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Extended reality applications in forest management and operations: a review

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ABSTRACT

This review examines integration of extended reality (XR) technologies – virtual reality (VR), augmented reality (AR) applications, and mixed reality (MR) – in forest management and operations. We synthesize XR applications across key forestry domains: harvesting, inventory and mapping, fire management, biodiversity monitoring, training, and stakeholder engagement. Reviewing 65 studies spanning 2014–2024 (especially 2020–2024) revealed a sharp increase in XR forestry research after 2019: VR, which is easily deployed in controlled settings, has dominated (approximately 72% of studies), while AR (approximately 23%) is growing as mobile/wearable technologies improve. We analyze technological enablers (hardware – e.g. headsets, drones, mobile devices – and software platforms – e.g. game engines) and discuss human factors (usability, user acceptance). Key challenges include technical limitations (e.g. accurate spatial alignment under the forest canopy, data interoperability, device ruggedness) and environmental and organizational constraints (connectivity in remote areas, costs, user training needs). We highlight emerging trends – integration of artificial intelligence (AI) for data processing, development of forest digital twins, multi-user collaborative XR – as pathways to enhance XR capabilities in forestry. We underscore XR's transformative potential to advance precision forestry and sustainable management through immersive visualization, interactive scenario simulation, and improved decision support, and conclude with recommendations to improve XR accuracy, efficiency, and adoption.

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Introduction

Forests are complex socio-ecological systems whose sustainable management benefits from the use of advanced digital tools. Extended reality (XR), an umbrella term for immersive technologies including virtual reality (VR), augmented reality (AR) applications, and mixed reality (MR), has emerged as a powerful approach for enhancing the visualization and understanding of spatial, ecological, and operational data in forestry (Çöltekin et al. 2020; Murtiyoso et al. 2024). These integrated AR and VR approaches are hereafter referred to as MR, representing systems that combine real-world interaction with immersive virtual environments. In this review, we use the term XR as an umbrella concept encompassing VR, AR, and MR. VR refers to fully immersive digital environments, typically experienced in controlled settings, whereas AR overlays digital information onto the real-world environment, supporting in-field applications. MR represents a continuum between these modalities, where digital and physical elements are interactively integrated. For clarity, we use the term "XR modality" to denote the specific technological implementation (VR, AR, or MR) in each study. Furthermore, we refer to "digital twins" as dynamic, data-driven virtual representations of forest systems that integrate real-world data with simulation and visualization capabilities. These definitions are applied consistently throughout the manuscript to improve clarity for interdisciplinary audiences. Throughout this review, we explicitly distinguish between VR (simulation-based applications), AR (field-based applications), and MR (integrated environments) to ensure conceptual clarity.

By blending digital information with physical forest environments or creating realistic virtual forest scenarios, XR can bridge the gap between data analysis and on-the-ground decision-making. For example, VR-based simulators allow forest managers and machine operators to interact with detailed virtual forests and machinery, thereby enabling safe training and scenario planning without field risks. AR applications using devices such as mobile tablets or headsets can overlay geo-referenced data (maps, tree metrics, and hazard markers) onto real-world forest views, providing real-time decision support in the field. This integration of digital and physical information is crucial, as forests face growing challenges from climate change, pests, and wildfires, and managers must balance timber production, biodiversity, and recreational use.

The integration of XR into forest management serves to bridge the gap between data analysis and practical forestry decisions by enabling direct interaction with spatial data in situ (Çöltekin et al. 2020). Forests play a critical role in biodiversity conservation, climate regulation, and hydrological cycles, as well as contributing to the economy and employment. Effective forest management relies on extensive digital datasets encompassing inventory, infrastructure, ownership, and environmental conditions (de Miguel-Díez F and Purfürst 2025). XR technology facilitates the visualization of these datasets in immersive environments. While visualization alone is not sufficient to improve forest management, XR technologies enable immersive interaction with complex datasets, thereby enhancing analysis, decision-making, and operational planning in forest management.

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To provide a clearer conceptual foundation for understanding the role of extended reality (XR) in forestry, we introduce a functional typology linking XR technologies to decision-making processes. In this study, XR applications are categorized into four primary functions: (1) visualization, which supports the immersive representation of complex spatial and ecological data; (2) interaction, enabling users to explore and manipulate forest information in real time; (3) simulation, allowing the evaluation of alternative management scenarios such as silvicultural treatments or disturbance dynamics; and (4) collaboration, facilitating shared understanding and participatory decision-making among stakeholders through multi-user environments. These functional categories provide a structured link between XR technologies and forestry workflows, spanning data interpretation, planning, operational decision-making, and stakeholder engagement. This framework is used throughout the review to interpret how XR applications contribute to different stages of forest management.

The importance of XR in forestry has been underscored by the growing volume of research and practical trials conducted in recent years. Traditionally, forest operations and management have relied on tools such as GIS (Geographic Information System), remote sensing, and two-dimensional (2D) maps for planning and monitoring. XR builds on these technologies by enabling immersive three-dimensional (3D) visualizations and interactive experiences. For instance, XR has been used to simulate silvicultural treatments and forest growth under different scenarios, improving our understanding of long-term outcomes (Taylor et al. 2025). Training and safety stand out as early use cases: VR harvester simulators and chainsaw operation training modules have been successful in preparing operators for hazardous tasks in controlled virtual environments. A recent study (Capecchi et al. 2023) demonstrated that forestry students trained with a VR chainsaw simulator (the "ForestVRoom" system) gained greater hazard awareness and understanding of felling techniques than those trained with traditional training alone. Such findings illustrate XR's value in education and workforce development, echoing broader trends in environmental education, where XR can increase engagement and knowledge retention.

Extended reality has also proven beneficial for stakeholder engagement and collaborative planning. Immersive visualization can intuitively convey management plans or conservation scenarios to stakeholders. For example, VR "virtual walks" through a forest parcel allow the public or decision-makers to experience the potential effects of interventions (such as thinning or controlled burning) before they are implemented. This helps build consensus by making abstract data tangible. AR applications have also been piloted for on-site stakeholder communication. In a recent study, AR and VR messaging was tested to inform forest visitors about invasive species management, and it was found that immersive messages can influence visitor perceptions and encourage pro-management preferences (Schneider et al. 2023). By enabling two-way interaction (users can virtually manipulate or query the environment), XR tools can incorporate local knowledge and values into forest planning processes, as seen in the use of VR to include Indigenous community perspectives in forest conservation discussions.

The adoption of XR improves training, safety, and stakeholder collaboration through the simulation of hazardous scenarios and silvicultural operations (Tarng and Hsu 2024; de Miguel-Díez F and Purfürst 2025). The overlay of digital information in forest environments provides real-time access to guidance, ecological monitoring, and workflow optimization (Çöltekin et al. 2020). This integration of digital and physical elements is crucial as forests face pressure from climate change, pests, and land-use conflicts (de Miguel-Díez F and Purfürst 2025).

Despite these advantages, the implementation of XR in forestry presents several challenges. Technical barriers include the requirement for high-precision sensors to ensure accurate spatial alignment between the digital content and the physical environment (Döllner et al. 2023). The heterogeneity of forest landscapes, the impact of the canopy on GNSS (Global Navigation Satellite System) signals (Lopatin et al. 2023), variable lighting conditions, and dense vegetation all complicate the deployment of XR hardware and the integration of sensor data. Additionally, cost, energy requirements, and wireless connectivity in remote areas present obstacles to adoption (Çöltekin et al. 2020; Döllner et al. 2023). Although digital solutions are advancing, their practical implementation remains limited (Vagizov et al. 2021; Döllner et al. 2023).

In addition to technology, human factors and organizational issues affect XR adoption. Forestry professionals may hesitate to trust or use new immersive tools without clear evidence of their benefits (Çöltekin et al. 2020; de Miguel-Díez F and Purfürst 2025). Early trials often involved small groups of tech-savvy users (e.g. students or researchers), so their results may have underestimated the ease of use of XR; the broader user base of field foresters may not have reported the same experiences. In addition, cost and infrastructure pose significant constraints. Advanced XR headsets and powerful computing hardware are expensive, and maintaining them under field conditions incurs additional costs. Rural broadband or mobile internet coverage is often poor at forestry sites, which complicates cloud-connected AR applications. The power supply for devices used in multiday field missions is another concern. These factors indicate that while XR in forestry is rapidly developing in research settings, its real-world deployment remains limited. Indeed, a recent review noted that the use of novel visualization technologies in forestry remains far less common than in domains such as construction or medicine (Murtiyoso et al. 2024).

In summary, XR technologies show great promise for addressing some of the pressing challenges in forest management and operations. They provide immersive and interactive means to visualize forest conditions, train personnel, and engage stakeholders in ways that are not possible with traditional tools. This review responds to the need for a systematic synthesis of recent developments to understand XR's current capabilities and the limitations of using XR in forestry. We surveyed the state-of-the-art within a 2014–2024 core dataset, with particular attention to developments after 2020. By compiling evidence from the literature and analyzing trends, we aim to support forestry professionals and researchers in understanding how XR technology is being applied today and how it could evolve to advance sustainable forest management in the near future.

Aim of the study

This study aims to critically review and synthesize state-of-the-art applications of XR technologies in forestry research and practice, with particular emphasis on developments since 2020. We examine how VR, AR, and MR technologies are applied across key forestry domains, such as forest operations (harvesting and logistics), forest inventory and mapping, management planning and decision support, training and education, and stakeholder engagement, and evaluate the benefits and challenges documented in these applications. By analyzing a core dataset of peer-reviewed literature from 2014 to 2024, with particular emphasis on developments during 2020–2024, we identify current trends in XR adoption and highlight emerging innovations. Selected 2025 studies are used only as contextual sources to discuss very recent developments and are not included in the core quantitative synthesis. This review also explores persistent barriers to XR deployment in forest environments, including technical, practical, and human factors, and discusses potential solutions and research directions. The insights and recommendations derived from this review are intended to inform both ongoing research and practical implementation, supporting advancements in precision forestry and sustainable forest management.

Materials and methods

Search strategy and data sources

We conducted a systematic literature review following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines to identify relevant studies on the application of XR technologies in forestry. The search covered the period from 1 January 2014, to 31 December 2024, capturing both early developments and recent advances in XR for forest management. We searched five major academic databases – Scopus, Web of Science, ScienceDirect, IEEE Xplore, and SpringerLink – which we selected for their broad coverage of forestry, environmental science, and technology publications.

The quantitative core dataset of the review was restricted to studies published between 1 January 2014 and 31 December 2024. This core dataset was used for all numerical summaries, including publication trends, modality distribution, geographic distribution, and application-scale analysis. A small number of very recent 2025 publications were considered only as contextual sources in the Introduction, Discussion, and comparison with previous research, because they became available after the core search window but were relevant to emerging trends in XR, forestry digitalization, user acceptance, or adjacent sectors. These 2025 sources were not included in the 65-study core dataset and were not ncluded in the quantitative summaries presented in the Results section.

We designed the search queries using Boolean combinations of XR-related and forestry-related keywords, adjusted to each database's syntax. The XR-related search terms included both full terms and abbreviations: "extended reality," "virtual reality," "augmented reality," "mixed reality," "XR," "VR," "AR," "MR," "immersive technology," and specific device/platform names (e.g. "HoloLens," "Google Glass," "Unity3D"). These were paired with forestry terms such as "forestry," "forest management," "silviculture," "forest inventory," "forest operations," "wildfire," and so forth. We restricted the results to English-language publications, including journal articles and conference papers, and required full-text availability. We intentionally omitted geographic and study-type filters in the initial stage to capture the widest possible range of XR applications.

The initial search across the five databases yielded 553 records after removing non-English and unrelated hits. We exported these results to the reference management software, where we identified and removed duplicate records.

Inclusion and exclusion criteria

We established clear inclusion and exclusion criteria to ensure that the review focused on high-quality studies that were directly relevant to the application of XR in forestry.

