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Augmented Reality for Carbon Capture, Utilization and Storage: Enhancing Worker Training and Safety in Ashaka Cement Plant

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ABSTRACT

This study explores the application of Augmented Reality (AR) technology to enhance worker training and safety in Carbon Capture, Utilization, and Storage (CCUS) operations within the cement industry, focusing on Ashaka Cement Plant in Gombe, Nigeria. As the cement sector faces growing pressure to reduce carbon emissions through CCUS technologies, the challenge of effectively training workers and ensuring safety in complex, high-risk environments has become increasingly critical. Traditional training methods, including manuals and classroom instruction, often fall short in providing practical, real-time hazard awareness and operational readiness. Through a cross-sectional survey of 19 workers involved in CCUS operations at Ashaka Cement Plant, this research assessed awareness, perceptions, and willingness to adopt AR-based training. The findings reveal a strong preference for AR training, with 84.2% favoring it over conventional methods and 73.7% willing to participate in trial programs. Respondents identified AR's key advantages, including enhanced hands-on experience and improved safety awareness, though challenges such as limited training materials, equipment access, and technical issues were also noted. Importantly, 57.9% of participants believed AR-based training could have prevented past safety incidents. The study concludes that while AR presents a promising solution to bridge the training and safety gaps in CCUS-enabled cement plants, successful implementation will require investment in tailored training content, infrastructure, technical improvements, and structured worker engagement. These findings offer valuable insights for industry stakeholders, training institutions, technology developers, and policymakers aiming to promote safer, more efficient CCUS operations in the cement sector.

Keywords: Augmented Reality (AR); Carbon Capture Utilization and Storage (CCUS); Cement Industry; Worker Training; Industrial Safety; Ashaka Cement Plant; Immersive Learning; Digitalization; Emission Reduction; Industrial Innovation.

1.0 INTRODUCTION

The concentration of atmospheric carbon dioxide (CO_2) has reached unprecedented levels, rising from 280 ppm in 1750 to 420.23 ppm in 2024 (Skrable et al., 2022), with an average annual increase of 2.4 ppm over the past decade. In 2021, global anthropogenic CO_2 emissions surged to a record 36.3 billion tones, primarily from fossil fuel combustion (Heiskanen et al., 2022). Key contributors to human-induced CO_2 emissions include fossil fuel consumption, land-use changes, and deforestation. According to the IPCC, limiting global warming to 1.5°C (2.7°F) requires a 43% reduction in global greenhouse gas emissions by 2030 (Tollefson, 2018). Various emission reduction strategies such as the Accelerated, Net Zero, and New Momentum scenarios outline potential pathways for achieving this goal (Bai et al., 2023).

The primary strategies for reducing carbon emissions and transitioning away from fossil fuels include: (1) improving energy efficiency, (2) replacing fossil fuels with clean energy sources such as renewables, (3) capturing and storing CO_2, (4) policy and economic measures and (5) social and political dynamics (Ampah et al., 2024; De La Peña et al., 2022). However, achieving net-zero emissions solely through renewables remains challenging in the near to medium term, making carbon capture, utilization, and storage (CCUS), crucial bridging technology toward a decarbonized energy economy (Glan Devadhas et al., 2022). Despite decades of CCUS development, high costs and concerns about the long-term stability of underground storage hinder widespread adoption (Glan Devadhas et al., 2022 ; Davoodi et al., 2023). Consequently, CO_2 utilization is gaining attention as a means to enhance the economic viability of CCUS (Saxena et al., 2024; McLaughlin et al., 2023), though most CO_2 conversion and utilization pathways remain in the early stages of development.

A key challenge in large-scale CCUS deployment is ensuring worker safety and effective training for handling complex capture, storage, and utilization operations. Augmented Reality (AR) presents a transformative approach to addressing these challenges by providing immersive, real-time training environments for workers in CCUS facilities (Devagiri et al., 2022). Unlike traditional training methods that rely on theoretical instruction and static simulations, AR-based simulations allow workers to engage in realistic, interactive learning experiences that mimic real-world CCUS operations (Ariansyah et al., 2024; Uçar, 2024). Operators can visualize CO_2 capture processes, interact with virtual control systems, and practice safety protocols in a risk-free digital environment, reducing the likelihood of errors and accidents in actual facilities. AR-based training programs can be customized to specific CCUS plants, adapting to different operational conditions and evolving regulatory requirements(Martins et al., 2023).

The successful deployment of large-scale CCUS projects necessitates overcoming design and operational challenges, particularly in managing system interactions under dynamic conditions. A network-wide evaluation of these factors requires precise data analysis and decision-making frameworks, where AR-based analytics can provide real-time insights and enhance situational awareness(Moghaddam et al., 2021). By integrating machine learning and AI-based analytics, AR applications can analyze CCUS system data, predict equipment failures, and suggest proactive maintenance strategies, minimizing downtime and improving system reliability.

