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Review

Research on the Application of Extended Reality in the Construction and Management of Landscape Engineering

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Abstract: Landscape engineering plays a crucial role in urban construction and the development of ecological civilization in China. It actively designs and modifies natural elements, such as water and mountains, acting as the primary living infrastructure. This field continually receives great recognition and praise. Recent academic research has prioritized the use of extended reality (XR) technology to create a real-time interactive visual environment to tackle the issues presented by the dynamic nature of landscape engineering. This paper utilizes the PRISMA method to filter out 68 research documents related to XR in landscape engineering construction and management for bibliometric analysis. A comprehensive review is conducted on the precise and efficient utilization of XR to solve various issues in the field of landscape engineering. Using Cite Space 6.2.R6 (a visual bibliometric software) to visualize knowledge structures and research topics, the analysis includes temporal and spatial examination, application scenario analysis, and technological hierarchy analysis. The paper summarizes the current challenges that XR still faces in the landscape engineering field and envisions extensible application scenarios for XR, providing a reference roadmap for the implementation of XR in landscape engineering.

Keywords: virtual reality (VR); augmented reality (AR); mixed reality (MR); landscape engineering; construction and management; bibliometric analysis

Citation: Liu, S.; Zhao, X.; Meng, X.; Ji, W.; Liu, L.; Li, W.; Tao, Y.; Peng, Y.; Yang, Q. Research on the Application of Extended Reality in the Construction and Management of Landscape Engineering. *Electronics* **2024**, *13*, 897. https://doi.org/10.3390/electronics13050897

Academic Editor: Osvaldo Gervasi

Received: 17 January 2024
Revised: 17 February 2024
Accepted: 23 February 2024
Published: 26 February 2024

1. Introduction

Landscape engineering creates a humanized and comfortable environment by incorporating plant-centric components, water bodies, architectural landscaping, and topography. Employing scientifically controlled design and management reduces and potentially reverses negative effects resulting from human development and ecological alterations. In recent years, China has placed significant emphasis on urban landscaping. As of March 2023, data from the '2022 China National Land Greening Report' indicates the presence of 218 national forest cities nationwide, with 3520 'pocket parks' developed across the country. The 'National Park Spatial Layout Plan' explicitly outlines the goal of establishing the world's largest national park system by 2035 [1].

Green landscaping projects are characterized by their dynamic nature, which involves aspects like plant phenology, seasonal stands, forest composition, spatial location, climate, and many multi-scale factors. These components, both biological and non-biological, undergo temporal alterations. The construction and management procedures of landscape engineering face problems due to spatiotemporal changes. Hence, it is crucial to implement proactive design and flexible operational tactics to successfully traverse these transformations. This involves creating a visual setting that enables managers and users to interact in real time, resulting in a high level of intelligent construction and management in landscape engineering.

Extended reality (XR), including virtual reality (VR), augmented reality (AR), and mixed reality (MR), is a technology we utilize to create powerful immersive interactive visualization interaction scenes. Virtual reality (VR) focuses on creating entirely virtual immersive environments; augmented reality (AR) overlays virtual content onto the real world, presenting enhanced information and experiences through devices to enrich user perception; mixed reality (MR) combines virtual and real elements, facilitating real-time interaction between virtual and physical objects, transcending the boundaries between the virtual and the real and generating entirely new integrated experiences.

In the Architecture, Engineering, and Construction (AEC) industry, XR holds immense potential for improving construction productivity, which enables effective control over construction progress, quality, and safety [2]. Specifically in the field of landscaping, XR has found extensive applications in areas such as the construction and simulation of landscaping models [3–15], monitoring and maintenance of plant growth [4,6,16–21], landscaping planning and design [9,13,14,22–35], perception and preference assessment of landscaping [11,36–50], virtual nature experiences in landscaping [6,18,39,51–64], as well as landscaping project management and maintenance [24,65,66]. XR addresses multidimensional challenges in landscaping construction and management by combining virtual information with real-world scenarios. The potential applications of XR in landscaping continue to be explored and encouraged.

Although the academic literature [3–67] extensively covers the applications of XR in the field of landscape engineering, existing research reviews predominantly focus on the application of individual XR technologies in specific stages or scenarios. There is a limited comprehensive literature review from the perspective of the overall experience [68–70]. For example, Chen et al. [69] summarized the application of VR or AR in informal scientific institutions (such as parks, botanical gardens, etc.), detailing the context and design of creating highly interactive immersive environments to facilitate learning. They further outlined the learning outcomes in nature education under the influence of XR. Lee et al. [70] systematically reviewed the psychological impacts generated by experiencing virtual forests and other green natural spaces using VR. They investigated and analyzed intervention strategies (duration, landscape observation locations, environmental descriptions, and sensory types) and types of psychological indicators (emotional recovery, cognitive restoration, stress reduction, etc.), concluding that virtual nature exposure can alleviate negative emotions, thereby enhancing the quality of life for individuals with mental and physical disabilities, as well as for healthy individuals. The limitations of these literature reviews are as follows: (1) The focus is limited to the domain of landscape engineering or a specific application perspective, depicting only a particular functional scenario within landscape engineering. (2) The review content encompasses XR solely as a powerful technology that can create immersive interactive visual scenes and only deals with the dimensions of application content analysis without analyzing and discussing the technical application level of XR.