Inclusion criteria

We used three inclusion criteria:

(1) Studies had to explicitly address XR technologies (VR, AR, and MR) applied within a forestry or forest-related context. This included applications in forest operations, management, planning, monitoring, training, and education.
(2) Studies had to present empirical findings (e.g. user studies, field trials) or detailed technical implementations. Purely conceptual discussions, commentaries, or reviews without original analysis were excluded.
(3) Studies had to demonstrate methodological rigor in their research and practical relevance to forestry, such as involving forestry professionals or simulating realistic forest scenarios, to ensure their applicability in real-world contexts.

Exclusion criteria

We excluded studies that were not about actual forest environments (e.g. those using "forest" metaphorically or focusing on unrelated domains such as agriculture or landscape architecture without a clear forestry angle). We also excluded review papers or editorials, as the objective was to review primary research ourselves, as well as publications with ambiguous methods or very small sample sizes that made their findings unreliable. Non-English articles and those without accessible full texts were also excluded. Finally, we removed duplicates or secondary reports, retaining only the most complete and relevant version of each study.

Study selection process

Study selection followed the PRISMA framework to ensure transparency and reproducibility. Figure 1 illustrates the selection process. After removing 249 duplicate records from the initial 553, we screened 304 unique titles/abstracts for their relevance.

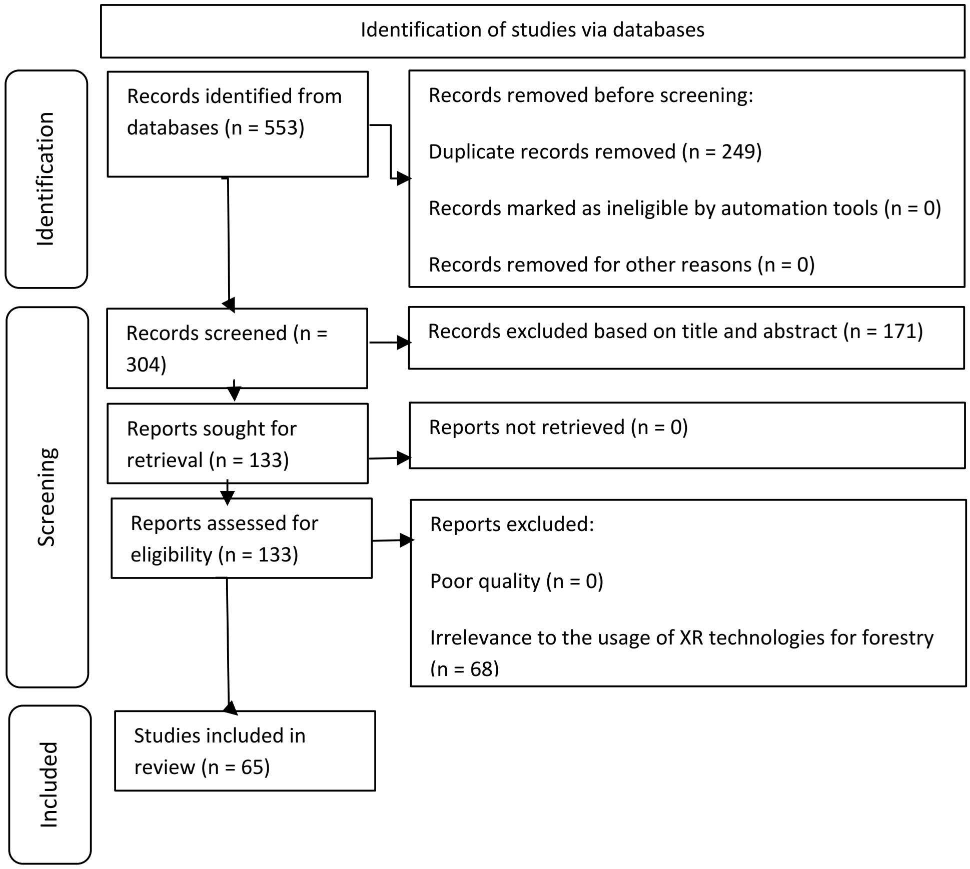

Figure 1. PRISMA flowchart showing the methodology of the systematic literature review.

From this screening, we excluded 171 records based on the aforementioned criteria (mostly because they did not focus on XR in forestry or were off topic). We searched the full texts of the remaining 133 studies, all of which we retrieved and reviewed. During this eligibility assessment, we excluded 68 studies for reasons such as lack of empirical content (e.g. being discussion-based papers), minimal relevance to forestry, or insufficient technical detail. This resulted in a final set of 65 studies that met all the inclusion criteria and were included in the qualitative and quantitative syntheses. We resolved any uncertainties or borderline cases through discussions among the coauthors to ensure consistency and rigor in the selection process.

Data extraction and synthesis

For each of the 65 included studies, we extracted key information and organized it into a data table. The information recorded included the publication year, the country/region of the study, the forestry application domain (e.g. training, inventory, fire management, landscape planning), the XR modality used (VR, AR, or both), details on hardware and software (types of headsets or devices, software platforms like Unity or custom apps), any integrated sensors or data sources (e.g. LiDAR data, GNSS, and drones), the scale of the application (tree-level, stand-level, landscape-scale, or purely virtual environment), reported technical challenges or limitations, and any user study results or feedback on the effectiveness or usability of the XR application.

We conducted the data extraction systematically using spreadsheets. To identify key trends, we performed basic quantitative analyses, including the number of studies published per year, the distribution of XR modalities (VR vs. AR vs. mixed) over time, and the geographic distribution of studies by country. We used simple descriptive statistics such as frequencies and percentages to summarize these patterns (e.g. the proportion of studies using VR headsets vs. AR mobile apps). To support this interpretation, we visualized selected trends in the Results section, including a timeline of XR-in-forestry publications and a breakdown of XR types used across the reviewed studies.

In addition to the quantitative analysis, we conducted text analysis to identify recurring themes related to challenges and technologies. We extracted text excerpts from all studies that discussed the "challenges" or "limitations" of XR in forestry, as well as those mentioning specific tools and platforms. Using a word cloud generator, we visualized the most frequently occurring words in the discussions. To improve the interpretability of qualitative findings, the originally presented word clouds were replaced with structured tables summarizing the most frequently reported challenges and technologies across the reviewed studies. Frequencies are reported in relative terms (e.g. high, medium, low) based on the recurrence of themes identified during the qualitative synthesis of the 65 studies. This approach provides a more transparent and reproducible representation compared to word clouds while preserving the interpretative nature of the review.

Quality assurance

After eligibility screening, we did not apply formal quality scoring to exclude any of the 65 studies retained for synthesis: however we appraised the methodological rigor of each study during the data extraction phase. We ensured that all the included studies were published in peer-reviewed journals or reputable conference proceedings, to achieve a baseline level of quality. We paid particular attention to the clarity and robustness of each study's methodology. Studies that lacked sufficient detail on how XR systems were evaluated or how data were collected were treated with caution. As noted earlier, we excluded some lower-quality studies, such as those with extremely small user samples or unclear research designs, during the eligibility screening. The final set of studies generally provided clear descriptions of their XR systems and included either technical validation or user evaluation. In summarizing the results, we assigned greater weight to findings from studies with more robust methods (e.g. we emphasized controlled experiments involving forestry professionals over anecdotal or purely conceptual prototypes). By acknowledging the limitations, both within individual studies and in our own review process, we aimed to deliver a balanced, transparent, and credible synthesis of the current state of XR in forestry.

Results

The results are interpreted through the proposed functional typology of XR (visualization, interaction, simulation, and collaboration), linking technological applications to forestry decision-making workflows.

Temporal trends in XR adoption within forestry research

Our review revealed rapid growth in XR-related forestry studies in recent years. Figure 2 presents the number of publications per year from 2014 to 2024 that focus on XR applications in forestry. The synthesis combines narrative interpretation with quantitative summaries, highlighting common challenges such as accuracy, data integration, and realism, as well as frequently used tools and platforms including Unity and Oculus. This approach provides both a high-level overview and deeper insights into XR adoption in forestry. While the early to mid 2010s saw only a modest number of studies, publication activity accelerated significantly after 2019. Notably, the number of studies approximately doubled between 2019 and 2020 and remained consistently high until 2024. This suggests that XR in forestry transitioned from an emerging concept to an increasingly mainstream research topic in the 2020 s. The year 2023 marked the peak in publication activity, representing the highest number of XR-in-forestry publications in the dataset. We note that the 2024 count reflects publications up to 31 December 2024, and may underrepresent the full year's output owing to delays in indexing or publication timing. The overall trend appears to be exponential rather than linear, indicating that as the benefits of XR become more evident and the technology becomes more accessible, the forestry community is increasingly adopting these tools. This surge aligns with broader trends in digital transformation and smart technologies in natural resource management.

Many early XR forestry studies before 2020 focused on exploratory prototypes or conceptual implementations, whereas more recent studies more often involved applied deployments, technical validation, or user evaluation. This shift suggests that XR research in forestry has moved from early experimentation toward applied research and implementation. The post-2019 increase also runs parallel to developments in related domains such as agriculture and environmental sciences, where recent reviews report growing use of XR for training, visualization, and decision-support applications (Anastasiou et al. 2023; Bigonah et al. 2025).

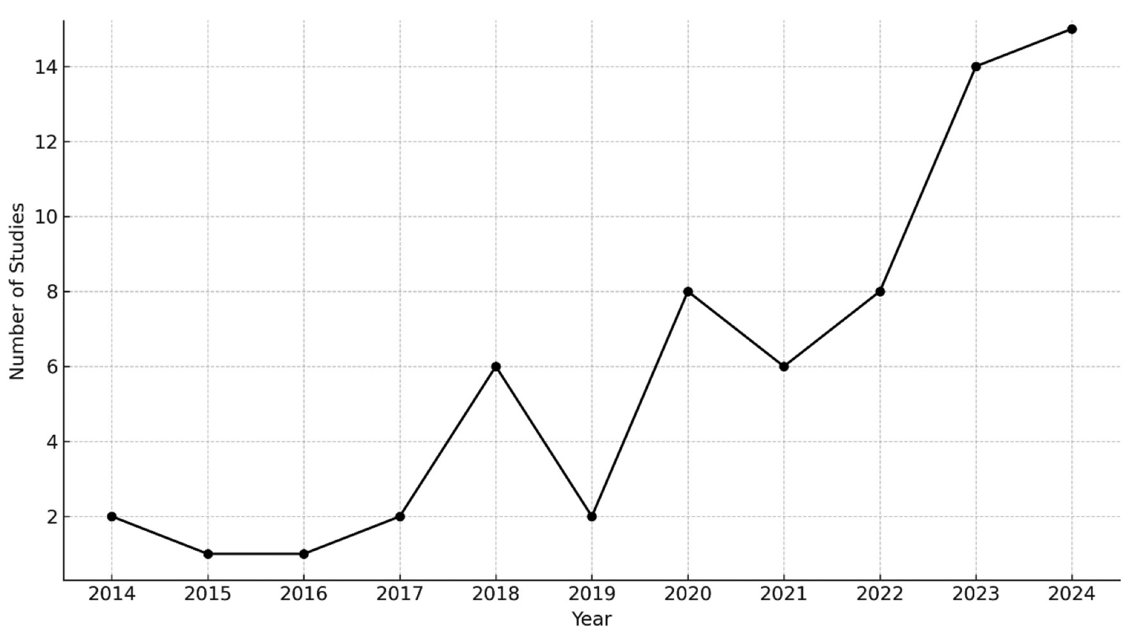

Figure 2. Annual number of included studies on XR applications in forestry, 2014–2024 (n = 65).

Overall, this temporal trend highlights XR as an emerging and rapidly expanding forestry research frontier. Just five years ago, only a handful of papers addressed XR in this context; today, dozens of articles are published annually, spanning a wide range of applications. This momentum is likely to continue as successful case study stories accumulate and XR hardware becomes even more capable and accessible to researchers and practitioners.