While significant advancements have been made in CCUS technologies, the cement industry remains one of the largest industrial contributors to CO_2 emissions, accounting for nearly 8% of global CO_2 emissions (Sanjuán et al., 2020; Supriya et al., 2023; Uliasz-Bocheńczyk & Deja, 2024). Cement plants require specialized CCUS strategies, as the carbon intensity of cement production stems not only from fuel combustion but also from the chemical decomposition of limestone ($CaCO_3$) into lime (CaO) and CO_2 during clinker production (Cormos et al., 2018; Wang et al., 2024). Despite the growing integration of CCUS in cement industries, a major gap exists in the training and safety preparedness of workers operating these complex carbon capture systems.

Currently, worker training programs in cement-based CCUS facilities are limited, often relying on manuals, classroom sessions, and occasional hands-on training (Hasan et al., 2022). However, these methods fail to provide interactive, real-time exposure to operational hazards and emergency response protocols. AR-based training systems can bridge this gap by immersing workers in realistic CCUS scenarios, allowing them to interact with digital twins of cement plant CCUS systems (Gong et al., 2024; Uçar, 2024). This enhances skill development, ensures faster response to system failures, and improves overall workplace safety.

Cement industries also face unique challenges, such as high-temperature environments, corrosive gases, and continuous emissions monitoring, which demand real-time decision-making and risk mitigation. AR-powered monitoring systems can significantly improve safety measures by providing real-time alerts, guiding workers through emergency shutdown procedures, and assisting with preventive maintenance tasks (Devagiri et al., 2022). This technology also enables remote supervision of CCUS operations, allowing experts from different locations to assist on-site personnel in critical situations.

With the rapid industrial adoption of digitalization, integrating AR-based worker training and safety solutions in cement-based CCUS facilities aligns with global efforts to enhance workforce preparedness in high-risk industrial environments (Ariansyah et al., 2024; Dong et al., 2025). The lack of empirical studies on AR-based CCUS training models for cement industries further highlights the need for research and development in this area. A comprehensive approach integrating AR, machine learning, and digital twins can revolutionize worker training, reduce occupational hazards, and improve the efficiency and safety of CCUS operations in cement manufacturing. By addressing these training and safety gaps through AR, cement industries can significantly enhance CCUS deployment, ensuring a safer, more skilled workforce while contributing to global decarbonization efforts.

The remainder of this paper is organized as follows. Section II demonstrates the study background and related work. Section III describes the methodology. Section IV displays the result and discussion. Finally, Section V concludes the paper.

2. 0 STUDY BACKGORUND AND RELATED WORK

This section provides a comprehensive review of the use of Augmented Reality (AR) to enhance worker training and safety in CCUS-enabled cement factories, beginning with an overview of Carbon Capture, Utilization, and Storage (CCUS) technologies and their integration into the cement industry, along with associated operational and safety challenges. It examines the current state of AR technologies, emphasizing their role in industrial training through learning environments, hazard visualization, and real-time decision support. The review also evaluates AR implementations in high-risk industries, identifying a gap in empirical research specific to CCUS operations in cement manufacturing. To address this, a case study of Ashaka Cement Factory in Gombe, Nigeria, is presented, offering practical insights into AR's potential to enhance worker preparedness, safety, and operational efficiency in CCUS-integrated settings.

2.1 CARBON CAPTURE

The impacts of global warming are growing more apparent, with estimates showing that human activities have already increased global temperatures by around 1.0 °C compared to pre-industrial levels. If current trends persist, this increase is projected to reach 1.5 °C between 2030 and 2052. However, the impact of anthropogenic (Karmalkar & Bradley, 2017). climate change can be mitigated by reducing net global CO_2 emissions to zero, alongside sustained decreases in other radiative forcing agents over the coming decades. In response, a range of strategies is being implemented to curb CO_2 emissions across major greenhouse gas-emitting sectors particularly the cement industry (Uliasz-Bocheńczyk & Deja, 2024).

The cement industry ranks as the third most energy-intensive sector and is a major contributor to CO_2 emissions, accounting for 7% of global greenhouse gas emissions (Supriya et al., 2023). The primary sources of CO_2 emissions in cement production stem from the decarbonization process and the combustion of fuels (Uliasz-Bocheńczyk & Deja, 2024). Reducing these emissions can be achieved through technological advancements, including the modernization of cement plants, improvements in energy efficiency, and the increased utilization of waste materials as alternative raw materials and fuels. However, despite ongoing mitigation efforts, direct CO_2 emissions have risen from 0.54 Mg CO_2 per Mg of cement in 2015 to 0.58 Mg CO_2 per Mg of cement in 2022, largely due to growing demand (Busch et al., 2022; Supriya et al., 2023).

