Augmented Reality for Enhanced Stakeholder Engagement in Land Reclamation Projects: A Review

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Abstract: Augmented reality (AR) is increasingly seen as a transformative instrument in land reclamation, facilitating immersive visualisation, participatory planning and improved stakeholder communication. Despite its growing relevance in the architecture, engineering and construction (AEC) industry, its application remains limited. This study conducted a systematic literature review (SLR) to serve as part of the preliminary work on a wider study of AR integration into environmental planning and to consolidate current knowledge on AR's adoption, benefits and implementation challenges. A structured search across four major academic databases yielded 272 articles, of which 53 met rigorous inclusion criteria. The results were thematically categorised into three core areas: (1) barriers to AR implementation, including technical limitations, cost concerns and institutional fragmentation, (2) AR benefits, such as improved public participation, project transparency and real-time collaboration and (3) AR real-world applications, spanning urban redevelopment, mining reclamation and ecological restoration. This review identified theoretical and practical gaps in AR's integration into regulatory frameworks, stakeholder training and interdisciplinary workflows. To address these gaps, a conceptual framework was developed and presented at the conclusion of the discussion, offering researchers and practitioners a strategic guide for aligning AR technologies with sustainable land reclamation objectives.

Keywords: Augmented reality, Land reclamation, Stakeholder engagement, Urban redevelopment

INTRODUCTION

Traditional methods such as 2D maps, technical reports and geographic information system (GIS) tools often fall short in conveying complex spatial and environmental data to non-expert audiences because they lack interactivity, leading to miscommunication, stakeholder resistance and delayed approvals (Bademosi, Blinn and Issa, 2019; Boos et al., 2023). By contrast, augmented reality (AR) enables real-time interaction through digital overlays, allowing stakeholders to visualise outcomes, engage in virtual site visits and participate more meaningfully in project planning and review (Bhanu et al., 2022; Süvari et al., 2023). AR is gaining recognition as a transformative technology in the built environment, particularly in applications that require immersive visualisation and improved stakeholder communication. In addition, AR offers

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the potential to address challenges in public engagement, environmental transparency and collaborative decision-making, which is critical to project success. This includes land reclamation, which is the conversion of degraded or underutilised land into productive use, often on a large scale, and is environmentally sensitive, involving diverse stakeholders (Lu, Li, and Li, 2020; Newton et al., 2021). Despite AR's increasing adoption in the architecture, engineering and construction (AEC) industry, where it has improved design clarity, site coordination and collaborative workflows (Albahbah, Kivrak and Arslan, 2021; Shaieb and El-Rahman, 2022), its integration into land reclamation remains limited. This underrepresentation presents a critical research gap, especially considering the importance of participatory planning and ecological accountability in reclamation initiatives.

Urban development and urban redevelopment are two concepts linked to land reclamation. Urban development generally refers to the planning and construction of infrastructure in previously undeveloped (greenfield) areas, typically associated with expansion or new growth (Newton et al., 2021). By contrast, urban redevelopment focuses on the renewal or rehabilitation of existing or degraded spaces (brownfields), often within the context of ecological restoration, climate adaptation or coastal resilience (Newton et al., 2021). Land reclamation projects frequently align with the goals of urban redevelopment, particularly in densely populated regions where available land is scarce (Newton et al., 2021; Süvari et al., 2023).

This article aimed to critically examine the current body of literature on the use of AR in land reclamation through a systematic literature review (SLR). Specifically, this article's objectives were: (1) to identify the key barriers to AR adoption in land reclamation, including technical, financial and institutional constraints, (2) to evaluate AR's benefits in enhancing stakeholder engagement, decision-making and project transparency and (3) to highlight gaps in the literature that can guide future research and practice. Therefore, this article analysed previous research rather than presenting original empirical findings to provide a consolidated understanding of current scholarship to support future studies and the development of AR-based strategies for sustainable land management.

LITERATURE REVIEW

AR transforms land reclamation by enhancing various aspects of the field, from participatory planning to stakeholder engagement, through innovative visualisation techniques and virtual interactions. Its incorporation into urban and environmental planning has proven to be a game-changer, as it presents planning concepts realistically and offers interactive and immersive tools that integrate with GIS to overcome the limitations of traditional planning methods.

AI improves participatory planning. Bhanu et al. (2022) observed in urban development projects in Vienna, Austria and Lucerne, Switzerland, that AR increased people's interest in participating in urban planning and improved the quality of their involvement. Moreover, in civil engineering, AR enables professionals to blend virtual elements with the real world, enhancing their interaction with project data in real time. This capability is crucial in designing, planning, constructing and maintaining land reclamation projects (Arslan et al., 2021). Spatial AR further extends AR's utility by visualising agriculture land suitability maps, thus helping stakeholders such as farmers understand land suitability for reclamation and agricultural purposes (Albahbah, Kivrak and Arslan, 2021; Bhanu et al., 2022).

Additionally, the technology's provision of immersive experiences that enhance stakeholder engagement in sensitive and culturally significant reclamation areas, including the reconstruction of cultural heritage sites such as Castillo de la Estrella in Spain (McMeekin et al., 2020; Snyder, 2019), underscores its potential to enhance cultural transmission and conservation efforts. This tool is also instrumental in raising awareness about environmental issues and planning-related restoration processes. Furthermore, its facilitation of virtual site visits enables stakeholders to visualise outcomes of land reclamation projects without physical presence.