Technological preferences: VR vs. AR in forestry applications

A notable finding from our review is the predominant use of VR over AR in forestry research. Of the 65 studies we analyzed, approximately 71.7% employed VR as the primary XR modality, while approximately 23.3% focused on AR. The remaining ~5% integrated both AR and VR. Figure 3 illustrates these proportions and their evolution over time, highlighting the early dominance of VR and the gradual emergence of AR applications in recent years.

The dominance of VR can be attributed to several practical advantages when simulating forest scenarios. Prior to 2020, many VR forestry applications focused on training and simulation in controlled environments, such as harvester operator simulators, virtual forest walk-throughs for education, and desktop-based VR visualizations for planning. VR allows full control over environmental variables (terrain, weather, tree positions, etc.) and is typically used indoors, which avoids the technical hurdles associated with deploying devices in the forest.

Our review confirms that VR has been the “low-hanging fruit” for immersive technology in forestry. Once a digital forest model is created, users can engage with it using a VR headset or a standard PC. Many studies have highlighted the benefit of avoiding real-world constraints such as inclement weather, limited connectivity, and safety risks. For instance, Capecchi et al. (2023) developed a VR-based chainsaw felling training program that allowed students to practice safely before entering the field. Similarly, landscape planners have used VR from offices to visualize forest change scenarios. Our quantitative analysis shows that VR was heavily favored up to approximately 2019.

Starting around 2020, AR applications began to increase, driven by advances in mobile AR technology. In the early years of the review period, only a few AR studies were published, often using rudimentary hardware such as handheld GPS (Global Positioning System) units with basic AR or older smartphones. By 2020–2023, there was a notable surge in AR-focused research, some of which leveraged modern AR software development kits (SDKs) and devices. These AR applications aimed to support field tasks, for example, using a tablet-based AR app to display tree inventory data when pointed at specific trees, or using the HoloLens to visualize proposed skid trails directly on the ground in front of a forest engineer (Çöltekin et al. 2020; de Miguel-Díez F and Purfürst 2025).

Despite this growth, AR's share remains modest at ~23% compared to VR's ~ 72%. A key reason for this is the technical complexity of deploying AR in outdoor forest environments. Accurate placement of digital overlays is challenging owing to GPS drift, inconsistent lighting, dense canopies, and the need for environmental markers. As a result, many AR studies were limited to small-scale pilots or short demonstrations, in contrast to VR applications which could simulate entire forests from a desktop or lab setting. Nevertheless, the growing number of AR studies suggests an increasing research interest, with AR being viewed as the next frontier rather than a failed approach.

In parallel, hybrid MR applications, although rare, are emerging as a promising direction. These accounted for

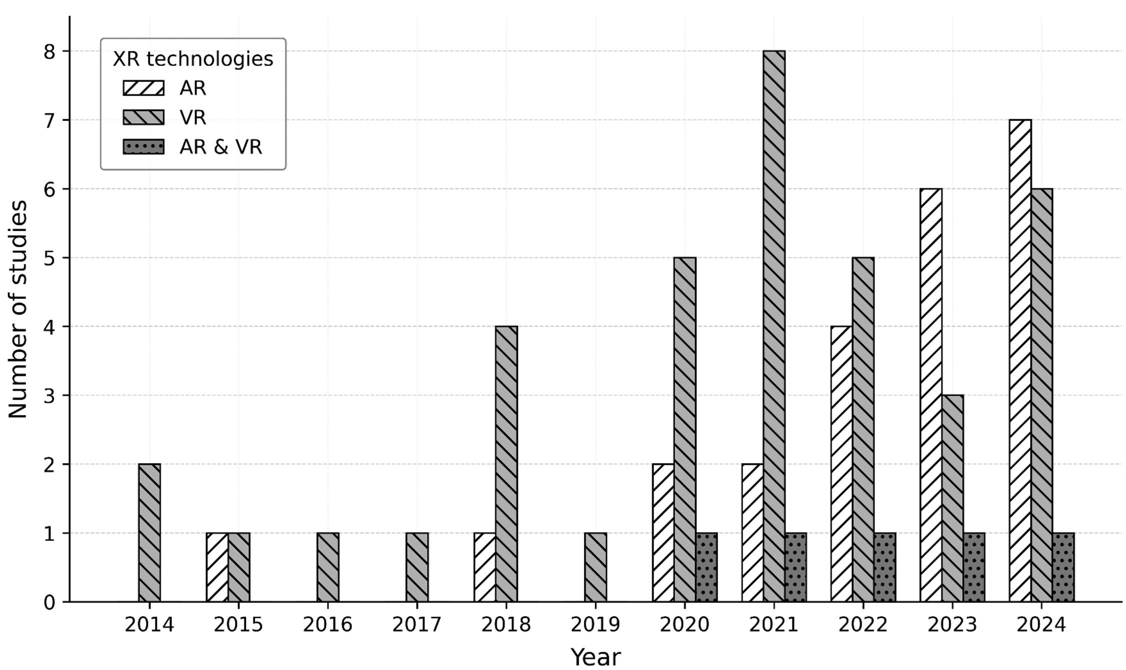

Figure 3. Use of XR modalities in forestry studies by year, 2014–2024.

roughly 5% of the studies, but showed the highest growth rate in 2023. The earliest example in our dataset dates to 2017, and more recent projects have explored an integrated workflow. For example, some studies have explored integrated workflows in which AR-based field data collection is combined with VR environments for subsequent collaborative analysis in office settings (de Miguel-Díez F and Purfürst 2025). As XR platforms evolve and unify AR and VR capabilities, such multimodal systems are becoming more feasible and may represent the future of immersive forestry tools, where planning is done in VR and operations are supported with AR in the field.

In summary, VR currently dominates AR in forestry applications by a ratio of approximately 3:1. VR's primary strengths, namely full immersion and complete control over environmental variables, have been effectively utilized for training simulators, planning tools, and visual impact assessments. In contrast, AR offers the advantage of situational context by overlaying digital information directly onto the real-world environment, making it particularly suited for in-field guidance. However, technical limitations such as challenges in accurate spatial alignment, GNSS inaccuracies under forest canopy, and difficulties in real-time data processing have constrained its adoption (Çöltekin et al. 2020; Döllner et al. 2023).

Despite this, AR is gaining traction as mobile devices and spatial computing technologies improve. Moreover, the emergence of integrated MR solutions, although these are still limited in number, suggests that in the future these modalities will be used complementarily rather than competitively, leveraging VR for off-site planning and training, and AR for real-time, on-site support. These findings align with observations in related fields, such as environmental education, where AR enables interactive learning in the field, while VR is employed for immersive conceptual understanding (Ladykova et al. 2024; Bajaj and Amin 2025). Each modality has a distinct role, and forestry research is increasingly exploring how to best combine them to maximize the impact.

Challenges of deploying XR in forest management and operations

Through our review of the studies' discussions and our word cloud analysis of frequent terms, we identified several key challenges associated with deploying XR in forestry. Table 1 presents a word cloud illustrating the most mentioned challenge-related terms in the literature. Prominent words include "realistic," "accurate," "data," "integration," "participant/user," and "environmental." These capture the crux of the difficulties, as we will now discuss.

Achieving realism and accuracy

Many studies have emphasized the difficulty of creating realistic and accurate virtual representations of forests, particularly due to the complexity of forest structure and data integration challenges (Fuller et al. 2020; Döllner et al. 2023; Murtiyoso et al. 2024). Forestry scenarios are inherently complex; a "realistic" simulation requires high-resolution terrain, detailed tree models, convincing physics for tree movement or cutting, and so forth. Both visual and functional realism are critical because the effectiveness of XR for training or decision-making depends on user trust. If the VR environment appears to be overly simplified or behaves unnaturally, trainees may not take it seriously or absorb the intended lessons. However, pushing for high fidelity quickly encounters technical limitations: rendering dense forest environments with thousands of trees and detailed foliage can strain even modern GPUs (graphics processing units). Similarly, in AR applications, accuracy is essential. Overlays must align precisely with real-world trees to be useful (e.g. an AR diameter indicator needs to attach to the correct tree). Achieving this level of precision, often at the centimeter scale, remains difficult in field conditions owing to GNSS error and sensor noise. Many studies have noted this accuracy issue as a key barrier to practical AR deployment. For instance, an AR tool for marking thinned trees may become ineffective or even hazardous if the holograms appear a meter off-target. Therefore, ensuring geospatial accuracy and visual realism remains a top technical priority in XR forestry applications.

Data volume and integration

The frequent appearance of the word "data" across the reviewed literature highlights the data-intensive nature of XR applications in forestry. Forests contain vast and complex datasets, including tree attributes, terrain models, and understory vegetation, which often originate from remote sensing techniques such as LiDAR (light detection and ranging), photogrammetry, or detailed field inventories. Integrating these heterogeneous data sources into

Table 1. Main challenges in XR forestry applications.

Challenge category	Specific challenge	Frequency (approx.)	Relative importance
Technical	Spatial accuracy and alignment	High	Very frequent
Technical	Data integration and interoperability	High	Very frequent
Technical	Realism of forest representation	High	Very frequent
Technical	Computational performance / large datasets	Medium	Frequent
Environmental	GNSS limitations under canopy	High	Very frequent
Environmental	Lighting conditions / visibility	Medium	Frequent
Environmental	Weather and outdoor robustness	Medium	Frequent
Environmental	Connectivity in remote areas	High	Very frequent
Human factors	Usability and user acceptance	High	Very frequent
Human factors	Ergonomics and device comfort	Medium	Frequent
Human factors	Training requirements	Medium	Frequent
Economic / operational	Cost of hardware and implementation	Medium	Frequent

Note. Frequency (approx.) indicates the relative recurrence of the challenge across the 65 included studies during qualitative synthesis. Relative importance reflects the prominence of the theme in the reviewed studies; it is a qualitative descriptor, not a statistical weight or effect size.

a cohesive virtual environment is not a trivial matter and far from straightforward. Several studies (e.g. Murtiyoso et al. 2024) have highlighted the difficulty of integrating heterogeneous 3D data sources, such as point clouds, polygonal meshes, and GIS layers, into a cohesive virtual forest environment. This process often requires custom software development, as off-the-shelf tools are rarely capable of seamlessly merging these formats. Even after integration, rendering and processing such data in real time remains a significant technical hurdle. Large point clouds or GIS datasets often exceed the capabilities of mobile AR devices or standard VR systems unless the data are heavily optimized or simplified. In many cases, developers have used generalized or representative tree models to reduce computational load – although this again affects realism and user experience. Another major issue is data interoperability. Ensuring that forest inventory databases can communicate with visualization engines, or that decision support models can dynamically feed into a VR scenario, is a major technical challenge. Without common data standards, many XR forestry applications are still one-off prototypes, hardcoded for specific datasets and environments. This limitation highlights the growing need for standardized frameworks or digital twin architectures, where real-world forest data can continuously synchronize with a virtual counterpart (Fuller et al. 2020; Buonocore et al. 2022).

Environmental constraints

The terms "environmental" and "natural" in the word cloud reflect the inherent difficulties of deploying XR technologies in outdoor forest settings. Unlike controlled indoor environments, forests have uneven terrain, physical obstacles, and a lack of reliable power or internet connectivity. Many studies piloting AR in real forest conditions reported issues such as device screens becoming unreadable in bright sunlight, reduced performance in rain or cold, and canopy cover disrupting the accuracy of tracking systems like camera-based SLAM (simultaneous localization and mapping) or GNSS (Lopatin et al. 2023). Users also faced ergonomic challenges: holding and operating a device while navigating rugged terrain can be physically demanding. AR applications that perform well in controlled or open environments may fail in dense forest conditions, where poor lighting and featureless vegetation structures can disrupt tracking and spatial alignment (Çöltekin et al. 2020; Döllner et al. 2023). To address these challenges, XR hardware for forestry must be adapted to withstand harsh outdoor conditions. Improvements such as brighter displays, waterproof casings, extended battery life, and hands-free operation (e.g. headsets and wearable devices) are often necessary (Çöltekin et al. 2020; Döllner et al. 2023; Hancko et al. 2025). In summary, the outdoor context of forestry introduces environmental constraints that are not typically encountered in other XR application areas, which demands more robust and context-specific solutions.