Various technologies are being explored to reduce CO_2 emissions, including the binding of CO_2 in cement products through mineral carbonation processes (Uliasz-Bocheńczyk & Deja, 2024). Currently, five parallel strategies are under consideration in the cement industry to support the transition to a low-carbon circular economy. Among these, Carbon Capture, Utilization, and Storage (CCUS) is recognized as a critical approach (Kashyap et al., 2024). According to the European cement industry, CCUS plays a vital role in mitigating CO_2 emissions, with its adoption expected to contribute to a 42% reduction in emissions by 2050 (Sanjuán et al., 2020).

2.2 ASHAKA CEMENT PLANT

Ashaka Cement Company Plc, a subsidiary of the global cement leader Lafarge and located in Bajoga, Gombe State, was selected for this study. The plant has an annual production capacity of up to 850,000 tons of cement (Tsunatu et al., 2015). It primarily relies on limestone sourced from Ashaka, Bajoga, and Bage in the Funakaye Local Government Area as its main raw material, while coal (lignite) from Maiganga Village in Akko L.G.A serves as its primary energy source. Operating at full capacity throughout the year, the plant undergoes annual turnaround maintenance. It is designed with a projected operational lifespan of 20 years. The plant's design specifications and emissions are presented in Table 1. Regulatory emission limits for cement plants in Nigeria are 2.42 kg/ton for NO_2 and 0.046 kg/ton for SO_2. The facility emits approximately 500,000 tons of CO_2 each year, with roughly 56% resulting from limestone calcination and the rest from coal combustion and electricity use (Tsunatu et al., 2015).A process flow diagram for the cement clinker burning (calcination) process at the plant is shown in Figure 1.

Table 1. Flue Gas Composition and Thermal Parameter Analysis

Parameters	**Stack inlet**	**Stack exit**
Gas Temperature (ºC)	35.2	38.4
Ambient Temperature (ºC)	29.6	34.9
O_2 (%)	16.66 (166,600 ppm)	14.36 (143, 600 ppm)
CO_2 (%)	3. 15 (31, 500 ppm)	4. 86 (48, 600 ppm)
CO (ppm)	0	0
Stack Loss (%)	0.9	0.4
η- Efficiency (%)	99.1	99.6
Dew Point (ºC)	20.3	27.5
λ- Lambda	4.87	3.16