AR's versatility and broad utility highlight its numerous applications. For example, its role in land reclamation is not merely technological innovation but also enhancing stakeholder interactions and democratising the decision-making process. According to Albahbah, Kivrak and Arslan (2021), increased stakeholder motivation and involvement enrich the planning process, contributing to sustainable urban development. Additionally, the ongoing integration of AR into various stages of project planning and management illustrates a significant shift towards more dynamic and responsive environmental governance. Although AR improves participatory planning and stakeholder involvement in urban development projects, some scholars argue that it may exclude stakeholders who lack access to it or are unfamiliar with it (Shaieb and El-Rahman, 2022). AR-enabled immersive experiences may also disconnect users from the real world and compromise land reclamation efforts (Albahbah, Kivrak and Arslan, 2021; Shaieb and El-Rahman, 2022).

To further understand AR's applicability across domains, several previous SLRs have examined its role in the AEC, education and infrastructure management industries. For example, Bhanu et al. (2022) conducted an SLR on 695 publications and focused on 12 high-impact studies on AR applications in AEC. Their findings demonstrated AR's significance in reducing task completion time, minimising errors and enhancing risk communication accuracy in collaborative workflows. Complementing this review, Albahbah, Kivrak and Arslan (2021) analysed 94 articles on AR and virtual reality in construction project management, identified AR's potential to streamline decision-making and optimise resource allocation. Kerr and Lawson (2020) explored AR's pedagogical potential in 25 studies, highlighting its role in improving student engagement and spatial understanding in landscape design pedagogy. Shaieb and El-Rahman (2022) expanded AR's relevance to civil engineering, emphasising its utility in project visualisation and on-site monitoring of construction accuracy and structural maintenance. They found that AR's integration of virtual elements with the real-world environment enhances design assessment, infrastructure placement and inspection processes, ultimately improving project efficiency and minimising errors. However, these reviews did not explore AR's use in land reclamation, a complex domain where spatial reasoning, stakeholder involvement and environmental compliance intersect. Specifically, critical deficiencies remain in applying AR to urban redevelopment, such as coastal urban regeneration to address climate resilience or housing shortages.

Moreover, while prior studies emphasise AR's technical advantages (e.g., error reduction and task efficiency), they call for deeper exploration of institutional frameworks and urban redevelopment contexts to bridge gaps between innovation and real-world implementation (Albahbah, Kivrak and Arslan, 2021; Bhanu et al., 2022; Kerr and Lawson, 2020; Shaieb and El-Rahman, 2022). For example, international treaties such as the United Nations Sustainable Development Goals and the Ramsar Convention guide reclamation ethics, but national agencies. For example, the US Army Corps of Engineers and Singapore's Building and Construction Authority enforce site-specific policies, such as permitting for dredge-and-fill activities under the Clean Water Act or AR-integrated audits (Mariano, 2022; Ward et al., 2023).

METHODOLOGY

Due to the scarcity of articles on the use of AR to enhance stakeholder engagement in land reclamation projects, the SLR conducted in this study focused on reclamation construction in the construction sector. The SLR was conducted in three phases: identification of literature, screening and analysis (as shown in Figure 1). In the first phase, the review methodology was synthesised (McMeekin et al., 2020; Snyder, 2019). This was followed by a comprehensive search on Google Scholar, ScienceDirect, Academia and ResearchGate search engines. The main indexes were journal articles and conference papers, which comprise the primary types of literature in construction research. Only papers that contained the keywords "augmented reality", "AR" and "reclamation" in their abstract or title were considered. The inclusion criterion was an explicit focus on AR applications in land reclamation, and the exclusion criterion was editorials, volume contents and articles that did not focus on AR in construction or reclamation.

A total of 272 articles were found in this search round. However, the results contained unwanted publications that mentioned the keywords but did not particularly address the topic of AR in construction.

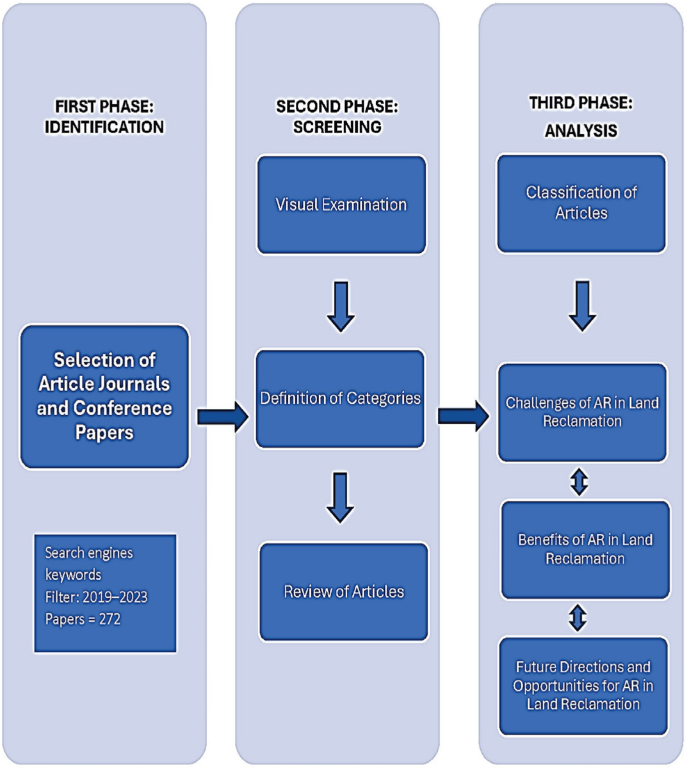

Figure 1. This study's systematic literature review approach

During the screening phase, article abstracts were reviewed for their explicit focus on AR applications within the context of land reclamation. Articles were excluded if they met any of the following criteria: (1) lacked empirical or conceptual analysis of AR in land or environmental applications, (2) focused solely on AR in education or entertainment without spatial or stakeholder relevance and (3) constituted editorials, book reviews or general commentaries. To ensure thematic relevance, each abstract was manually assessed against a coding schema aligned with the study's three analytical dimensions: benefits, challenges and applications. Articles that discussed AR in the broader construction industry but did not address the study's core objectives of land reclamation, participatory planning or environmental visualisation were excluded. Following this rigorous evaluation, 53 articles were deemed methodologically and topically appropriate for the synthesis.