User experience and engagement

The frequent appearance of terms like "participant," "user," and "engagement" highlights the human-factor challenges associated with XR in forestry. Even when the technology functions as intended, its success ultimately depends on whether users – be they foresters, field workers, or students – can and will operate it effectively. Several user studies have reported issues such as motion sickness in VR, discomfort from prolonged headset use, and difficulties with interface interaction, particularly among users unfamiliar with immersive technologies (Mercan and Selçuk 2024; de Miguel-Díez F and Purfürst 2025). These challenges are especially relevant in forestry contexts, where users operate in physically demanding environments and require intuitive and reliable systems. In addition, studies have highlighted that user acceptance depends strongly on usability, ergonomics, and training requirements, which can significantly influence the adoption of XR technologies in practice (Çöltekin et al. 2020; Schneider et al. 2023). If an XR system is too complex, is not intuitive, or causes fatigue, users may abandon it. Engagement is especially critical in training applications; low engagement often results in poor learning outcomes. In fact, some VR training studies limit sessions to just 15–20 minutes owing to user fatigue or boredom. A review of XR in forest education (Mercan and Selçuk 2024) found that many apps lacked long-term engagement data; it is often assumed that novelty alone guarantees interest, but sustained engagement remains unproven. User acceptance also depends on mindset and culture; those working in forestry, which is a traditional and conservative industry, may resist new tools unless they clearly improve safety, efficiency, or usability. An interview-based study in Germany (de Miguel-Díez F and Purfürst 2025) reported skepticism among some forestry professionals; while they acknowledged the potential of AR for hazard detection and real-time mapping, they stressed the need for seamless functionality. In demanding and high-risk environments, technology must "just work." Therefore, making design human-centered, including through intuitive interfaces, ergonomic hardware, and proper user training, is just as critical as technical performance in determining XR's real-world viability.

Beyond general usability concerns, recent research highlights the importance of accessibility and inclusivity in the design of technologies deployed in complex outdoor environments such as forestry. While many XR studies focus on training effectiveness and user acceptance, fewer explicitly consider how diverse user groups – including individuals with varying physical abilities, levels of digital literacy, and operational experience – interact with such systems.

Insights from related domains, particularly human – robot interaction in forestry, provide valuable parallels. For example, Ehrlich-Sommer et al. (2025) demonstrate that effective deployment of robotic systems in forest environments requires not only technical performance but also accessibility, adaptability, and consideration of heterogeneous user needs. Their findings emphasize that usability must extend beyond basic interaction efficiency to include universal access principles and inclusive design approaches.

These insights are directly relevant to XR technologies, which face similar challenges in ergonomics, environmental constraints, and user diversity. Consequently, XR systems for forestry should be designed using human-centered and inclusive design principles to ensure usability across diverse operational contexts and user groups.

In summary, the challenges of implementing XR in forestry fall into three overlapping domains: technical (e.g. realism, spatial accuracy, data handling and integration); environmental (adapting technology for use in forest conditions); and human (ensuring usability, comfort, and use acceptance). These challenges apply to both VR and AR technologies, although they manifest differently depending on the context. VR applications are primarily affected by issues related to realism, rendering performance, and user experience, whereas AR systems face additional constraints related to spatial alignment, environmental conditions, and field deployment. These findings align with observations in related fields; for example, a review of XR in spatial sciences by Çöltekin et al. (2020) similarly identified alignment accuracy and hardware limitations as key barriers to outdoor AR. Overcoming these challenges is essential if we are to move XR beyond small-scale pilots and into widespread forestry practice. Encouragingly, awareness of these issues appears to be high within the research community, with many studies explicitly acknowledging them. This is a critical first step toward developing effective, scalable solutions (Çöltekin et al. 2020; Döllner et al. 2023; Reis and Câmara 2023; Murtiyoso et al. 2024).

Dominant tools and platforms for XR in forest management and operations

Analyzing the technologies employed across the studies, we identified common patterns in the hardware and software platforms used for XR implementations in forestry. Table 2 presents a word cloud of the most frequently mentioned tools, devices, and software. Notable entries include game engines such as Unity and Unreal Engine, VR headsets like Oculus (now Meta Quest) and HTC Vive, mobile platforms (Android), and peripherals like drones (DJI) and 3D sensing devices. These tools form the technical foundation for most XR applications reviewed, reflecting a convergence around accessible and widely supported XR ecosystems.

Game engines

Unity emerged as the most widely used development platform for creating forestry XR applications, a predictable choice given its popularity in academia and independent software development (Çöltekin et al. 2020; Murtiyoso et al. 2024). Unity provides a flexible 3D environment and strong support for both VR and AR through its extensive ecosystem of libraries and toolkits. As a result, many studies leveraged Unity to build custom VR forest simulations and field-based AR apps. Unreal Engine also appeared, though less frequently, primarily in projects requiring high-fidelity visual, such as realistic forest visualizations intended for public outreach, thanks to its advanced rendering capabilities (Döllner et al. 2023). The prominence of game engines in XR forestry demonstrates that researchers favor existing, robust graphics and physics engines over building systems from scratch. This approach not only accelerates development but also ensures that forestry tools benefit from ongoing improvements in VR/AR integration, platform compatibility, and community-developed plugins (Çöltekin et al. 2020; Döllner et al. 2023; Murtiyoso et al. 2024).

VR headsets

Oculus (now Meta Quest) and HTC Vive emerged as the most used VR hardware in forestry XR studies. Earlier research (pre-2016) used older or more specialized systems, such as CAVE (cave automatic virtual environments) or custom-built simulators. However, beginning in 2016, the Oculus Rift, and later the standalone Quest, became the dominant platforms for immersive forestry simulations. Also widely adopted were HTC Vive and Vive Pro, particularly in studies requiring room-scale tracking. Several papers noted the use of Vive's Lighthouse tracking system to achieve high-precision spatial tracking in lab-based setups. These devices offer relatively affordable, accessible, and well-supported VR solutions, making them attractive to forestry researchers. A few studies experimented with low-cost smartphone-based VR platforms such as Google Cardboard or Gear VR, although these were rare and typically served as proof-of-concept demonstrations. The dominance of Oculus and Vive indicates that forestry research leveraged the rapid evolution of gaming industry hardware, benefiting from improvements in display quality, field of view, and user comfort. However, these headsets are designed primarily for indoor environments, requiring either PC tethering (Rift/Vive) or limited onboard computing (Quest). As a result, VR applications in forestry have largely remained confined to offices, labs, and classrooms rather than being deployed in the field (Çöltekin et al. 2020; Döllner et al. 2023; Murtiyoso et al. 2024).

Table 2. Common tools and technologies used in XR forestry.

Category	Tool / Technology	Frequency (approx.)	Notes
Game engines	Unity	High	Most widely used platform
Game engines	Unreal Engine	Medium	Used for high-fidelity visualization
VR headsets	Oculus / Meta Quest	High	Dominant VR device
VR headsets	HTC Vive	High	Common in lab setups
AR platforms and devices	Android (ARCore)	High	Most common AR platform
AR platforms and devices	iOS (ARKit)	Medium	Widely used but less frequent
AR hardware and devices	Microsoft HoloLens	Low–Medium	Limited by cost and outdoor usability
Data acquisition and sensing tools	UAVs (DJI drones)	High	Key source of 3D data
Sensors	LiDAR	High	Critical for forest modeling
Software and modeling tools	GIS software	Medium	Base data preparation
Software and modeling tools	SketchUp / 3D modeling tools	Medium	Used for object creation
Media tools	360° cameras (e.g. GoPro)	Low–Medium	Training environments

Note. Frequency (approx.) indicates the relative recurrence of the tool or technology across the 65 included studies. The categories are qualitative summaries rather than exact counts.

AR platforms and devices

In the reviewed studies, Android-based mobile devices emerged as the most common hardware platform for AR applications in forestry. Many AR implementations in our review were developed as tablet or smartphone apps using ARCore (Android) or ARKit (iOS) frameworks. Android devices seemed a bit more common, likely owing to easier customization and a variety of hardware options, including rugged tablets. Also used were iPads and iPhones, particularly in applications leveraging ARKit's precise tracking capabilities on Apple's A-series chips, but the word cloud data showed "Android" as the most frequently mentioned, suggesting slightly greater share overall. Standalone AR headsets, especially the Microsoft HoloLens, were used in a limited number of studies, primarily where hands-free operation was essential during forest tasks. These studies explored overlaying holographic labels on trees or navigation lines on forest terrain using HoloLens 2. The HoloLens offers true see-through AR with spatial mapping, but its adoption was constrained by high cost and outdoor usability issues (e.g. glare and weather sensitivity). One study in Germany (de Miguel-Díez F and Purfürst 2025) addressed this by using a custom outdoor visor, demonstrating that such high-end AR devices can be viable in forestry when modified for field conditions. Overall, however, mobile devices remain the dominant hardware for AR in forestry owing to their accessibility, ease of deployment, and compatibility with existing workflows.

Parallel research on human – robot collaboration in forestry further reinforces these findings. For example, Schraick et al. (2024) demonstrated, using the System Usability Scale (SUS), that the effective deployment of collaborative robotic systems in simulated forestry environments depends strongly on human-centered design and accessibility considerations. These results highlight that, similarly to XR technologies, ensuring usability, ergonomics, and universal access is critical for the successful integration of intelligent systems in complex outdoor operations.

Data-acquisition and sensing tools

Peripheral technologies such as drones and action cameras played a supporting role in many XR workflows. The term "DJI" (Da-Jiang Innovations, e.g. the Phantom or Mavic series) frequently appeared, reflecting the use of drones to collect input data, such as imagery, video, or LiDAR scans, for generating XR content. For example, some studies used drone-captured imagery to generate 3D models via photogrammetry, which were then visualized in VR. Others integrated live drone feeds into VR environments for remote monitoring of forest areas. The mention of GoPro indicates the use of action cameras, likely to produce 360-degree training videos or ground-level footage for VR playback. This technique was especially useful in creating immersive training environments without the complexity of full 3D modeling. For example, some studies recorded forest operations using 360-degree cameras, which trainees later experienced in VR headsets (Tarng and Hsu 2024). Also central to several XR applications, although not explicitly named in the word cloud, were LiDAR sensors, with mobile and backpack-mounted LiDAR systems used to generate point clouds for forests visualization. These peripheral tools collectively enhanced the realism and context of XR environments in forestry.

Software and modeling tools

The word cloud also highlights the use of tools such as Photoshop and SketchUp, which were commonly used for digital content creation. Photoshop was typically used for editing textures or panorama images, while SketchUp was used to create 3D models, for example simplified representations of trees, buildings, or equipment for use in VR simulations. This reveals that developing forestry XR applications requires not only coding and data integration but also a significant amount of visual and interface design work. Some forestry VR applications used existing 3D models of machinery or terrain, but in many cases custom modeling was necessary, such as designing a specific forest machine or creating a virtual forest cabin. SketchUp, known for its user-friendly interface, was a popular choice for these tasks when high-end modeling tools were unnecessary. Additionally, GIS software was sometimes employed to generate base maps or terrain data, which were then imported into game engines like Unity to serve as geospatially accurate backdrops for the XR environment.