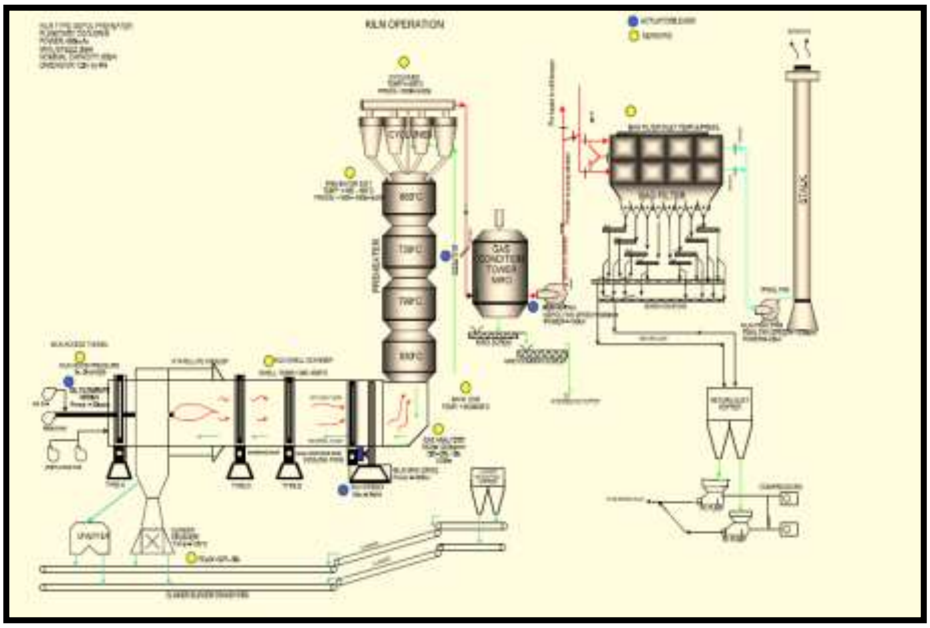

Figure 1: Illustration of Ashaka cement plant kiln operation

2.3 Co2 Capture Design and Simulation using Selexol at Ashaka Cement Plant

Flue gas from the Ashaka Cement Plant a central to this study on Carbon Capture, Utilization, and Storage (CCUS) is typically discharged into the atmosphere via the stack at a temperature of 180 ºC. Prior to release, the gas passes through the Gas Conditioning Tower (NIRO), where a substantial amount of SO_2 is removed and particulate matter is filtered out. It then flows to the Bag Filter House, where any remaining particulates, especially dust, are captured. This treatment results in a clean flue gas with low levels of SO_2 and particulate matter, making it well-suited for the Selexol-Based CO_2 Capture Process, as shown in Figure 2 and modeled using Aspen Hysys™ (Karmalkar & Bradley, 2017; Sanjuán et al., 2020; Tsunatu et al., 2015).

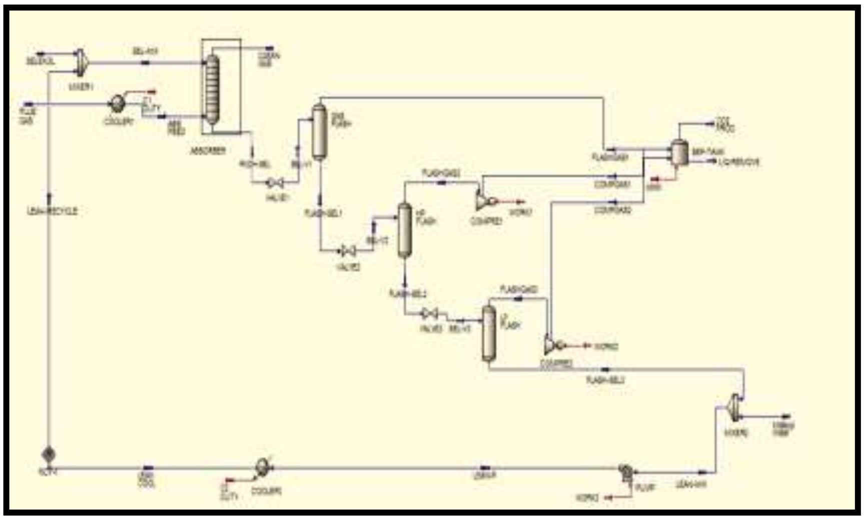

Figure 2: Illustration of Selexol-based CO_2 Capture

The CO_2 capture system at Ashaka Cement Plant is designed to remove 97% of CO_2 from the flue gas stream emitted from the plant's flue stack. The flue gas is first cooled from 180ºC to 40ºC in a cooler, with the gas exiting the cooler at a pressure of 100 kPa and a temperature of 40ºC, which is optimal for the absorber's operation. The cooled flue gas then enters the bottom of the absorber, while lean Selexol (33.4 wt.%) with a CO_2 loading of 0.37 mole CO_2/mole Selexol enters the top of the column in a counter-current flow at a pressure of 100 kPa and 27.99ºC (Tsunatu et al., 2015; Zajac et al., 2021).

Maintaining a low temperature for the lean Selexol solution is critical for two primary reasons: (i) to minimize Selexol and water makeup, and (ii) to maximize CO_2 capture efficiency. Based on the findings of this study, the absorber has been designed with 10 stages, achieving a rich Selexol-CO_2 loading of 0.4 mole CO_2/mole Selexol and 97% CO_2 recovery. The clean gas existing at the top of the absorber meets the emission standards set by the World Bank and USEPA, as shown in Table 2, and is safely released into the atmosphere (Monteiro & Roussanaly, 2022; Tsunatu et al., 2015). The absorber operates at a temperature of 50ºC and a pressure of 2360 kPa, which facilitates the absorption process. According to Henry's law of CO_2 solubility in physical solvents, higher partial pressure increases absorption, making it crucial to set the absorber pressure at approximately 2360 kPa. The absorption process within the absorber is exothermic, as Selexol physically reacts with CO_2, forming weak bonds that can be regenerated by reducing the pressure in the Flash Tanks in series, releasing the captured CO_2, (Busch et al., 2022; Tsunatu et al., 2015).

The rich Selexol existing the bottom of the absorber is sent through a valve to reduce its pressure from 2403 kPa to 1800 kPa before entering the GASFLASH system, where it undergoes separation into vapor and liquid phases. The vapor stream contains approximately 0.9980 mol-fraction of CO_2, while the liquid Selexol is directed to VALVE2, where the pressure is further reduced from 1800 kPa to 980.7 kPa. This pressure reduction continues until the rich Selexol enters the LP FLASH system, operating at 98.07 kPa (near atmospheric pressure), where most of the CO_2 absorbed in the Selexol is released (Tsunatu et al., 2015; Zajac et al., 2021). The separation process in the Low-Pressure Flash Tank results in a CO_2 stream with a mol-fraction of 0.9814, which is then compressed in COMPRES2 to increase its pressure from atmospheric to 1961 kPa. This CO_2 stream is subsequently combined with other CO_2 streams from FLASHGAS1 and COMPGAS2 for further separation and removal of any liquid traces in a separation tank, preparing the CO_2 for either compression or utilization. In this study, the CO_2 is compressed to a pressure of 1800 kPa and a temperature of 179.7ºC, making it suitable for pipeline transportation, although this aspect falls outside the scope of the research (Tsunatu et al., 2015; Wang et al., 2024).