In this paper, the transparent reporting of systematic reviews and the meta-analyses (PRISMA) method are used to filter the research literature related to XR in landscape engineering construction management (detailed methods are explained in Chapter 2, Materials and Methods). Utilizing bibliometric analysis, the study reviews research performance and conducts a scientific mapping of the literature. A total of 68 literature entries were retrieved, screened, and included from the Web of Science and Scopus databases. Using Cite Space 6.2.R6, this paper visualizes knowledge structures and research topics, conducting spatial–temporal analysis, application scenario analysis, and technological hierarchy analysis. This paper summarizes various application scenarios of XR, providing a comprehensive review of the precise and efficient utilization of XR in addressing diverse challenges in landscape engineering construction and management. It offers a reference roadmap for the future implementation of XR in the field of landscaping.

The research objectives of this paper are as follows: (1) Retrieve and compile publication information, exploring the temporal and spatial distribution patterns of the relevant literature. (2) Extract information regarding the extent of XR coverage at the content level and the implementation status of XR at the technical level to determine the progress and insights of XR applications in landscape engineering. (3) Summarize the challenges currently faced by XR applications in landscape engineering. (4) Propose envisioned future expansible application scenarios for XR.

2. Materials and Methods

The PRISMA guidelines, an acronym for "Preferred Reporting Items for Systematic Reviews and Meta-Analyses", constitute a set of standardized criteria designed to assess the quality of systematic reviews. They are specifically applicable to reviews conducted on the published literature containing original data, aiming to enhance the scientific rigor and comparability of systematic reviews [71]. As of October 2023, PRISMA, introduced in 2009 [72], has been adopted in over 60,000 publications across various disciplines. In review articles featured in journals such as "*Buildings*" [2], "*Forests*" [69], "*Virtual Reality*" [70], and "*Automation in Construction*" [73], a similar approach leveraging PRISMA's three-stage or four-stage flow diagram for data selection has been observed. This study aligns with the updated PRISMA three-stage flow diagram from 2020 [74] for the screening of literature data. PRISMA flow diagram of the data screening process is shown in Figure 1.