Toolkit summary

The XR toolkit in forestry largely leverages commercial off-the-shelf technologies: mainstream VR headsets, widely available mobile devices for AR, popular game engines like Unity and Unreal Engine for development, and standard peripherals such as drones and 3D scanners for data capture. This offers a clear advantage because researchers and practitioners can build immersive applications using the same hardware and software tools used in the gaming and tech industries, benefiting from extensive documentation and a robust support ecosystem. However, these tools are not designed specifically for forestry, which means that extra effort is required to adapt them to rugged outdoor conditions or large-scale forest datasets. For example, rendering a Unity scene with 10 million trees presents unique challenges. The dominance of certain platforms also has implications for standardization: it facilitates knowledge sharing, method replications, and even code reuse. As XR adoption continues to expand in forestry, we might see more forestry-specific tools emerge, but for now the community is wisely capitalizing on the momentum of general XR technology advances.

Location and scale of XR studies in forest management and operations

Our review also examined the geographic distribution of XR studies in forestry, and the spatial scale at which these applications were implemented, ranging from individual trees to forest stands, landscapes, or purely virtual environment. These aspects provide context for understanding both the global uptake of XR technologies and the typical operational and research settings for XR applications.

Geographical distribution

Figure 4 shows that XR forestry research is geographically uneven. China accounted for the largest share of included studies, followed by the United States, while several European countries and New Zealand contributed smaller numbers. The pattern suggests that XR research in forestry is currently concentrated in countries with strong digital-technology research capacity and active forestry or environmental-technology programs. We interpret the implications of this distribution in the Discussion rather than treating country counts as a direct measure of forestry-sector need or forest area.

It is noteworthy that some countries with large forest areas, such as Brazil, Canada and Russia, had few XR-related studies represented in our review. While the focus of this review is on forestry applications, a small number of studies from closely related domains such as agriculture were included where they address XR technologies in contexts directly transferable to forestry, particularly in terms of spatial data visualization, field-based interaction, or environmental monitoring. This may suggest that XR research is not yet a major focus within their forestry sectors. The observed pattern indicates that the geographic distribution of XR research in forestry correlates more strongly with technological infrastructure and research funding than with forest extent. As discussed later, this highlights an opportunity and a clear need for more international collaboration to help transfer XR expertise and tools to countries with vast forests but limited digital capacity. Such efforts would ensure that the benefits of XR innovations can be more equitably distributed, supporting sustainable forest management on a global scale.

Spatial scale of applications

Figure 5 categorizes the reviewed studies based on the spatial scale of their XR application: individual tree level, forest stand level (or small plots), landscape level (outdoor settings), or completely virtual environments representing forest scenarios. Most of the studies, approximately 58.3%, focused on virtual environments that simulated forests. This category includes all VR-based simulations, whether depicting a single stand or an entire fictional forest, and reflects that many projects opted to create a virtual representation of forest areas rather than augmenting the real-world forest directly. The preference for virtual environments reflects both practical and technical considerations. VR allows for full immersion without the constraints of field conditions, such as weather, terrain, or connectivity issues. These simulations were commonly used for training, scenario analysis, and/or visualization, offering a controlled and repeatable setting for engaging with complex forest systems.

About 16.7% of the reviewed studies operated at the landscape scale using AR technologies. In these cases, AR was used to overlay information across broad spatial extents, for example visualizing forest health data from an elevated position, or through urban forestry AR applications in parks. Notably, this category may also include studies where the user does not physically traverse the landscape but the AR content represents landscape-level data (e.g. viewing a holographic 3D terrain model of a forested region on a tabletop using an AR device). The defining characteristic of this category is the scope of the content, not necessarily the user's physical movement. Unlike tree- or stand-level applications, these scenarios focus on broad spatial representation, providing a macroscopic view of forest systems or management scenarios.

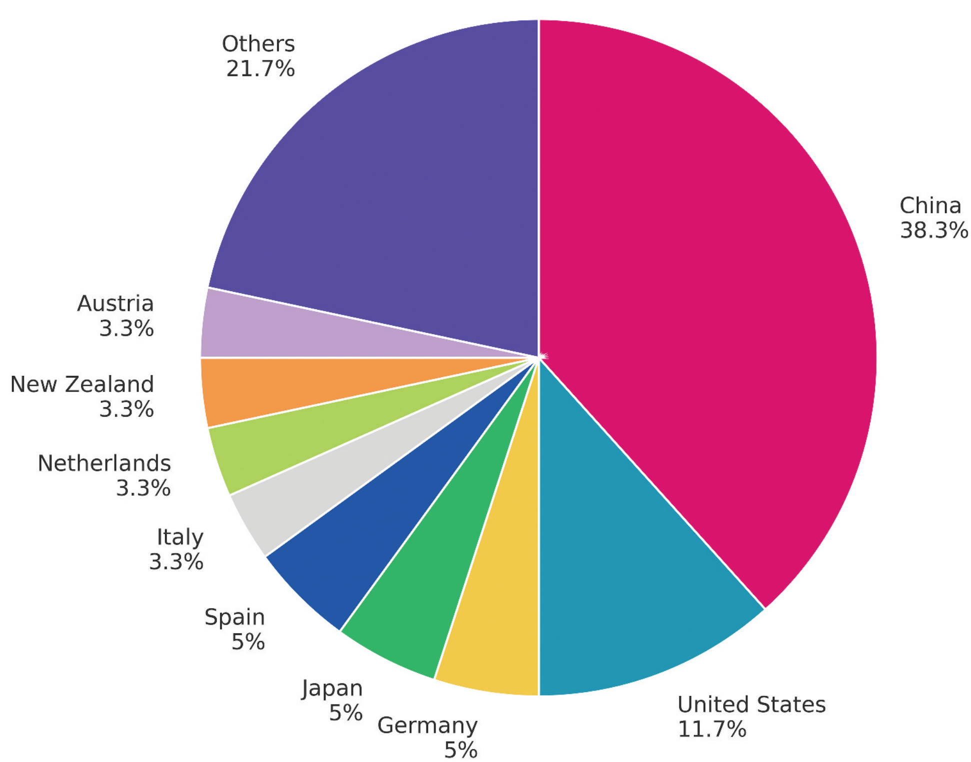

Figure 4. Geographic distribution of included XR forestry studies by country or study population.

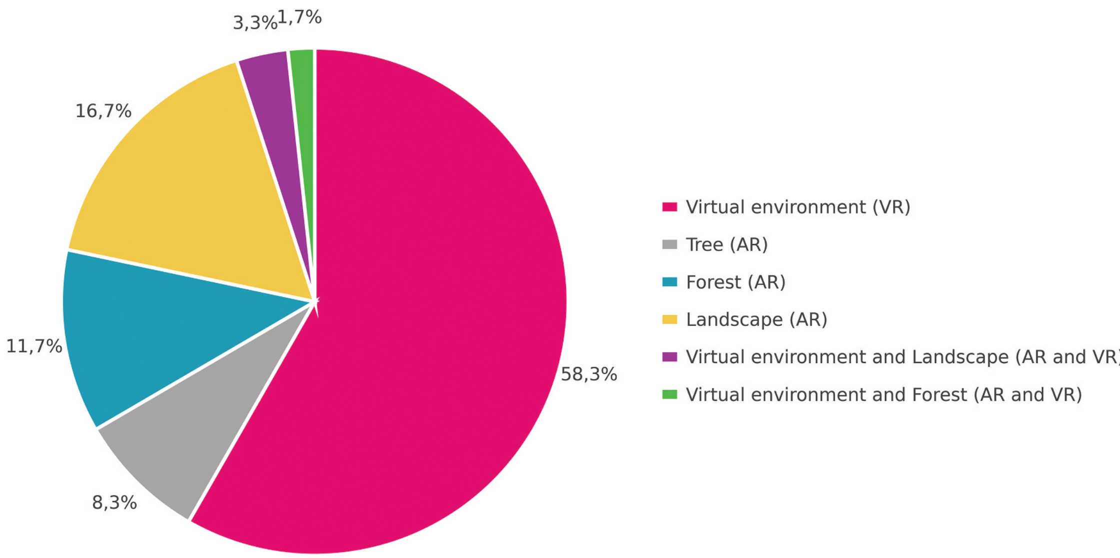

Figure 5. Spatial and operational scale of XR applications in the reviewed forestry studies.

Approximately 11.7% of the studies focused on forest-level AR in the sense of directly augmenting real forest stands. These were on-site AR applications, where users in a forest environment viewed digital overlays projected onto their physical surroundings, for example marking selected trees for harvest using AR tags that were visible through a tablet or headset. The relatively small proportion of studies in this category highlights the ongoing technical and practical challenges of deploying AR in field conditions.

Only around 8.3% of studies focused on individual tree-level AR. These applications typically involve pointing a device at a single tree to display its attributes, such as species, height, or ID number, in real time. While several studies demonstrated this functionality (e.g. for tree identification or measurement), most were technical demonstrations or prototypes rather than fully operational systems. This limited adoption reflects the challenges of reliably recognizing individual trees in the field and aligning AR content with sufficient accuracy for meaningful use.

Finally, approximately 5% of the studies were categorized as hybrid environments, combining both AR and VR elements within a single workflow. For example, one study overlaid a simulated wildfire (virtual) onto the view of a real forest to train firefighters, creating an immersive, MR training scenario. Another example involved using VR for planning or simulation phases and AR for real-time field execution, combining the strengths of both modalities. While this hybrid approach is quite rare (hence only 5%), it reflects a cutting-edge direction in XR forestry research, demonstrating novel experimentation and the potential for more integrated solutions in the future.

In practical terms, the predominance of virtual simulations (VR) and large-scale AR indicates that researchers often begin with broad approaches, either creating fully virtual forests or augmenting landscape-level data, rather than focusing on fine-grained, tree-level AR. As noted earlier, creating reliable AR at the single-tree scale is technically challenging, which helps to explain the relatively small number of such studies. Those that did attempt it, such as mobile AR apps for measuring tree height using the phone's camera, were largely proof-of-concept demonstrations aimed at showcasing feasibility. As computer vision and spatial mapping algorithms continue to advance, particularly for trunk detection and automatic alignment, we can expect more tree-level AR applications to emerge. Meanwhile, VR allows researchers to leap directly to *landscape-scale* representations, since rendering a virtual forest is limited only by computing power, not by physical constraints like terrain or mobility. This flexibility helps to explain why more than half of the reviewed studies focused on forest environments, albeit in virtual form.

The geographic and spatial scale findings together suggest a clear pattern: high-tech countries are primarily using XR to simulate forests virtually, developing and testing applications in controlled environments, before gradually transitioning these solutions into real-world forests at smaller scales. Looking ahead, it will be interesting to see whether the next five years bring a shift toward more widespread, on-the-ground AR use in operational forestry, potentially expanding to a broader range of countries. Our data suggest that the concept of "virtual forests" is currently more developed than that of "augmented forests." In other words, it is more common for users to interact with a forest's digital twin in VR (Tagarakis et al. 2024) than to engage with the physical forest through AR interfaces. This aligns with observations by Murtiyoso et al. (2024), who note that the immersive technologies that are gaining traction remain largely those that are confined to controlled or experimental settings. As XR technologies mature, bridging this gap and bringing robust, field-ready XR tools into real forest environments will likely become a major focus of future research and development.

Discussion

Interpretation of key findings

Our review shows a clear and accelerating adoption of XR technologies in forestry research, particularly since 2019. The sharp increase in studies (Figure 2) suggests that XR has evolved from a niche technology to a recognized tool within the field. This surge aligns with the broader trend of digitalization in forestry and natural resource management (Murtiyoso et al. 2024). VR dominates the landscape, appearing in roughly 72% of studies, compared to about 23% for AR. This imbalance highlights how forestry researchers have thus far engaged with immersive technologies. The appeal of VR lies in its practicality: it enables fully controlled training and simulation environments, such as harvester simulators or virtual forest walks, without the constraints of field conditions. These indoor settings help overcome common technical barriers like unreliable internet or GNSS signals in forested areas. Accordingly, early XR adoption in forestry has largely focused on off-site applications, especially for training and visualization. VR-based tools for forest machine operator training or silvicultural planning exemplify this trend.