The choice of packing material and the amount used were optimized to achieve maximum CO_2 recovery while minimizing Selexol consumption. After simulating the entire process, the CO_2 capture system demonstrated a recovery rate of 97%. As a result, the plant's CO_2 emissions were reduced from 4.86% to 0.1288%, as detailed in Table 1, illustrating the significant impact of CCUS technology in lowering emissions at the Ashaka Cement Plant (Guo et al., 2024; Kashyap et al., 2024; Tsunatu et al., 2015).

TABLE 2. COMPONENT CONCENTRATION IN FLUE GAS BEFORE AND AFTER ABSORPTION TREATMENT

Elements	Pre-absorption flue gas (%)	Post-treatment flue gas (%)
CO_2	4.86	0.1288
SO_2	0.2629	0
O_2	94.7426	99.8697
NO_2	0.1283	0.0005
Selexol	0	0
H20	0.0062	0.001

2.4 Augmented Reality

Augmented Reality (AR) is an advanced technology that superimposes computer-generated digital content onto the real world, allowing users to interact with virtual elements in real time within their physical environment. (Gong et al., 2024). Unlike traditional interfaces that rely on screens or input devices, AR enhances users' perception of reality by embedding three-dimensional, context-aware digital elements directly into their environment. The foundational concept of the reality–virtuality continuum was introduced by Milgram and Kishino (1994), while Azuma (1997) formally defined AR through three core characteristics: the integration of real and virtual content, real-time interactivity, and precise spatial registration in three dimensions (Pamparau, 2023) (Skarbez et al., 2021). Since its inception, AR has evolved significantly and demonstrated strong potential across various industries, including manufacturing, healthcare, and education (Bottani & Vignali, 2019; de Souza Cardoso et al., 2020). In the context of this research which focused on enhancing training and safety in CCUS-enabled cement plants like Ashaka Cement in Gombe, Nigeria, AR's ability to simulate complex industrial environments and improve hazard awareness is particularly relevant. AR applications are generally categorized as either immersive or non-immersive (Bottani & Vignali, 2019; de Souza Cardoso et al., 2020; Gong et al., 2024; Uçar, 2024). Immersive AR typically uses wearable technologies such as headsets or smart glasses to provide high levels of realism and user engagement, while non-immersive AR is accessed via handheld devices or fixed screens, offering more accessible but less immersive experiences.

2.5 Related Work

Recent advancements in Carbon Capture, Utilization, and Storage (CCUS) technologies, along with digital innovations such as Industrial Augmented Reality (IAR) and Artificial Intelligence (AI), are reshaping industrial strategies particularly in high-emission sectors like cement manufacturing. CCUS is increasingly recognized as a critical pillar in global decarbonization efforts. For example, Wang et al., 2024 conducted a comprehensive life-cycle assessment of CCUS deployment schemes in China's cement industry, revealing the intricate balance required between carbon mitigation, energy consumption, and water usage. Their findings underscore the importance of managing resource trade-offs as CCUS scales across industrial applications.

(de Souza Cardoso et al., 2020) provides a comprehensive review of the evolution of IAR technologies, highlighting their progression from basic visualization tools to sophisticated systems integrated with digital twins, the Internet of Things (IoT), and context-aware environments. Their classification of IAR applications into training, design, inspection, and remote assistance underscores the wide-ranging potential of AR across industrial domains, while also identifying persistent challenges such as real-time responsiveness, ergonomics, and system interoperability.

Extending this discussion, Farfan et al., (2019) evaluated global trends in the cement sector, exploring the long-term potential of Power-to-X (PtX) systems for carbon utilization. Their work highlights the regional disparities in infrastructure and resource availability, emphasizing the need for CCUS strategies tailored to local energy systems and market conditions. Similarly, (Dong et al., 2025) employed agent-based modeling to simulate CCUS adoption under various policy scenarios, concluding that carbon pricing, subsidies, and regulatory mandates can significantly accelerate diffusion—though policy uncertainty remains a persistent barrier.