In the analysis phase, the selected articles were categorised into three themes: benefits, challenges and potential applications of AR in land reclamation. The themes were consistent with the study's objectives and conceptual framework. Under benefits, sub-themes included the positive impacts of AR on enhancing stakeholder engagement, improving decision-making and increasing project transparency. Under challenges, sub-themes comprised technical limitations, cost implications and integration issues (corresponding to the 'technical, financial and institutional constraints' in the first objective). Under potential applications, sub-themes included participatory planning and design, environmental visualisation and impact assessment and site monitoring and project evaluation. These sub-themes were used to determine the proportion and distribution of articles across each thematic area. The subsequent sections provide detailed explanations of each theme and its corresponding sub-themes.

RESULTS AND DISCUSSION

Table 1 summarises the most frequently cited journals and conferences represented in the final selection. Meanwhile, Table 2 presents their categorisation into themes and sub-themes. From the analysis of the classified articles, overall conclusions were drawn.

Table 1. Retrieved journal articles and conference papers

Journal/Conference	Phase 1	Phase 2	Source
IOP Conference Series: Earth and Environmental Science	12	1	Edelbro, Ylitalo and Furtney (2021)
Journal of Physics: Conference Series	20	2	Lu, Li and Li (2020); Zhou (2020)
Journal of Construction Engineering, Management and Innovation	3	1	Albahbah, Kivrak and Arslan (2021)
International Journal of Art and Design Education	2	1	Kerr and Lawson (2020)
International Journal of Advances Engineering and Civil Research	5	1	Shaieb and El-Rahman (2022)
Multimodal Technologies and Interaction	8	2	Moya et al. (2023); Tomkins and Lange (2019)
Journal on Computing and Cultural Heritage	6	1	Süvari et al. (2023)
Land	31	2	Novelli, Moino and Borsotto (2022); Rodríguez et al. (2022)

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Table 1 *Continued*

Journal/Conference	Phase 1	Phase 2	Source
Education and Information Technologies	5	1	Sari et al. (2021)
Proceedings of the ACM on Human – Computer Interaction	2	1	Wells, Potts and Houben (2022)
IEEE Transactions on Visualization and Computer Graphics	2	1	Sereno et al. (2020)
Landscape Ecology	3	1	Chandler et al. (2022)
Sustainability	42	4	Belaroussi et al. (2023); Blanco-Pons et al. (2019); Bazargani et al. (2022); Szostak et al. (2019)
Frontiers in Built Environment	12	1	Xu and Moreu (2021)
Buildings	30	2	Gerger, Urban and Schranz (2023); Ratajczak, Riedl and Matt (2019)
Remote Sensing	3	1	Xiong et al. (2022)
Frontiers in Virtual Reality	8	2	Reaver (2023); Wang and Lin (2023)
Journal of Location Based Services	3	1	Boos et al. (2023)
Journal of Information Technology in Construction	5	1	Bademosi, Blinn and Issa (2019)
Journal of Science and Research	2	1	Zhao and Anderson (2018)
Journal of Information Technology in Construction	6	1	Fenais et al. (2020)
Applied Sciences	3	1	El Kassis, Ayer and El Asmar (2023)
Applied Ecology and Environmental Research	4	1	Kun (2019)
The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences	23	3	Cantatore, Lasorella and Fatiguso (2020); Hairuddin, Abdul Rasam and Razali (2022); Li, Amerudin and Mohamed Yusof (2019)
Digital	5	1	Gong, Wang and Xia (2022)
Journal of Ecological Engineering	4	1	Petryk (2023)
International Journal of Coal Science and Technology	6	1	Xiao et al. (2022)

(*Continued on next page*)

Table 1 *Continued*

Journal/Conference	Phase 1	Phase 2	Source
Restoration Ecology	2	1	Pape (2022)
Virtual Archaeology Review	5	2	Barrile et al. (2019); Gherardini, Santachiara and Leali (2019)
International Journal of Environment and Climate Change	4	1	Kaushal and Bhatnagar (2023)
Proceedings of the Human Factors and Ergonomics Society Annual Meeting	1	1	Bhanu et al. (2022)
Journal of Geography and Environmental Management	1	1	Fan and Liu (2022)
ARCHive-SR	1	1	Mariano (2022)
Science	1	1	Ward et al. (2023)