In contrast, AR's smaller share in the literature does not suggest lesser value but rather highlights the technical challenges of deploying XR in real-world forest environments, a point echoed by many studies and discussed in our Results section on challenges. Unlike VR, AR must seamlessly integrate digital content with dynamic and often complex outdoor settings. This involves difficulties such as accurate georegistration of holograms on uneven terrain, occlusion by trees, variable lighting conditions, and the need for lightweight, field-ready hardware. As a result, most AR implementations, typically via mobile devices, were limited to small-scale demonstrations or early-stage prototypes. MR, or combined AR+VR approaches, accounted for only about 5% of studies, reflecting the compounded technical demands of blending real and virtual elements in situ. These findings align with prior observations (e.g. Çöltekin et al. 2020), which emphasize that while outdoor AR faces significant hurdles, its potential to overlay actionable data onto forest environments remains compelling (Murtiyoso et al. 2024).

The synthesis of reported challenges across the reviewed studies suggests that bottlenecks to XR adoption in forestry are not solely technological but also data-related and human-centered. Frequent terms such as "realistic," "accurate," and "simulation" reveal a central concern: how to achieve sufficient realism and accuracy in virtual representations of forests. This is critical because forestry decisions, such as estimating timber volume or assessing fire risk, depend on how faithfully a system mirrors the forest's complex natural conditions. Many studies reported difficulty in striking the balance between simplicity and realism: models that are too simplistic compromise training value, while highly realistic simulations demand intensive data (e.g. high-resolution LiDAR scans) and significant computing resources. Handling such large, heterogeneous environmental datasets emerged as a recurring obstacle, with "data" standing out prominently in the word cloud. Forest ecosystems are inherently data-rich, with each tree carrying numerous attributes, and landscapes varying greatly; integrating this complexity into XR systems continues to push current hardware and software to their limits. Our findings align with Murtiyoso et al. (2024), who emphasized that as the use of geospatially faithful 3D data in forestry increases, one of the major challenges lies in integrating diverse data sources into a coherent system while managing the associated computational load. Like us, they note that achieving interoperability between technologies and data types is essential for building a truly "virtual forest system."

Another key theme concerns the human factor. Words such as "participant," "user," and "engagement" appeared frequently in the challenge texts, highlighting that, beyond technical performance, user experience and training effectiveness remain central concerns. For XR tools to make a meaningful impact in forestry, they must not only function reliably but also be accepted and actively used by professionals and students. Several studies reported obstacles such as motion sickness in VR, ergonomic discomfort with headsets, or steep learning curves associated with AR applications in the field. High user engagement, coupled with demonstrable learning or productivity outcomes, is essential if XR is to transition from laboratory experiments into routine forestry operations. For instance, in training contexts, an XR system can be considered effective only if it sustains immersion and results in better knowledge or skill retention compared to traditional methods. While many of the reviewed simulation studies emphasized improved safety or learning outcomes, relatively few included long-term evaluations or comparative trials, leaving a notable gap in evidence regarding real-world effectiveness. In summary, the efficacy of XR in forestry, whether in learning, decision support, or operational efficiency, requires continual validation.

Lastly, our interpretation of the geographic and application-scale findings reveals a noteworthy mismatch: the most active countries in XR forestry research tend to be those with strong research and development (R&D) infrastructures and technology sectors, rather than those with the largest forest resources. This suggests that XR research activity is driven more by investment capacity and technological ecosystems than by the immediate forestry needs of individual countries. For example, China accounts for just over 38% of studies, likely reflecting substantial investment in digital innovation and national interest in emerging technologies, despite its moderate proportion of forest cover. Similarly, the United States and Germany stand out owing to their well-established research communities and funding frameworks. In contrast, countries with vast forest resources, such as Brazil, Canada, Russia, and Indonesia, appear less frequently in our dataset, possibly owing to having fewer XR-focused projects or limited publication output in English in this domain. This absence does not diminish the potential value of XR for these regions; rather, it underscores the need for global collaboration and knowledge transfer to ensure that XR innovations support forestry worldwide. We interpret this as a call for outreach: researchers and developers in leading countries should actively pursue partnerships and pilot projects in forest-rich regions, testing XR applications under diverse ecological and operational conditions (e.g. tropical forests, boreal landscapes). Such efforts would not only validate XR technologies across contexts but also ensure that their benefits extend beyond high-tech hubs to the broader global forestry community.

In terms of spatial scale, most studies favored fully virtual forests or landscape-level AR over tree- or stand-level AR in real forests. This pattern reflects feasibility: creating entire virtual forest environments on a computer is, in many respects, simpler than augmenting actual forest sites with live digital overlays, which requires robust field hardware and real-time data integration. Notably, only about 8% of studies explored individual-tree AR, for example displaying tree attributes such as species or height via a tablet or headset. These few efforts often faced challenges related to overlay stability, interface usability, and ergonomics when applied in uneven terrain. By contrast, landscape-level AR (16.7%) was more common, often in controlled contexts like urban parks or aerial perspectives, where conditions are less complex than dense forest environments. The relatively rare hybrid MR approaches (5%) stand out as an emerging frontier: they combine AR for field awareness with VR for phenomena not directly observable in real time (e.g. overlaying a simulated fire spread on an actual forest). While it is still a niche, we interpret this as a promising direction, likely to expand as field-stable hardware and MR platforms advance, offering a continuum between the fully real and the fully virtual in forestry applications.

In summary, XR in forestry is experiencing rapid growth, with VR leading adoption owing to its practical advantages, while AR is gradually expanding as technical challenges are addressed. The main constraints lie not only in technology but also in data management and user engagement. Across the reviewed studies, successful forestry-oriented XR applications were most often associated with a combination of sufficient realism, reliable data integration, and usable interfaces. Overall, XR in forestry remains in an experimental phase, with promising potential but many lessons still to be learned about what works best in the unique conditions of forest environments.

Lessons learned from reviewed studies

Across the diverse set of studies reviewed, several common lessons and best practices emerge regarding how XR can be effectively applied to forestry:

XR enhances precision and data visualization in forestry

A consistent finding is that XR platforms excel at integrating and displaying complex forest data in intuitive and interactive formats. Multiple studies highlighted that visualizing information from remote sensing, GIS, and field sensors within immersive 3D environments enables users, forest managers, researchers, and students to discern patterns and relationships that would be difficult to grasp from 2D maps or spreadsheets. For instance, Hartsch et al. (2021) integrated harvester production data into a VR environment to analyze wood supply chains, allowing users to virtually "step into" the data and identify operational bottlenecks. Similarly, Klippel et al. (2021) demonstrated how "embodied digital twins" can link geospatial datasets with VR, creating immersive experiences that strengthen comprehension of environmental information. The key lesson is that XR is not merely a technological novelty: when applied to spatially complex, multilayered forest information, such as stand structure, terrain, or habitat, XR can provide cognitively accessible visualizations that enhance both analysis and decision-making.

AR platforms integrate data from remote sensing, geographic information systems, and field sensors to generate interactive forest representations directly in the field (Hartsch et al. 2021; Klippel et al. 2021; Liu et al. 2024). In contrast, VR environments are used to simulate silvicultural treatments and assess environmental change under controlled conditions (Liu et al. 2024). Extended reality has also proven effective in communicating forest disturbances, such as insect outbreaks, to both specialists and wider audiences (Uusitalo and Orland 2001; Hartsch et al. 2021). Beyond visualization, XR supports automation through operator training and remote supervision (Asino et al. 2022; Mercan and Selçuk 2024), with training modules often tailored to specific equipment (Asino et al. 2022; Tarng and Hsu 2024).

Nevertheless, several challenges persist. Integrating diverse datasets into coherent XR systems remains a major technical hurdle (Hartsch et al. 2021; Liu et al. 2024), while issues with scalability to large, heterogeneous forests and cost barriers further limit deployment (Reis and Câmara 2023). User acceptance is another critical factor: overly complex interfaces can reduce usability and diminish the effectiveness of XR tools (Schneider et al. 2023). Looking ahead, wider adoption is likely as hardware is becoming more affordable and data integration is improving (Klippel et al. 2021; Reis and Câmara 2023). Importantly, XR shows particular promise in supporting collaborative decision-making (Uusitalo and Orland 2001; Reis and Câmara 2023) and in enhancing precision forest management by enabling the manipulation and analysis of ecological and operational data (Uusitalo and Orland 2001; Reis and Câmara 2023; Liu et al. 2024; Murtiyoso et al. 2024).

Simulation of forest operations and scenarios is a strong use-case

Some forestry schools already integrate VR-based training into curricula, preparing students with virtual practice before transitioning to fieldwork. More recently, Kaakkurivaara et al. (2025) evaluated the freely available Husqvarna Limberjack immersive VR platform for motor-manual tree delimbing and reported learning-curve improvements, further supporting the role of VR as a pre-field training aid for chainsaw work. The broader lesson is that VR simulations combine safety, repeatability, and long-term scenario visualization, making them powerful tools for both operator training and strategic forest management. A central lesson from the reviewed studies is that XR, particularly VR, is highly effective for simulating forestry operations and ecological processes. Many applications recreate tasks such as timber harvesting, tree planting, or firefighting, as well as natural dynamics like tree growth or fire spread, to support both training and planning. For example, Liu et al. (2024), developed VR scenarios to model silvicultural treatments, allowing forest managers to visualize how stands might evolve under different interventions (e.g. thinning vs. no thinning) over a decade. This "sandbox" approach enables experimentation with management decisions without real-world consequences. On the training side, XR modules for equipment operation (e.g. forwarders, chainsaws) have been developed (see Asino et al. 2022), providing risk-free, repeatable practice for tasks that are otherwise hazardous or resource-intensive. Mistakes such as dropping a log or felling a tree incorrectly become learning opportunities rather than costly accidents. Some forestry schools already integrate VR-based training into curricula, preparing students with virtual practice before transitioning to fieldwork. The broader lesson is that VR simulations combine safety, repeatability, and long-term scenario visualization, making them powerful tools for both operator training and strategic forest management.

Extended reality technologies can play a pivotal role in advancing sustainable forest management by enhancing visualization, communication, and collaboration. VR environments allow stakeholders to immerse themselves in forest landscapes and "experience" the potential impacts of management decisions before they are implemented (Uusitalo and Orland 2001; Schneider et al. 2023). This fosters mutual understanding and helps build consensus around contested management choices.

XR improves engagement and communication

A consistent lesson across the reviewed studies is that XR enhances engagement and improves how forestry concepts are communicated. Immersive environments provoke emotional and cognitive responses that raw data or static visuals cannot. Early research by Uusitalo and Orland (2001) showed that even basic VR visualizations helped stakeholders better grasp management plans. More recent work reinforces this: Tarng and Hsu (2024) demonstrated how a VR 360-degree system effectively raised awareness of Indigenous culture and environmental conservation. For public outreach, education, or stakeholder dialogue, XR can transform abstract scenarios into tangible experiences. Walking through a virtual forest affected by invasive pests, clear-cuts, or fuel treatments communicates impacts in ways that are visceral and memorable. The broader lesson is that XR is not just a training tool but also a powerful medium for communication and consensus-building. By making management outcomes visible and emotionally resonant, XR can foster greater awareness, stakeholder buy-in, and collaborative decision-making.

Integration challenges persist – data and interoperability need attention

Despite the successes, many studies flagged that integrating diverse datasets into XR is a major pain point (as discussed in the Results section on challenges). While XR in forestry shows promise, integrating diverse datasets remains one of the most consistent bottlenecks. Studies by Hartsch et al. (2021) and Liu et al. (2024) highlight the difficulty of merging forest inventory data, sensor streams, and simulation outputs into a single XR environment. Many projects underestimated the groundwork required for data preparation, cleaning, formatting, and simplifying, which often led to suboptimal performance or narrow applications. Looking ahead, several authors (e.g. Döllner et al. 2023; Reis and Câmara 2023) argue that XR will increasingly depend on digital twins and cloud-based data infrastructures. Achieving this vision, however, requires clear standards, such as consistent ways to represent a tree in a database, so that both a growth model and a VR visualization can seamlessly interpret the same data. The key lesson is pragmatic: developers must plan the data pipeline early and involve geomatics or information technology specialists from the outset. Without robust data integration and interoperability, even well-designed XR applications risk falling short of their potential.