Expanding on this discourse, (Devagiri et al., 2022) examine the synergistic integration of AR and AI in industrial contexts. They demonstrate how AI techniques, including deep learning and computer vision, are enhancing AR systems to become more intelligent, adaptive, and context sensitive. Their analysis also points to emerging trends such as the adoption of edge computing, 5G connectivity, and the development of industrial Metaverse platforms. Additionally, they emphasize the critical role of cybersecurity, user interface design, and data governance in the successful deployment of AR-AI solutions within complex industrial environments.

In a related but distinct area, (Kashyap et al., 2024) explore the techno-economic feasibility of CO_2 capture and utilization in the Indian cement industry, with a specific focus on green urea production. Although not directly connected to AR or AI, their research reflects the broader scope of Industry 4.0 innovations aimed at improving environmental sustainability through digitalization and process optimization. Their findings underscore the value of simulation tools and integrated chemical pathways in reducing emissions and promoting circular economy practices within high-emission sectors.

Together, these studies provide a solid foundation for understanding how digital technologies are reshaping traditional industries. Building on this foundation, the present research investigates the application of intelligent AR systems in industrial settings, with a particular focus on enhancing safety, sustainability, and operational efficiency in cement production environments.

3.0 METHODOLOGY

This research adopts a cross-sectional non-experimental research approach to assess the awareness, perception, and potential adoption of Augmented Reality (AR)-based training for Carbon Capture, Utilization, and Storage (CCUS) operations among workers at Ashaka Cement Plant in Gombe, Nigeria. A cross-sectional approach is suitable because it allows data collection at a single point in time, offering a snapshot of current training practices, safety experiences, and attitudes toward digital innovations such as AR within a real-world industrial setting. The study employs a quantitative method of data collection through structured questionnaires, ensuring objective analysis and facilitating the generalizability of findings across similar high-risk, technology-integrating industrial environments.

The target population for this study comprises employees and technical staff at Ashaka Cement Plant, Gombe, who are directly or indirectly involved in the operation, maintenance, safety, and environmental management of cement production processes. This includes individuals working in departments such as kiln operations, process engineering, environmental health and safety, and training. The inclusion criteria consist of workers who have been employed at the plant for at least six months, ensuring they possess sufficient familiarity with current operational protocols and safety practices. Employees who decline participation or are unavailable during the data collection period are excluded from the study.

3.1 Sample Size Determination

In this study, the sample size was determined using Yamane's formula, suitable for small populations (Adam, 2020). With a total population of 20 employees involved in operational and environmental roles at Ashaka Cement Plant, and a 5% margin of error at a 95% confidence level, the calculated sample size was 19. This sample was deemed sufficient to provide reliable insights while ensuring feasibility in data collection and analysis.

Yamane's Formula:

$$n = \frac{N}{1+N(e)^2} \qquad \ldots\ldots\ldots\ldots (1)$$

Where:

n = sample size

N = population size

e = margin of error (0.05 for 95% confidence level)

Therefore: $n = \frac{20}{1+20(0.05)^2} \quad = \frac{20}{1+20(0.0025)} \quad = \frac{20}{1+0.05} \quad = \frac{20}{1.05}$ = 19.05

However, to account for potential non-responses or incomplete submissions, all 20 participants were approached, with the goal of obtaining a high response rate to enhance the reliability and representativeness of the findings related to AR and CCUS adoption in the cement industry.

3.2 Data Analysis

The data collected was entered and analyzed using Microsoft Excel. Descriptive statistics such as frequencies and percentages were used to summarize categorical variables, providing a clear overview of respondents' demographic profiles, levels of awareness, and practices related to Carbon Capture, Utilization and Storage (CCUS) and Industrial Augmented Reality (IAR). Simple charts and tables were generated to visually represent the data. Where applicable, Excel formulas and functions, such as pivot tables and chi-square tests using built-in functions or manual calculations, were used to explore associations between variables. A p-value of less than 0.05 was considered statistically significant.

4.0 RESULTS AND DISCUSSION

The data presented in this section were collected during fieldwork conducted as part of the study on the application of Augmented Reality (AR) in enhancing worker training and safety within Carbon Capture, Utilization, and Storage (CCUS) operations at Ashaka Cement Industry. The responses obtained from participants provide insights into their awareness, experience, and perceptions regarding AR technologies and safety protocols related to CCUS processes.

4.1 Involvement in CCUS Operations

A total of 19 participants were surveyed from the Ashaka Cement Industry to evaluate the application of Augmented Reality (AR) in training and safety within Carbon Capture, Utilization, and Storage (CCUS) operations. Of these, 63.2% (n=12) confirmed their direct involvement in CCUS-related activities, while 36.8% (n=7) reported no direct connection. This distribution confirms that the majority of the respondents possess firsthand experience with the operational and safety challenges in CCUS processes, ensuring the relevance and reliability of the feedback obtained.