Table 2. The study themes and sub-themes, with sample studies

Theme	Sub-Theme	Sample Study
Benefits and challenges of AR in land reclamation	Enhanced stakeholder understanding; Improved communication and collaboration; Increased public awareness and support; Technical limitations and infrastructure requirements; Cost implications and accessibility; Integration with existing reclamation workflows	Lu, Li and Li (2020); Süvari et al. (2023); Novelli, Moino and Borsotto (2022); Sari et al. (2021); Moya et al. (2023); Wells, Potts and Houben (2022); Chandler et al. (2022); Belaroussi et al. (2023); Kosa et al. (2019)
Case studies of AR implementation in reclamation projects	AR for participatory planning in urban redevelopment; Visualisation of reclamation processes in mining sites; Virtual site visits for community engagement in ecological restoration	Reaver (2023); Wang and Lin (2023); Bulgarelli-Bolaños (2018); Kun (2019); Cantatore, Lasorella and Fatiguso (2020); Rodríguez et al. (2022); Gerger, Urban and Schranz (2023); Fan and Liu (2022); Scianna, Gaglio and Guardia (2019)
Future directions and opportunities for AR in land reclamation	Advancements in AR technology and software; Integration with other emerging technologies; Scalability and applicability across different reclamation contexts	Xiao et al. (2022); Xiong et al. (2022); Bazargani et al. (2022); Kaushal and Bhatnagar (2023); Pape (2022); Süvari et al. (2023); El Kassis, Ayer and El Asmar (2023); Barrile et al. (2019)

The principal outcome of this review was a conceptual framework (as shown in Figure 2). The framework was developed to structure AR's multifaceted role in stakeholder engagement and environmental restoration. This framework synthesised the key findings from the thematic analysis in this study and addressed the central aim of linking AR technologies to practical stakeholder needs.

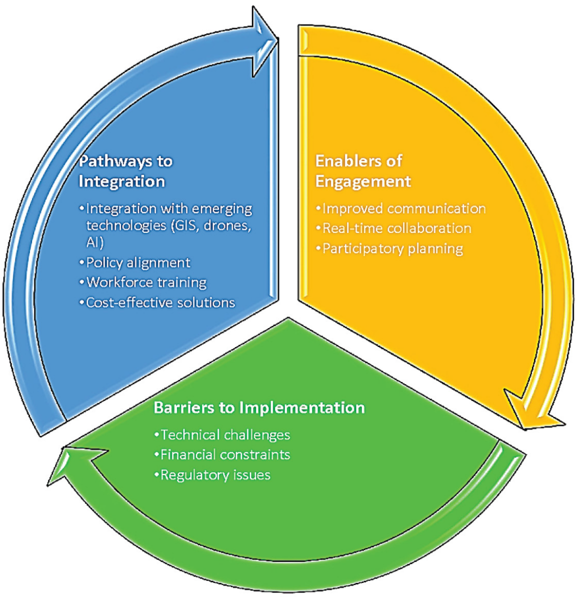


Figure 2. Conceptual framework of AR use for stakeholder engagement in land reclamation

The framework (as shown in Figure 2) consisted of three interrelated domains. The first domain, Enablers of Engagement, captures AR's ability to enhance communication, real-time collaboration and participatory planning through immersive site visualisations that improve stakeholder understanding and trust. The second domain, Barriers to Implementation, encompasses technical, financial and regulatory constraints to AR adoption, particularly in developing regions, such as hardware limitations, high development costs and the absence of standardised institutional policies. The third domain, Pathways to Integration, outlines strategic approaches to embedding AR in land reclamation workflows, emphasising the importance of integrating AR with emerging technologies (e.g., GIS, drones and AI), aligning policy frameworks, investing in workforce training and developing scalable, cost-effective solutions.

Overall, this framework clarified AR's functional roles in enhancing stakeholder engagement and highlighted the interdependencies among technology maturity, stakeholder inclusiveness and regulatory capacity. It offered a strategic lens through which practitioners and policymakers could evaluate existing AR efforts, identify implementation gaps and chart more inclusive and sustainable pathways. Future studies can also employ this framework to assess readiness, prioritise investments and foster interdisciplinary collaboration in advancing the use of AR for sustainable land reclamation.

The reviewed literature revealed a range of benefits and challenges associated with AR in land reclamation. Figure 3 classifies these attributes according to the frequency of their discussion across publications.

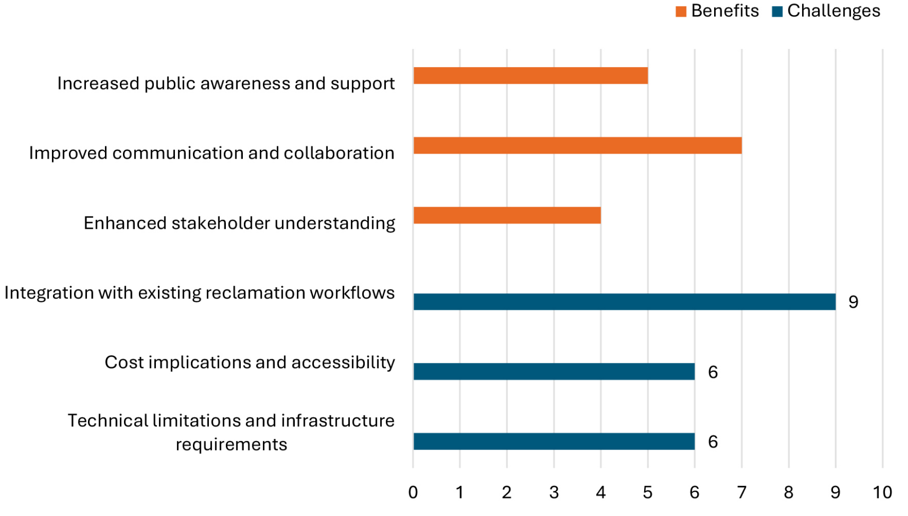


Figure 3. AR attributes classified into benefits and challenges

Challenges in Augmented Reality Implementation in Land Reclamation

AR has shown promise in enhancing stakeholder engagement and operational efficiency in land reclamation projects. However, its widespread adoption faces several challenges. These include technical limitations, cost implications and difficulties in integrating AR into existing reclamation workflows. Overcoming these obstacles is crucial to ensuring AR's full emergence as a practical and scalable solution in reclamation projects.

