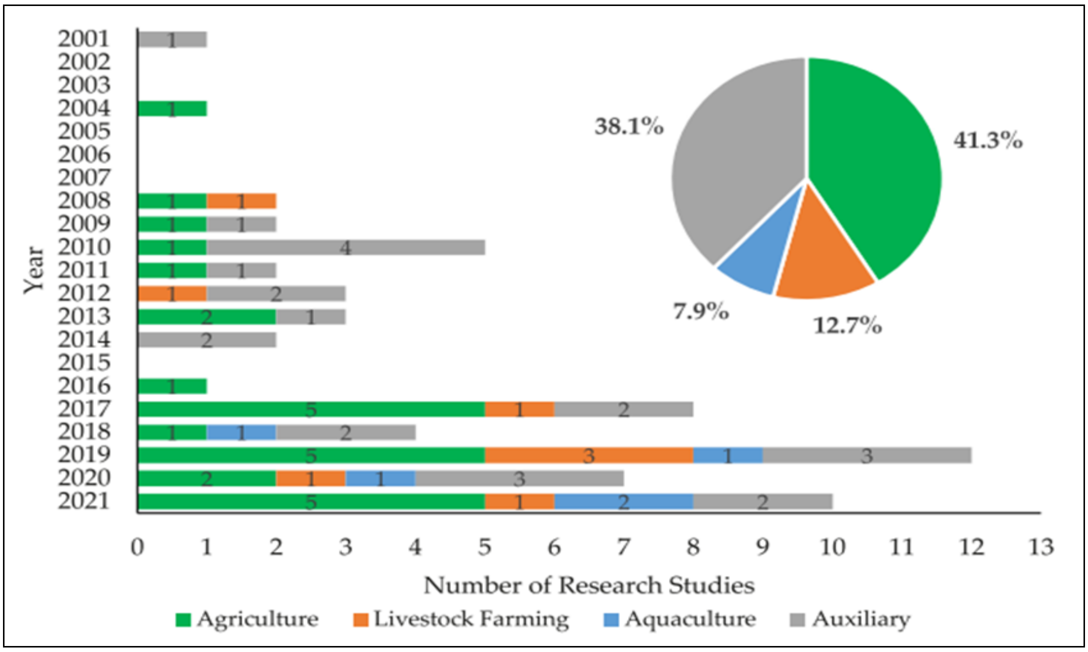

Fig 3: XR technology use per focus area and year (Anastasiou E, *et al.* 2023) [3, 4]

Fig 4: The Think Digital coach travels Australia to provide agriculture education using XR (Gentle T, (2023) [15]

Fig 5: FMD Virtual Reality training (Wilson & Wilson, 2020 & Gentle T, (2023)) [44, 15]

Fig 6: MR being used for plant management (Plant Vision, 2023 & Gentle T, 2023) [44, 15]

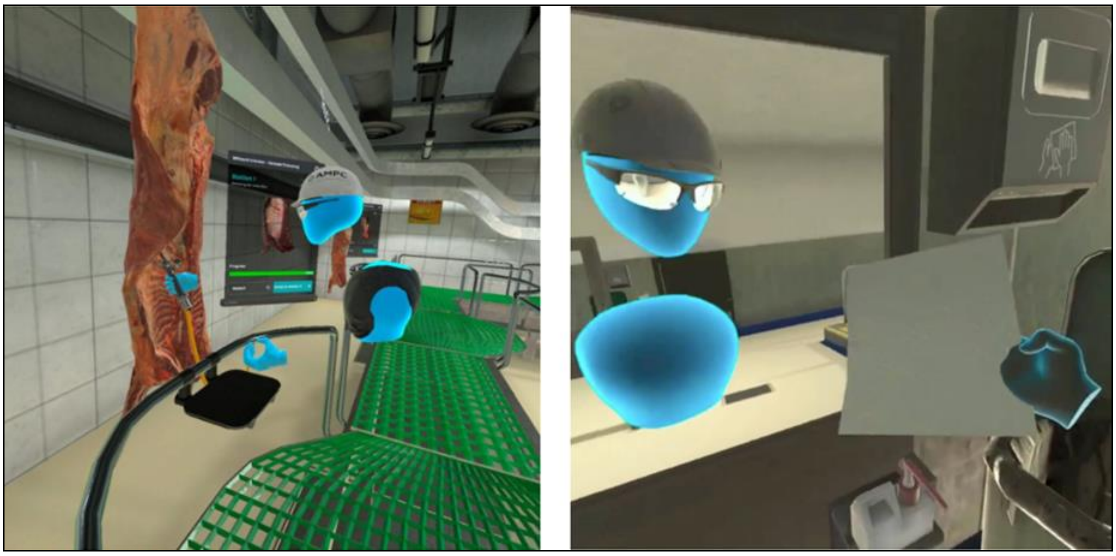

Fig 7: Metaverse-powered VR meat processing employee training (Think Digital Studios, 2022 & Gentle T, (2023) [44, 15]

Conclusion

This study highlights the growing significance of Augmented Reality (AR) and Virtual Reality (VR) technologies across diverse fields, with a particular emphasis on education. The integration of AR/VR into the educational landscape has shown promising results in enhancing student engagement, comprehension of complex concepts, critical thinking, and overall learning effectiveness. These technologies serve as valuable tools for immersive and interactive learning, especially during disruptive events like the COVID-19 pandemic.

In agricultural education, AR/VR enables learners to virtually explore real-time environments such as farmlands, crop conditions, and weather scenarios without being physically present. This enhances practical learning experiences while maintaining safety and accessibility. Although high implementation costs remain a challenge, technological advancements such as the advent of 5G and the decreasing cost of processors and hardware are steadily making AR/VR more affordable and accessible.

There is increasing interest among researchers to further develop these tools and integrate them into traditional education systems. With ongoing innovation, AR/VR has the potential to become a transformative force in education, making learning more engaging, effective, and future-ready.

Additionally, Extended Reality (XR) which includes AR, VR, and Mixed Reality offers transformative applications in agriculture, livestock, and aquaculture. A review of 55 studies revealed that XR can improve decision-making, streamline operations, support training, and assist in system development across these sectors. By extending human capabilities and enabling high levels of interaction through advanced XR devices, these technologies promote improved performance and engagement compared to traditional methods.

Despite its promise, XR in agriculture is still an emerging area. Future research should explore its integration with technologies such as IoT, robotics, and teleoperation to fully leverage its potential. Moreover, careful attention is needed to address potential risks, particularly those concerning user health and data privacy.

With continued research and thoughtful implementation, XR technologies hold great potential to revolutionize education and agriculture, making them more adaptive, efficient, and technologically advanced.

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