4.2 Training on CCUS

When asked about their exposure to AR-based training, 36.6% reported that they had not received any such training, highlighting a notable gap in current training practices. Only 31.6% had undergone online AR training, while 15.8% each reported receiving physical AR training and hands-on training. The relatively low percentage of participants with immersive, interactive training underscores the need for broader implementation of AR technologies to support skills development in CCUS operations.

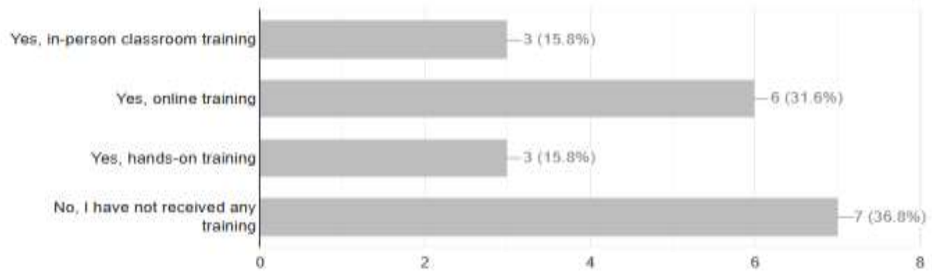

Figure 4: Illustration of training approach

4.3 Advantages of AR-based Training

Participants recognized several key benefits of AR-based training in CCUS processes. The most cited advantage was the provision of hands-on experience (57.9%), suggesting that AR effectively bridges the gap between theoretical knowledge and practical application. Additionally, 42.1% indicated that AR helps visualize complex CCUS procedures, while 36.8% noted its positive impact on engagement, learning retention, and real-time problem-solving. A further 26.3% reported that AR-based training is time-efficient compared to traditional methods. These results underscore AR's potential as a valuable educational tool that enhances experiential, visual, and interactive learning in CCUS.

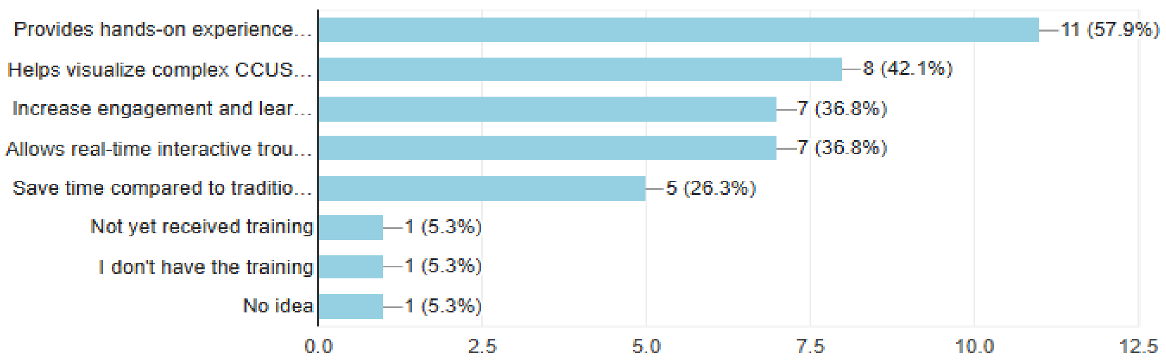

Figure 5: Illustration of Advantages of AR-based training

4.4 Challenges in AR Implementation

Despite its recognized advantages, several challenges to AR adoption were reported. The most prominent barrier was the lack of adequate AR training materials (52.6%), indicating a critical need for content development tailored to CCUS applications. Limited access to AR equipment was the second most common challenge (47.4%), reflecting infrastructure constraints. Additionally, 36.8% faced difficulties adapting to new technologies, while an equal percentage cited technical issues such as glitches and low resolution. Discomfort from prolonged use of AR headsets was reported by 31.6% of respondents. These challenges suggest that successful integration of AR will require not only technological improvements but also user support and resource allocation.