Technical limitations and infrastructure requirements

AR can enhance the efficiency and efficacy of land reclamation initiatives by offering interactive virtual overlays in real-time environments. Nevertheless, AR implementation is impeded by several technological obstacles and infrastructure requirements (Zhou, 2020). Considerable technological challenges are posed by human physiological and cognitive limitations, which impact users' experiences with AR devices in outdoor settings, such as land reclamation sites. Specifically, these constraints influence vision and perception, as demonstrated by El Asmar et al. (2021) and Xu and Moreu (2021). Furthermore, the absence of recognised criteria for AR use in specific civil infrastructure fields has slowed its acceptance therein, despite rapid advances in its hardware, such as head-mounted devices (Xu, Doyle and Moreu, 2021) and this challenge, while primarily institutional, can indirectly exacerbate cognitive limits by creating uncertainty in standardised usage and increasing the mental effort required for users to adapt to varying protocols.

To expand the use of AR in land reclamation projects, it must be able to successfully address the challenges posed by the dynamic and evolving nature of these projects (Xu, Doyle and Moreu, 2021). This requires robust data integration and continuous real-time information updates, such as the ability to synchronise AR visualisations with frequently changing site conditions, incorporate live sensor data on soil stability and water levels and update 3D models promptly when reclamation designs are revised (Zhou, 2020). Moreover, the environmental concerns associated with land reclamation, such as maintaining soil stability, necessitate the long-term implementation of AR to enhance planning and monitoring (Ratajczak, Riedl and Matt, 2019). To effectively tackle these obstacles, a standardised framework must be established for evaluating the effectiveness of AR devices and enabling their seamless integration with conventional engineering approaches (Xu, Doyle and Moreu, 2021; Zhou, 2020). Research findings on the constraints of AR adoption in land reclamation have yielded a thorough understanding of the steps needed to overcome these limitations. They emphasised that, for AR to truly revolutionise land reclamation, scientific progress in the field must be bridged with field-level implementation by prioritising standardisation, enhancing user experience, and integrating with current workflows.

Cost implications and accessibility

AR implementation in land reclamation has been impeded by exorbitant expenses, accessibility challenges and the intricacy of its execution in demanding conditions. The inclusion of sophisticated hardware, such as depth-sensing cameras and IMU sensors, in AR systems contributes to their high cost and limited accessibility, especially in low-income countries, where the requisite technical knowledge is typically also scarce (Wang and Lin, 2023; Xu, Doyle and Moreu, 2021). Furthermore, the limited acceptance of AR in the civil infrastructure community is partially attributed to the lack of comprehension of its potential in this context (Shaieb and El-Rahman, 2022). To illustrate, AR has the potential to enhance geographical education and training for land reclamation and prevent disagreements resulting from insufficient data (Boos et al., 2023). However, studies are necessary to develop successful instructional methods (Bademosi, Blinn, and Issa, 2019).

The current SLR focuses on the full realisation of AR's potential to improve visualisation, situational awareness, and stakeholder involvement in land reclamation, particularly through its broader acceptance and implementation in the field, which necessitates not only the continued advancement of AR technology but also ensuring its economic feasibility and user-friendliness. Recommended priority measures include the development of affordable AR technologies that can withstand the demanding conditions of land reclamation sites, as well as educating and sharing information with civil infrastructure experts on AR.

Integration with existing reclamation workflows

The current SLR found the intricate network of technological and practical factors that required meticulous management for the effective integration of AR into land reclamation operations. The hesitation of the civil engineering sector to accept AR has been influenced by the sector's uncertainties regarding AR's level of development and concrete advantages, unwillingness to embrace developing technology, limitations in managing data and hardware and the substantial amount of data required for AR applications (Bademosi, Blinn and Issa, 2019; Huh et al., 2020; Reaver, 2023).

AR integration into land reclamation projects has been hindered by the absence of dependable digital information on subterranean utilities, which is crucial for visualisation and strategic development (Fenais et al., 2020; Reaver, 2023). Further challenges include those related to visual perception, such as occlusion, unpredictable outdoor circumstances and the need for accurate tracking (El Kassis, Ayer and El Asmar, 2023; Xu, Doyle and Moreu, 2021). For instance, AR is challenging to implement in densely populated areas or those with dense vegetation due to blocked satellite signals, which weaken the location-tracking capabilities of AR devices (Wang and Lin, 2023; Xiong et al., 2022). This feature is significant because accurate location-tracking underpins the correct alignment of virtual overlays with real-world coordinates, ensuring that visualisations remain spatially reliable for planning and monitoring activities. Additionally, AR systems must be continually upgraded to ensure their compatibility with evolving software platforms, sensor technologies and mobile operating systems and optimal performance amid the constant growth in mobile computing (El Asmar et al., 2021). Furthermore, their resilience and flexibility must be enhanced, given their use in post-disaster scenarios, specifically for evaluating the extent of damage and developing strategies for providing aid (El Asmar et al., 2021). These challenges indicated that progress in AR must align with breakthroughs in other technology fields, including high-resolution remote sensing, improved geospatial data processing algorithms, cloud-based integration platforms and real-time environmental monitoring systems to address the collection and processing of geographical data.

Benefits of Augmented Reality in Land Reclamation

The reviewed literature highlighted three key benefits of AR in land reclamation: enhanced stakeholder understanding, improved communication and collaboration and increased public awareness and support. These advantages reinforced AR's potential to transform decision-making, optimise planning and foster sustainable development.