Scalability and cost remain key barriers

These limitations are consistent with broader observations on digital forests and virtual forest systems, where data preparation, interoperability, rendering performance, and infrastructure costs are repeatedly identified as barriers to operational deployment (Döllner et al. 2023; Reis and Câmara 2023; Murtiyoso et al. 2024).

Many XR forestry studies demonstrate promising prototypes but struggle to scale them to operational levels. Applications that work in a 10-hectare pilot plot or with a limited feature set often require major adaptation to function across entire forest districts. Cost compounds the issue: high-end XR hardware and immersive training rigs remain expensive, and even VR setups with motion platforms can strain institutional budgets. Reis and Câmara (2023) emphasize that affordability remains a barrier to broader adoption. The lesson is pragmatic: prototypes often underestimate deployment costs and infrastructure needs. For XR to move from the lab into the forest, solutions must either be cost-effective or deliver clear returns on investment that justify the expense. Encouragingly, hardware costs are trending downward; the Meta Quest 2, for instance, brought advanced VR capabilities to market at a fraction of the earlier system prices. In the meantime, developers should plan budgets and infrastructure early, and consider low-cost alternatives, such as leveraging widely available smartphones for AR, to ensure accessibility in resource-limited forestry contexts.

Making design and training user-centered is crucial

Several studies highlighted that XR tools failed when end-user needs were overlooked. Projects that returned to the design stage and engaged users in iteration often saw improved adoption. For example, an early VR system required foresters to annotate trees through complex controller menus; after user feedback, it was redesigned into a simpler point-and-click interface. Schneider et al. (2023) underscored the importance of tailoring XR content to the audience, ensuring clarity and accessibility. The broader lesson is that XR in forestry should be problem-driven, focusing on user needs and workflows, rather than technology-driven experimentation. Training is equally essential; one study noted that forestry staff initially relied on researchers to operate AR devices because of unfamiliar interfaces. With structured training and more intuitive design, however, users adapted and internalized the tools. Neglecting this process risks XR systems being underused or abandoned.

In essence, the collective lessons from current research suggest that XR can bring substantial benefits to forestry by enhancing visualization, training, and stakeholder communication. However, realizing these benefits requires directly addressing integration and usability challenges. Successful case studies share a common pattern: they start by identifying a clear forestry problem (e.g. unsafe training, limited public understanding, inefficient data analysis) and then design an XR solution tailored to that need, rather than beginning with the technology in search of an application. When implemented thoughtfully, complementing rather than replacing the expertise of foresters, XR was reported positively in several reviewed studies when it complemented rather than replaced the expertise of foresters. By contrast, projects that introduce XR as a high-tech novelty without embedding it into workflows rarely advance beyond the prototype stage. These insights provide a foundation for our upcoming recommendations on future research and practical implementation.

Comparison to previous research

Since XR in forestry is still an emerging domain, prior reviews and related studies are limited, but those that exist reveal both similarities and contrasts with our findings. Our review aligns with observations (Ladykova et al. 2024; Bajaj and Amin 2025) from adjacent fields such as agriculture and environmental science, where VR has typically served as the entry point for immersive technologies, with AR adoption growing as hardware and software mature. For example, Murtiyoso et al. (2024), in their review on virtual forests, noted that screen-based visualization still dominates but "immersive techniques such as XR are gaining traction," consistent with our documented surge in XR studies after 2020. They also emphasized challenges in integrating diverse technologies and the transformative potential of "virtual forest systems" for stakeholder engagement, points echoed in our results, particularly regarding data integration and multi-stakeholder training. Moreover, Murtiyoso et al. (2024) highlighted the increasing role of AI in processing 3D forest data, which dovetails with our identification of emerging trends like AI-enhanced XR. Taken together, these findings reinforce a shared conclusion: while XR research in forestry is progressing rapidly, significant questions remain open, around standardization, interoperability, and practical implementation, and these need to be answered before its full potential can be realized.

Another relevant study is that by Choi et al. (2023), a systematic review focusing on XR technologies in forest education programs. Unlike our broad review across forestry operations, management, and training, Choi et al. (2023) found AR to be the dominant technology in education, most often implemented via mobile devices. This contrast is instructive: in educational contexts, AR's accessibility and interactivity, leveraging widely available smartphones and tablets, make it a natural fit for engaging students and the public. By contrast, our review shows VR to be more prevalent in professional forestry contexts, where immersive simulations (e.g. harvester cab environments or virtual thinning exercises) provide safe, repeatable training and decision-support scenarios. The divergence highlights that the "best" XR modality is use-case dependent: AR excels when real-world context and interactivity are central to learning, while VR excels in hazard-free training and replicating complex environments. Encouragingly, AR's success in education could pave the way for greater adoption in field operations once hardware becomes more common in the forestry workforce. Together, the two reviews suggest a complementary picture, with VR and AR each offering unique strengths, and hybrid applications potentially bridging the gap.

Comparing our geographic findings with broader technology diffusion literature, it is well established that early adoption clusters in economically developed or tech-focused regions. Our observation that China and the US dominate XR forestry publications aligns with their overall scientific output and heavy investments in XR and digital R&D (China's national digital leadership initiatives are a likely driver). Notably, we found no prior studies that analyze the geography of forestry tech adoption, making this a novel contribution of our review. A useful next step would be to compare this pattern with the geography of forestry research more generally. For instance, countries such as Finland, Sweden, and Canada traditionally lead in forest engineering and harvesting research, yet their lower XR presence may suggest a gap or a prioritization of other digital tools (e.g. simulators not framed as XR, GIS-based decision systems). This suggests untapped potential for a more globally distributed research landscape, ensuring that XR applications are tested in diverse forest contexts beyond high-tech hubs.

Our review's identified challenges align closely with those reported in the broader XR literature. In outdoor AR, for example, researchers such as Çöltekin et al. (2020) and Döllner et al. (2023) highlight the same problems of alignment accuracy, device limitations, and environmental interference. The consistency of these findings across domains underscores their urgency. (Murtiyoso et al. 2024) noted that forestry still lags behind sectors like construction and gaming in adopting new visualization technologies. Our data empirically confirm this: while interest has grown, the ~60–65 forestry-related XR studies published globally over the past decade are a modest contribution compared to the hundreds reported in manufacturing or medicine. This suggests that forestry is behind the adoption curve, likely owing to its unique challenges (high variability of outdoor environments, rugged conditions) and resource constraints, as forest agencies and companies often operate with tighter innovation budgets than automotive or defense sectors where XR has flourished. These findings reinforce arguments in prior literature that cross-sector learning is essential: forestry XR adoption could advance by adapting proven approaches from other industries, provided they are tailored to ecological data and field conditions (e.g. ruggedized hardware, forestry-specific visualization software).

Finally, when assessing effectiveness and outcomes, we found that relatively few studies rigorously measured the impact of XR on forestry tasks (e.g. quantifying gains in inventory accuracy with AR, or reductions in accidents through VR training). This mirrors a broader gap in the literature. For example, forestry simulator studies conducted before the time frame of our review suggested improved operator performance, but systematic evidence remains limited. The Choi et al. (2023) review of XR in education reported mostly positive cognitive and affective outcomes, which is encouraging, and our findings similarly noted anecdotal user feedback, such as participants feeling better prepared after VR training or describing AR tools as "helpful." However, only a few studies employed control groups or rigorous evaluation designs. Meta-analyses from general education and training fields indicate that XR can enhance learning retention and engagement, but only when it is well-designed. Compared to other engineering domains where the return on investment (ROI) of XR has been examined, forestry lacks robust data. This underscores a clear research need: future studies must evaluate XR's benefits quantitatively in operational forestry settings, moving beyond prototypes to demonstrate measurable outcomes.

In summary, our review aligns with the few existing syntheses: XR use in forestry is expanding but remains modest compared to its potential, with VR currently outpacing AR in research applications. Persistent challenges, particularly data handling, system integration, and user acceptance, are evident across studies. We add value to the discourse by providing detailed quantitative insights and shedding light on underexplored dimensions, such as the geographic distribution of XR research and the breakdown of application scales. Our findings complement focused reviews like Choi et al. (2023) by situating them within a broader operational and research context. The overall message is consistent: XR tools must be refined, scaled, and rigorously tested if they are to progress from being experimental prototypes to taking their place as practical, everyday instruments in forestry.

Limitations of reviewed studies

The limitations summarized below were reported across multiple strands of the reviewed literature, especially studies dealing with user evaluation, outdoor AR deployment, data integration, and XR-based training (Çöltekin et al. 2020; Choi et al. 2023; Murtiyoso et al. 2024; de Miguel-Díez F and Purfürst 2025; Ehrlich-Sommer et al. 2025).

While our review highlights many promising developments, it is important to acknowledge the limitations present in the body of literature we analyzed. These limitations temper the conclusions we can draw and point to areas where the evidence is still weak or incomplete. Several common limitations of the reviewed studies are now discussed.

(1) *Limited sample sizes and short study durations*: A large share of empirical evaluations involved very small participant groups, sometimes fewer than 10 individuals, and often relied on forestry students or researchers rather than professional end-users. Evaluations typically covered a single short session, without longitudinal follow-up. As a result, claims that XR improves learning, safety, or decision-making are based on preliminary, short-term evidence. The long-term retention of skills and the sustained adoption of XR tools in operational forestry remain untested.

(2) *Prototype and simulation bias*: Most works can be classified as prototypes or proof-of-concept simulations, designed primarily to show feasibility. These projects often demonstrated that "XR can be applied to forestry," but rarely measured whether it outperformed conventional methods. Publication bias also likely plays a role, as unsuccessful or less impressive trials are less frequently reported. Consequently, the literature may present an overly optimistic view, with limited critical assessment of XR's actual advantages or drawbacks in forestry practice.

(3) *Hardware constraints and environmental validity*: Older studies (2014–2018) frequently reported severe device limitations, such as poor tracking, narrow fields of view, and brightness problems, which constrained outdoor usability. Although more recent hardware has improved, significant issues remain: limited battery life in remote conditions, headset discomfort during prolonged use, and dependence on internet or GPS signals that are unreliable in dense forests. Furthermore, most trials occurred in relatively controlled or "clean" stands. Few studies tested XR in more challenging environments (e.g. steep terrain, dense undergrowth, extreme weather), leaving questions about operational robustness unresolved.

(4) *Usability and human factors remaining underexplored*: Although many studies claimed that their applications were "user-friendly," few conducted systematic usability testing with forestry professionals. Ergonomic concerns such as motion sickness, headset fatigue, or difficulties using AR devices while wearing gloves were seldom addressed. Moreover, reliance on students or researchers as test subjects may have inflated acceptance, since they are typically more open to new technologies than older or less tech-savvy forestry workers. Understanding how XR fits into real work processes, and whether users find it efficient, safe, and comfortable, remains an underdeveloped area.

(5) *Lack of standard metrics and comparative baselines*: Success indicators varied widely across studies, ranging from subjective satisfaction ratings to task completion times and accuracy measures. This heterogeneity makes it difficult to compare results or conduct meta-analyses. More critically, almost no studies compared XR approaches against established forestry practices in a controlled manner. Without such benchmarks, it is unclear whether XR solutions genuinely offer improvements in efficiency, accuracy, and/or cost-effectiveness.