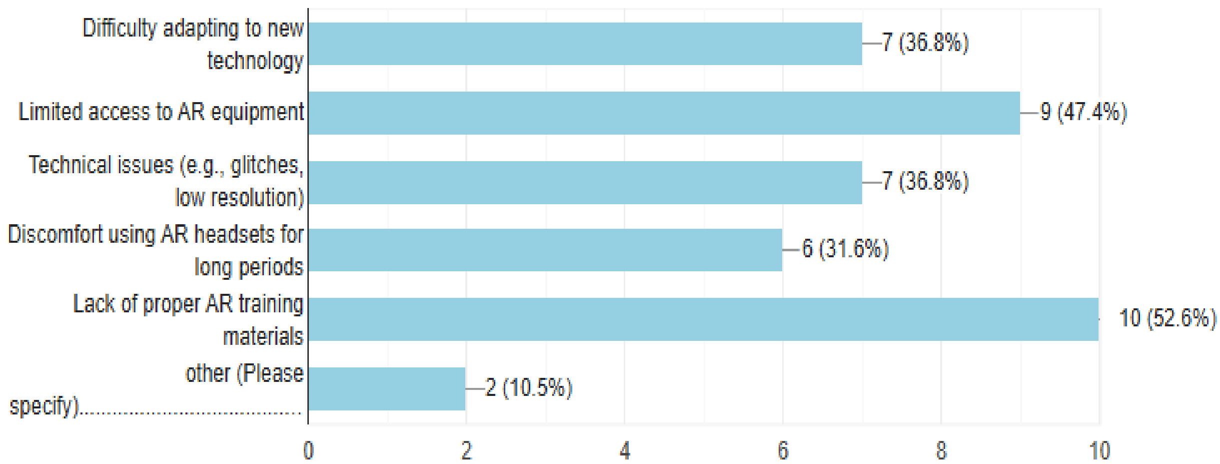

Figure 6: Illustration of challenges in AR implementation.

4.5 AR and Safety Awareness

Regarding safety awareness, 57.9% of respondents expressed confidence that AR can enhance safety practices in CCUS operations, with 10.5% strongly agreeing. However, 15.8% remained neutral, and a combined 26.3% disagreed or strongly disagreed, indicating some skepticism. This suggests that while AR holds promise for safety improvement, further validation and demonstration of its effectiveness in real-world settings are necessary to build a broader consensus.

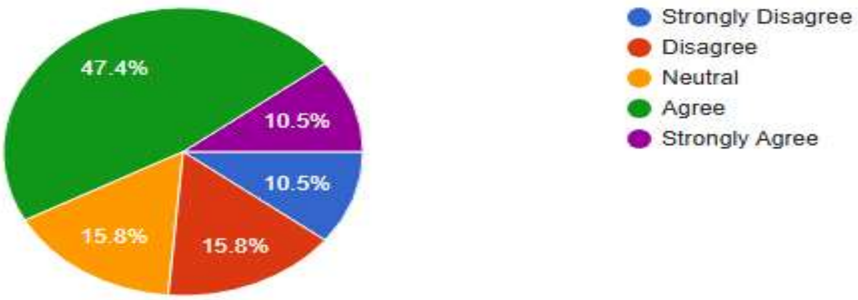

Figure 7: Illustration of AR safety awareness

4.6 Preference for AR-based Training

A significant majority, 84.2%, stated a preference for AR-based training over traditional methods, while only 5.3% preferred conventional approaches, and 10.5% were uncertain. This strong preference aligns with earlier findings on AR's perceived benefits and indicates readiness among workers for the integration of AR technologies in their training programs.

4.7 Suggestions for Improvement

Open-ended responses on improving AR-based training revealed limited actionable feedback, with suggestions scattered and minimal. While some respondents proposed adopting digital strategies, ensuring timely training, and securing sufficient resources, a significant portion (10.5%) admitted to having no idea or suggestions. This indicates a general positive attitude towards AR but also highlights a gap in detailed user insights, likely to stem from limited exposure to advanced AR implementations.

4.8 Overall Implications

The findings suggest that AR is viewed positively for its potential to improve training effectiveness and safety awareness in CCUS operations. However, addressing challenges related to content availability, equipment access, technical performance, and user adaptation will be crucial to realizing its full benefits. The strong preference for AR-based training indicates fertile ground for future deployment and further research.

5.0 CONCLUSION

This study has concluded that Augmented Reality (AR) offers significant potential to transform worker training and safety practices in Carbon Capture, Utilization, and Storage (CCUS) operations within the cement industry. Evidence from the Ashaka Cement Plant shows that workers are generally receptive to adopting AR-based training, with many recognizing its advantages in providing hands-on experience, improving safety awareness, and preventing incidents. The interactive and immersive nature of AR addresses key limitations found in traditional training methods, which often lack practical exposure and real-time hazard simulation. Despite the presence of certain challenges such as insufficient training materials, limited access to equipment, technical glitches, and user discomfort, the workforce demonstrates a strong willingness to engage with AR technology. Importantly, the study highlights that while workers are eager to adopt AR solutions, many require further exposure and structured guidance to fully participate in the development and refinement of such training programs. Overall, the findings affirm that AR can play a vital role in enhancing worker competence, reducing operational risks, and supporting the successful deployment of CCUS technologies in the cement sector, provided that the identified barriers are effectively addressed through targeted interventions.

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