Enhanced stakeholder understanding

AR is transforming stakeholder participation in land reclamation by enhancing stakeholder understanding and enabling a more immersive and participatory experience that facilitates active engagement of diverse users. This cultivates community backing while sharing accountability for the ecological and visual consequences of land reclamation (Mridul et al., 2019; Sereno et al., 2020). AR revolutionises stakeholder understanding of land reclamation projects by enabling effective project visualisation through the superimposition of digital information onto real-world situations. This closes the divide between abstract designs and real-world implementations, improving spatial assessments and decision-making processes (Lu, Li and Li, 2020; Zhou, 2020). It also improves stakeholder understanding of reclamation procedures and of the effects of reclamation on architecture and the environment, enabling stakeholders to contribute to informed decision-making and programme optimisation (Lu, Li and Li, 2020; Zhou, 2020). Specifically, AR contributes to the protection of cultural heritage by safeguarding historical sites and enhancing the bond between stakeholders and their legacy (Süvari et al., 2023). It is also a valuable tool for instructing students on the ethical dimensions of land reclamation to enhance their comprehension of its wider ramifications (Novelli, Moino and Borsotto, 2022). Moreover, AR solutions such as the AR Pipeline Visualiser enhance safety and efficiency in reclamation activities by offering a thorough comprehension of underground utilities. This safety improvement arises from reducing the risk of accidental damage to hidden infrastructure and minimising hazardous excavation errors (Sari et al., 2021).

Improved communication and collaboration

AR transforms visualisation in several sectors by enabling stakeholders to clearly interpret how reclamation will affect built structures and the environment, thereby supporting well-informed decisions and optimising programmes (Lu, Li and Li, 2020; Zhou, 2020). It achieves this by overlaying data-rich, three-dimensional models on physical spaces, allowing geographically dispersed participants to see identical, context-specific information simultaneously, thereby improving collaborative decision-making. In industrial settings, particularly where humans and robots collaborate, human mental effort is reduced as they are assisted with complex tasks, thereby enhancing efficiency and safety (Moya et al., 2023). This is achieved by simplifying complex procedural steps into visual guides that reduce cognitive load and minimise operational errors. Its adaptability enables smooth information transmission and cooperation across various devices and geographical limitations (Wells, Potts and Houben, 2022).

Increased public awareness and support

AR is gaining wider recognition for its capacity to improve public awareness and assistance in land reclamation endeavours. It enhances community participation and comprehension of reclamation procedures by generating detailed and immersive visuals of potential environmental outcomes. According to Chandler et al. (2022), it could successfully communicate the ecological and societal consequences of land reclamation initiatives. Belaroussi et al. (2023) and Kosa et al. (2019) demonstrated how AR may be utilised to simulate ecosystem restoration and convey the ecological consequences of mining, respectively, therefore improving public understanding of these undertakings. Newton et al. (2021) and Gherardini, Santachiara and Leali (2019) highlighted AR's potential to generate informative and captivating experiences that encourage active community participation in environmental conservation. These applications work by converting complex environmental datasets into intuitive visual narratives, enabling lay audiences to comprehend and appreciate the long-term benefits of restoration projects. The studies propose the development of AR applications that not only educate but also actively engage the public in supporting and participating in restoration efforts. In short, powering AR's capacity to graphically and interactively showcase the benefits of ecological actions while combining intricate environmental data with common knowledge. This process democratises information and promotes public participation in land reclamation initiatives, which are essential for their success.

Case Studies of Augmented Reality Implementation in Reclamation Projects

The findings from the case studies on AR implementation in reclamation projects highlight significant outcomes and insights that emphasise the influence and potential of AR technology in different areas of urban redevelopment, mining reclamation and ecological restoration. These findings can be categorised into three themes: AR for participatory planning in urban redevelopment, visualisation of reclamation processes in mining sites and virtual site visits for community engagement in ecological restoration. The corresponding case studies and research are presented in Table 3.

Table 3. Case studies of AR implementation in land reclamation projects

Category	Country and Project	Sources
AR for participatory planning in urban redevelopment	Norway (Oslo Trees plan), Turkey (Ayazini Village), Austria and Switzerland (Vienna and Lucerne urban planning), China (Shanghai's Bund area), General (Building Information Modelling-enabled projects)	El Kassis, Ayer and El Asmar (2023); Gong, Wang and Xia (2022); Ratajczak, Riedl and Matt (2019); Reaver (2023); Wang and Lin (2023)
Visualisation of reclamation processes in mining sites	Costa Rica (heritage building restoration), South Korea (UMineAR app), Sri Lanka (EAR app)	Bulgarelli-Bolaños (2018); Kun (2019); Petryk (2023)
Virtual site visits for community engagement in ecological restoration	Italy (Cryptoporticus of Egnatia and I-Access project), Spain (San Isidro Pass), Austria (BRISE-Vienna Project), China (ecological restoration transaction cost analysis)	Cantatore, Lasorella and Fatiguso (2020); Fan and Liu (2022); Gerger, Urban and Schranz (2023); Rodríguez et al. (2022); Scianna, Gaglio and Guardia (2019)

Augmented reality for participatory planning in urban redevelopment

The wide-ranging applications of AR in urban rehabilitation and land reclamation demonstrate its substantial capacity to enhance stakeholder involvement and project effectiveness. The Oslo Trees project in Norway utilised AR to actively engage young people in urban planning, thereby enhancing their understanding of and participation in design principles. Nonetheless, certain concerns over location monitoring were observed (Reaver, 2023). These concerns stem from the need for AR applications to continuously track users' positions and movements to provide accurate spatial overlays. In participatory projects, such monitoring can raise privacy issues, particularly when involving minors, as location data might inadvertently reveal personal movement patterns or be susceptible to misuse. Such apprehensions can limit user willingness to engage fully, especially in communities where trust in data governance is low.