(6) *Geographical and topical gaps*: Research is clustered in technologically advanced regions (e.g. China, the US, Germany), while countries with large forest resources (e.g. Brazil, Canada, Russia, Indonesia) are underrepresented. Topically, most XR studies focus on training, education, or inventory visualization. Very few address pressing forestry challenges such as climate adaptation, pest and disease monitoring, or participatory forest governance. Similarly, tropical forestry applications are almost absent, despite unique ecological conditions that might particularly benefit from XR visualization tools.

(7) *Inconsistent reporting quality*: Finally, reporting standards vary greatly. Some conference papers omitted basic details such as sample sizes, participant demographics, or the specific hardware and software used. This inconsistency undermines reproducibility and limits the ability of future researchers to build upon prior work. The field would benefit from adopting clearer reporting guidelines, similar to those used in medical XR studies.

Given these limitations, the overall picture is that evidence for XR in forestry remains tentative. Many projects demonstrate that "it works in principle," but not yet that "it works better than existing methods, at scale, with full end-user adoption." This is typical for a nascent field, where early efforts focus on feasibility, and broader validation comes later. Recognizing these gaps is essential so that future research can design larger studies, include control groups, test systems under varied forest conditions, and report outcomes more transparently.

A limitation of our own review should also be noted: because our scope included studies up to 2024, we may not fully capture the very latest developments. The XR landscape is evolving rapidly; new hardware (e.g. Apple's Vision Pro) and emerging software frameworks could significantly alter the possibilities for forestry applications within just a year. While we have aimed for comprehensive coverage up to our cutoff, readers should remain alert to breakthroughs beyond that horizon.

In summary, the research to date shows substantial promise but should be interpreted as exploratory rather than conclusive. Current findings chart a promising direction, but do not yet provide definitive evidence of broad effectiveness. Acknowledging these caveats is crucial for shaping stronger research strategies in the future, as outlined in the next section on future directions.

Future research directions

Building on the findings and limitations identified in this review, several key directions can guide future research into and development of XR in forestry. Progress in these areas will help move XR from small-scale demonstrations and prototypes to practical, impactful tools in management, training, and decision-making.

(1) *Rigorous effectiveness studies*: Most current XR forestry studies focus on feasibility rather than impact. A critical next step is to conduct controlled experiments that directly compare XR to conventional methods. For instance, VR-based training in machine operation could be compared to traditional classroom or field demonstrations, with performance measured during practical tests. Similarly, AR inventory tools should be evaluated against standard equipment (e.g. compass, relascope), with outcomes like time savings, data quality, and user fatigue quantified. Longitudinal studies are especially needed: does VR training improve retention weeks or months later? Do field crews continue to use AR tools after the novelty wears off? Such research will provide robust evidence of ROI and identify where XR is genuinely transformative versus where it may be less effective.

(2) *Hardware integration and environmental resilience*: Another priority is developing XR systems that can withstand the realities of forestry environments. Current devices are often fragile, heavy, or optimized for indoor use. Future work should emphasize lightweight, rugged AR glasses with extended battery life, waterproofing, and displays that are visible in bright daylight. Multi-sensor integration, GNSS, inertial units, cameras, and LiDAR will be essential to improve AR alignment in dense canopies where GPS alone fails. Research should also explore connectivity solutions, such as edge computing or offline caching, to manage data in remote forests with limited internet. Partnerships with device manufacturers and extensive field trials across diverse conditions (dense brush, steep slopes, different climates) will be necessary to make XR devices truly "forest-ready."

(3) *Data integration and digital twins*: A major research frontier is linking XR with digital twins of forests. Digital twins, which are continuously updated virtual models fed by inventory databases, remote sensing, and IoT (Internet of Things) sensors, can make XR applications far more powerful. For example, AR glasses could display thinning history, stand density, or growth projections directly in the field. VR platforms could allow managers to "fast-forward" decades and compare the outcomes of different silvicultural treatments. Achieving this requires interoperability standards for 3D forest data, APIs (application programming interfaces) for linking existing forest management systems, and methods to keep twins updated in real time. Pilot projects that combine growth simulators or fire spread models with immersive XR would demonstrate how these systems can move from static visualization to interactive decision support.

(4) *User-centered design and training*: The design of XR tools must start with users. Forestry workers, machine operators, and managers should be involved in participatory design processes to ensure that systems fit real workflows. Research can test interaction modes such as voice commands, hand gestures, or simplified interfaces to determine what works best in field conditions. Comfort, ergonomics, and health factors also matter, so priorities should include reducing VR motion sickness (Chattha et al. 2020), avoiding eye strain in prolonged AR use, and ensuring that devices remain usable in gloves or protective gear. Beyond design, user training is critical: simply handing a device to a crew will not guarantee adoption. Studies should develop and evaluate XR training curricula that not only teach forestry tasks but also train users in XR device operation. Effective adoption requires both intuitive design and structured training.

(5) *Expanding applications and inclusivity*: Current XR forestry research is concentrated in education, harvesting, and inventory. There is scope to expand into biodiversity monitoring, fire management, and participatory planning. For example, AR could support real-time firefighting by overlaying predicted fire spread or evacuation routes, while VR could immerse policymakers in forest restoration scenarios. Inclusivity is also vital: XR should not become a tool the use of which is limited to wealthy organizations. Future research should develop low-cost XR systems that run on smartphones or open-source platforms, making the technology accessible to forestry agencies and communities in developing regions. Citizen science applications, for example AR tools that allow local communities to collect and share forest data, offer opportunities for broader engagement.

(6) *Collaboration with AI and advanced analytics*: The convergence of XR with AI will open new frontiers. Future research could integrate machine learning into XR systems to make them smarter and more autonomous. For example, an AR headset could use computer vision to automatically identify tree species or detect signs of pest infestation on bark, then display that info to the user in real time. Some initial attempts exist (e.g. using basic image recognition for tree ID), but applying deep learning models on devices or via edge computing could drastically improve what AR can do, like recognizing dozens of species, assessing tree health from leaf color, and so on. In VR training, AI could act as a virtual coach, tracking a trainee's actions and giving adaptive feedback or altering scenario difficulty on the fly. This has already been seen in some military and medical VR training (Balushi et al. 2024; Kang et al. 2024); forestry could adopt similar approaches (e.g. an AI coach that monitors how a virtual chainsaw operator moves and then highlights unsafe motions). Predictive analytics could also be brought into AR; imagine an AR app that not only shows current tree data but also, using model predictions, highlights trees at risk of pest attack or forecasts growth. For instance, "this stand will likely need thinning in five years" could be an overlay based on growth models. Edge computing could facilitate these advanced features by handling heavy computations (like running a deep neural network on video feed for tree detection) near the user but not on the headset, to keep latency low. Research should explore the architecture of such setups, perhaps small computing units that forestry teams could carry (in a vehicle or backpack) that connect to AR devices. There is also potential in data analytics in VR, in using AI to generate numerous forest scenarios or to perform risk analyses that the user can interact with in VR. For example, AI could simulate hundreds of fire spread paths in VR so that a manager could visualize worst-case versus best-case outcomes. Merging AI with XR will make these tools far more powerful, essentially giving decision-support intelligence within the immersive experience.

(7) *Multi-user and collaborative XR*: Most current forestry XR applications are single-user. Future work should explore collaborative XR environments where teams share information in real time. In AR, this could mean multiple workers viewing the same hazard overlays or tree maps simultaneously. In VR, planners and stakeholders from different regions could meet virtually in a shared forest environment to assess management options. Remote expert assistance, where an off-site specialist "joins" a field worker's AR view, could also improve decision-making. Research in other sectors (Perz et al. 2024; Wang et al. 2024) shows the potential of multi-user XR; forestry applications should be tested for their ability to improve teamwork, safety, and stakeholder communication.

(8) *Policy, ethics, and socioeconomic research*: Finally, as XR expands, broader questions must be addressed. Regulatory frameworks are needed to ensure that XR use does not compromise safety, for example AR overlays distracting machine operators. Data privacy and ownership issues arise with digital twins that include private land information. Ethical questions also matter: immersive XR can be persuasive in stakeholder engagement, but there is a risk of misuse if simulations are biased. Socioeconomic analyses are needed to evaluate the costs and benefits of XR adoption, ensuring that investments are justified. Studies should also explore business models, such as XR-as-a-service, to lower barriers for smaller organizations.

(9) *Alignment with Forestry 5.0 and human-centered AI*: An emerging direction relevant to XR development in forestry is the transition toward Forestry 5.0, which builds on Industry 5.0 principles emphasizing human-centered, sustainable, and resilient technological systems. Forestry 5.0 integrates advanced digital technologies, including artificial intelligence, robotics, and immersive environments, with a strong focus on human – machine collaboration and societal value. Recent work highlights that human-centered AI approaches are essential for bridging the gap between technological capabilities and real-world forestry applications (Holzinger et al. 2024). In this context, XR technologies can play a key role by providing intuitive interfaces for interacting with complex data, supporting collaborative decision-making, and enhancing transparency in forest management. Future research should explore how XR systems can be integrated within Forestry 5.0 frameworks, ensuring that technological innovation remains aligned with human needs, environmental sustainability, and operational practicality.

In conclusion, the future of XR in forestry lies at the intersection of technical innovation, human-centered design, broadened application areas, and supportive policy frameworks. Progress will require close collaboration between forest scientists, computer scientists, engineers, educators, and policymakers. If these communities collectively invest in the research directions outlined here, XR can mature from pilot projects into an integral part of forest management. Within the next decade, it could become routine for forest managers to plan operations in VR, for field crews to use AR glasses for navigation and data capture, and for stakeholders to explore management proposals through immersive platforms, all seamlessly connected to dynamic, data-driven forest models. Achieving this vision depends on systematically addressing today's gaps with focused, innovative research and cross-sector cooperation.

Conclusions

Extended reality technologies show strong potential as tools for forest management and engineering, but realizing this promise requires further refinement and validation. Between 2020 and 2024, research activity in forestry XR expanded considerably, spanning VR simulators for safe operator training, AR applications for field data visualization, and immersive tools for stakeholder engagement. These developments highlight XR's capacity to enhance training safety, decision-making, communication, and operational efficiency.

Yet, XR in forestry remains at an emergent stage. Most applications are prototypes or small-scale trials, with limited deployment in real-world operations. VR currently dominates because it avoids outdoor constraints, while AR is only beginning to overcome challenges such as accurate geo-registration, device robustness, and usability in complex field environments. As hardware advances and pilot projects mature, AR's role in operational forestry is expected to grow. Machine operators will make better, faster, and safer decisions with an AR-supported view of their environment.

Typically, forestry and forest management rely on mature practices that have been developed over decades or even centuries. Fast technological developments can offer great improvements in terms of efficiency and accuracy, and also decrease the need for highly sophisticated education and training for managers and workers. However, authorities and practitioners often are reluctant to introduce new approaches, because interactions in the management systems may create a need for remarkable, laborious, and costly redesigns.

A central conclusion of this review is that progress will depend on interdisciplinary collaboration. Technical advances alone are insufficient; effective XR tools must align with forestry workflows, human ergonomics, and education practices, and must address economic and policy considerations. Developing forest digital twins, for example, requires forest scientists working with data engineers, while VR-based safety training needs input from behavioral experts to validate learning outcomes.

Encouragingly, qualitative evidence suggests openness to XR among forestry professionals, students, and stakeholders. Participants report positive experiences with VR training, interest in AR use for navigation and hazard detection, and appreciation for immersive visualizations in planning contexts. These successes, however, must be backed by quantitative evaluations that measure long-term effectiveness and ROI.

Looking ahead, XR could become a routine part of forestry: AR glasses labeling trees and hazards in the field, planning teams meeting in virtual forests to explore scenarios, and trainees gaining realistic practice in VR before operating machinery. To reach this point, though, future work must focus on technical robustness, user-centered design, and measurable impact. By addressing these challenges and scaling beyond prototypes, XR can transition from experimental novelty to everyday utility, helping to make forestry safer, more efficient, and more collaborative in the digital age.

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