In Turkey, AR was utilised to safeguard cultural heritage and promote local engagement by digitally reconstructing ancient houses in Ayazini Village (Reaver, 2023). AR has also significantly contributed to the improvement of urban planning procedures in Vienna, Austria and Lucerne, Switzerland, resulting in more sustainable development results (Wang and Lin, 2023). Shanghai has enhanced cultural tourism in the Bund region by providing immersive experiences using AR, thereby strengthening the area's cultural reputation (Zhao and Anderson, 2018). Furthermore, AR has contributed to advancements in construction operations by enabling building information modelling (BIM) projects by improved communication, safety and efficiency while reducing costs (Bademosi, Blinn and Issa, 2019; Fenais et al., 2020; Bazargani et al., 2022).

Although AR has demonstrated advantages, its implementation encounters obstacles, such as tracking inaccuracy and economic and accessibility limitations, especially in low-income regions. These case studies indicate that to optimise the potential of AR, customised solutions are necessary for its effective integration and to enhance user engagement. Moreover, the use of AR in civil infrastructure could be encouraged to increase innovation by further investigating its long-term effects on urban and environmental development, as well as by establishing legal and regulatory systems (Gong, Wang, and Xia, 2022; Reaver, 2023; Wang and Lin, 2023).

Visualisation of reclamation processes in mining sites

AR has been demonstrated to be highly useful and versatile in a range of reclamation operations at mining sites worldwide, improving efficiency, safety, and stakeholder involvement. Costa Rica has successfully employed it to repair heritage buildings, exhibiting its adaptability in project management and conservation. This suggests that AR may have broader applications in the reclamation of mines (El Kassis, Ayer and El Asmar, 2023). The UMineAR app, developed in South Korea, visually represented mine GIS data and reclamation sites to improve the location and comprehension of underground settings, which is essential for effective reclamation (Bulgarelli-Bolaños, 2018). In Sri Lanka, the EAR app has enhanced operating efficiency, safety and training in mine reclamation (Kun, 2019).

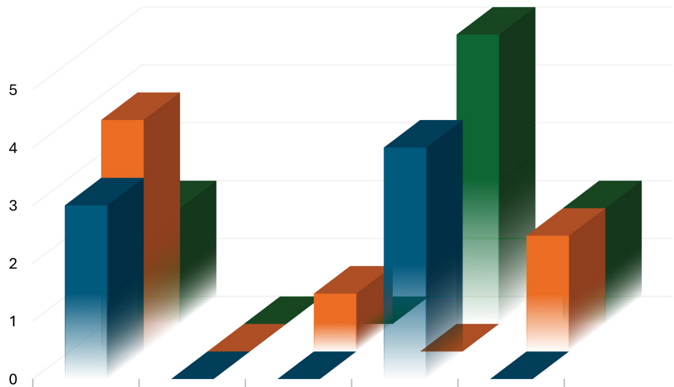
Virtual site visits for community engagement in ecological restoration

The case studies on AR deployment in ecological restoration, which implement virtual site visits, demonstrate the technology's significant impact and adaptability in various locations and operational scenarios. Such visits were utilised at the Cryptoporticus of Egnatia in Italy to improve comprehension of ancient sites by offering technical aid and expert guidance (Cantatore, Lasorella and Fatiguso, 2020). They were also employed by the I-Access Project in Italy to enhance access to cultural and natural resources, fostering community engagement and conservation initiatives (Scianna, Gaglio and Guardia, 2019). AR-powered site visits supported educational objectives in the San Isidro Pass in Spain, focusing on geological characteristics, to facilitate sustainable restoration efforts (Rodríguez et al., 2022). They were also used by the BRISE-Vienna Project in Austria to investigate the potential of AR to accelerate the process of obtaining ecological restoration licences (Gerger, Urban and Schranz, 2023). Finally, AR was employed in China to perform transaction cost analysis in ecological restoration through virtual site visits, thereby enhancing project management and community engagement (Fan and Liu, 2022).

These case studies illustrate the substantial contributions of AR to effective ecological restoration and management through improved stakeholder engagement, knowledge dissemination, and regulatory streamlining, and demonstrate its adaptability in tackling a wide range of challenges, from restoring historic sites in Italy to promoting educational geotourism in Spain and simplifying regulations in Vienna. Future studies can use these findings to develop AR applications that improve data accuracy and visibility. In addition, studies can examine the economic implications of utilising AR to enhance its practicality and efficiency, as well as foster multidisciplinary cooperation.

Future Directions and Opportunities for Augmented Reality in Land Reclamation

Based on the preceding analysis, the following future paths and prospects for AR are outlined, which can make reclamation initiatives more data-driven, interactive, and sustainable. Individuals with a vested interest in discovering new opportunities for rehabilitating deteriorated environments and fostering ecological responsibility might adopt these innovations and investigate further novel uses of AR technology. These future paths and prospects are categorised into three themes: advancements in AR technology and software, integration with other emerging technologies (e.g., GIS and drones) and scalability and applicability across different reclamation contexts. Figure 4 indicates the number of reviewed publications that cover each theme.



	2019	2020	2021	2022	2023
Advancements in AR technology and software	3	0	0	4	0
Scalability and applicability across different reclamation contexts	4	0	1	0	2
Integration with other emerging technologies (e.g., GIS, drones)	2	0	0	5	2

Figure 4. Future directions and opportunities for AR use in land reclamation from the reviewed publications (2019–2023)

Advancements in AR technology and software

The incorporation of AR into land reclamation signifies notable progress, echoing the precise methodologies employed in medical domains. This suggests that comparable levels of precision could be applied to critical undertakings such as the positioning and supervision of infrastructure and ecological components in reclamation projects (Xiao et al., 2022). This characteristic is essential for guaranteeing efficient project interventions and results. Moreover, the integration of AR with UAVs and GPS presents novel approaches to efficient overseeing and monitoring of extensive reclamation areas. For example, technologies such as AerialAR utilise this capability to detect significant regions in UAV imagery that demand focus, such as erosion or vegetation areas, hence improving project management and situational awareness (Xiong et al., 2022).

Additionally, the capability of AR to offer instantaneous data on underground conditions or plant development has the potential to transform management methods at reclamation projects completely. Combining MT-InSAR with AR can further provide novel methods for predicting and visualising land settlement, therefore assisting in the planning and mitigation of future difficulties (Szostak et al., 2019). The utilisation of AR in dynamic settings also has the potential to enhance operational effectiveness by facilitating the observation of ecological indicators such as the development of pioneer plants and soil stability. This, in turn, may provide crucial information for implementing adaptive management methods (Pape, 2022). These advancements demonstrate how AR may significantly improve the accuracy, productivity and efficacy of land reclamation initiatives.

Integration with other emerging technologies

The integration of AR with GIS and drones revolutionises land reclamation endeavours by improving the administration and representation of geographical data. Research indicates that the integration can greatly enhance the precision of land surveys, as well as data accuracy and visualisation, which can support more informed decision-making and facilitate sustainable development (Xiong et al., 2022). Moreover, AR-enhanced autonomous drone technology is optimising surveying navigation and improving data collection efficiency to effectively monitor ecological changes and properly appraise land (Barrile et al., 2019).

Furthermore, the use of AR to preserve historical monuments provides a non-intrusive approach to restoration while enabling immersive virtual experiences that promote public engagement and safeguard cultural heritage (Kaushal and Bhatnagar, 2023; Kosa et al., 2019). For example, the development of AR apps for tourism can revolutionise the experiences of visitors on reclaimed lands by offering educational material and improving interaction, hence opening up new opportunities for local communities to generate cash (Bazargani et al., 2022). Thus, AR enhances education and tourism by augmenting cultural and economic worth. These innovations demonstrate that AR has the potential to greatly enhance the effectiveness, inclusiveness and long-term viability of land reclamation operations, making it an indispensable tool for the successful administration of complicated projects and for community engagement.

Scalability and applicability across different reclamation contexts

The implementation of AR in land reclamation holds significant promise in a range of applications, emphasising its ability to bring about dramatic changes and paving the way for future improvements. Süvari et al. (2023) highlighted the capacity of AR to accurately and immediately represent underground utilities, therefore greatly improving operational safety and efficiency. Furthermore, AR's capacity to support cultural heritage preservation by offering scalable and non-intrusive restoration techniques that uphold historical authenticity while enhancing accessibility and interpretability was exemplified by its role in the restoration of the Virgin Mary Church in Ayazini Village (Barrile et al., 2019; El Kassis, Ayer and El Asmar, 2023). Its promise in the tourism sector lies in its ability to boost economic growth by improving visitor engagement and access to cultural treasures. In the field of construction and land reclamation, it enables coordinated communication, thereby supporting decision-making, training and stakeholder engagement (Xu, Doyle and Moreu, 2021). Subsequent studies may prioritise AR integration into construction management systems to enhance cooperation and operational efficiency further.

Nevertheless, to ensure the successful implementation of AR, issues related to unpredictable external settings must be addressed. More resilient AR systems, which can adjust to various environmental conditions, must be developed to maintain performance quality (Blanco-Pons et al., 2019). Furthermore, the utilisation of True AR—an advanced form of augmented reality that achieves precise alignment of virtual content with the physical environment in real time—in cultural asset protection highlights its capacity to generate highly accurate landscape depictions, thereby enhancing its educational value and potential for public engagement (Li, Amerudin and Mohamed Yusof, 2019). Tackling these obstacles and pursuing these possibilities may greatly enhance the influence of AR and transform it into a crucial tool for reinventing land reclamation by enhancing safety, efficiency and cultural involvement.

CONCLUSION

The current SLR demonstrated AR's potential to bridge planning and real-world implementation by showcasing its versatility in diverse contexts through case studies in urban redevelopment, mining reclamation and ecological restoration. These examples reinforce AR's role in making land reclamation more transparent, efficient and sustainable. A key contribution of this study was the development of a novel conceptual framework that systematically categorised AR's role in addressing technical barriers, optimising stakeholder communication and aligning policy regulations. The framework advanced academic discourse by linking AR applications, such as real-time monitoring and risk assessment, to sustainability goals while offering a practical roadmap for policymakers and practitioners to maximise AR's benefits in reclamation projects and navigate implementation challenges. Future research and industry practices should prioritise advancing AR technologies by (1) integrating them with tools such as GIS, drones and AI-driven analytics and (2) improving accessibility in low-resource settings through technological evolution, cross-sector collaboration and adaptive regulatory frameworks. By addressing these dimensions, AR's potential to redefine land reclamation planning and implementation is demonstrated through innovation, inclusivity and ecological resilience, ultimately contributing to global sustainable development agendas.

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