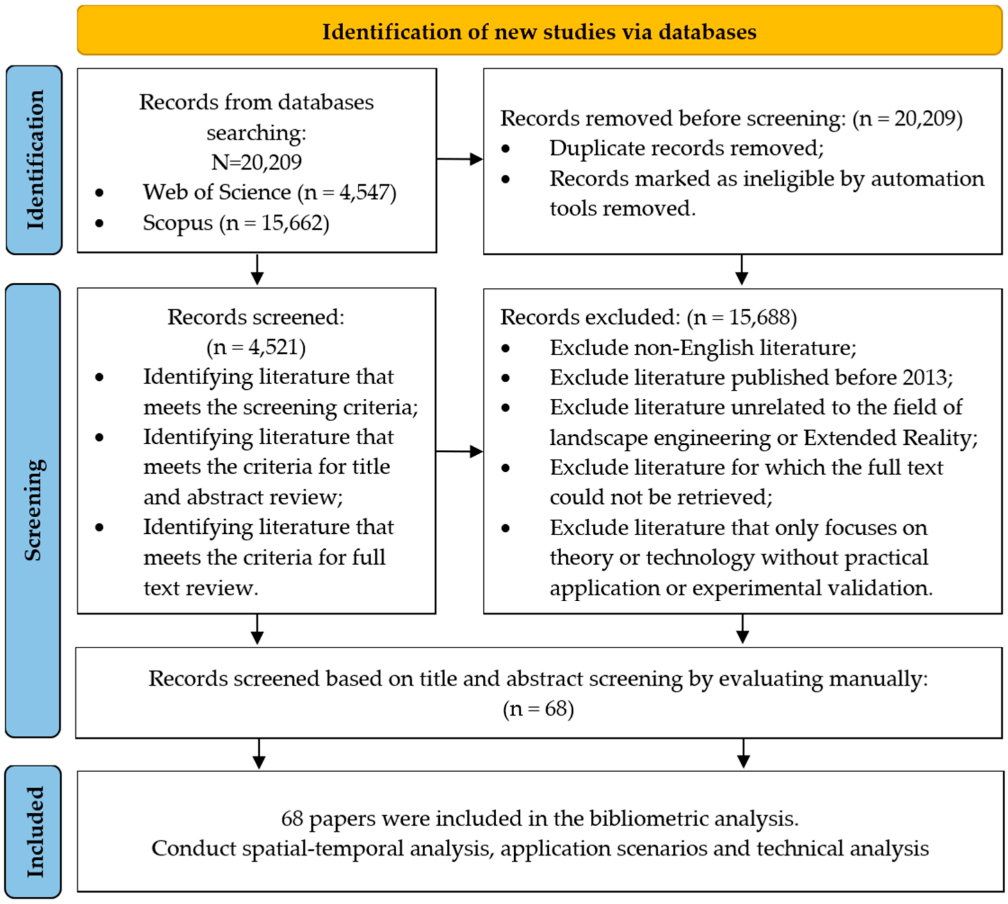

Figure 1. PRISMA flow diagram of the data screening process.

The remaining sections of this paper are organized as follows: Section 2 describes the overall bibliometric analysis method for the application of XR in the construction and management of landscape engineering; Section 3 clarifies the restrictions on the collection of the relevant literature in this review, including the basic requirements of retrieval, screening, and inclusion, so as to obtain accurate and rigorous literature data. Section 4 introduces the survey results of bibliometrics analysis, which are discussed from four aspects: temporal distribution, space distribution, application scenario analysis, and application technology analysis. The latest application scenarios of XR in landscape engineering construction and management and the matching between XR and application scenarios are emphasized. At the same time, the application technology dimension of XR itself and its combination with other technologies are analyzed. In Section 5, the challenges of applying XR in landscape engineering are summarized, and the potential application scenarios of XR are proposed to provide information reference for future research activities. Section 6 summarizes this review. The bibliometric analysis procedure of this study is shown in Table 1.

Table 1. Bibliometric analysis procedure.

Step 1 Define the purpose and scope of bibliometric research.		
Provide a comprehensive overview of research application scenarios and technologies, achievements, and challenges to determine the progress and insights of XR in landscape engineering. On this basis, look forward to future research agenda.		
RQ1: In the field of landscape engineering, what are the application scenarios of XR, and how compatible are they with these scenarios? RQ2: In the realm of landscape engineering, what is the current state of development of XR itself, and how is it applied in conjunction with other technologies? RQ3: What limitations and challenges persist in the application of XR in the construction and management of landscape engineering? RQ4: What potential application scenarios can be envisioned for XR in the construction and management of landscape engineering?		
Step 2 Select bibliometric analysis tools.		
Step 3 Collect bibliometric analysis data.		
Term	Technology-related	(“immersive* technology*” OR “extended reality” OR “virtual reality” OR “augmented reality” OR “mixed reality” OR “XR” OR “VR” OR “AR” OR “MR” OR “virtual prototype*” OR “virtual environment”)
	Related to landscape engineering	(“arboretum” OR “botanic garden*” OR “botanical garden*” OR “botanic park” OR” botanical park” OR “plant” OR “landscape” OR “landscape engineering“ OR “horticulture”)
PRISMA-ScR Flow Diagram.		
(1) Identification (2) Screening and inclusion		
Step 4 Perform bibliometric analysis.		
Temporal distribution	(1) Number of papers published annually.	
Spatial distribution	(1) Article distribution (2) Periodical distribution (3) Geographical distribution	
Application scenario analysis	(1) Landscape model construction and simulation (2) Plant growth monitoring and maintenance (3) Landscape planning and design (4) Landscape perception and preference assessment (5) Virtual natural experience of landscape (6) Landscape project management and maintenance	
Applied technical analysis	(1) XR application technical hierarchy analysis (2) Analysis of XR combined with other technologies	
Step 5 Analysis result		
(1) Summarize the limitations and challenges of XR in the construction and management of landscape engineering. (2) Propose the potential application scenarios of XR in landscape engineering.		
Step 6 Conclusion		

3. Data Collection for the Literature Review

3.1. Identification

3.1.1. Selection of Database

Web of Science (WoS) [75] stands as a crucial database for accessing global academic information. The Science Citation Index Expanded (SCIE), one of the three core collections within WoS, covers 176 subject areas, making it an authoritative and highly influential citation index database for scientific journals. Scopus [76], recognized as the world's largest peer-reviewed literature abstract and citation database, surpasses WoS in terms of the breadth and quantity of disciplines and papers it encompasses. It provides researchers with a convenient and powerful retrieval system, facilitating efficient searches. While Scopus boasts broader coverage, WoS enjoys slightly higher visibility and recognition [77]. Therefore, this study employs both Web of Science and Scopus databases for literature retrieval purposes.

3.1.2. Selection of Keyword Set

The keyword set used to retrieve the literature related to the topic of this review is divided into two aspects: one is the keyword set related to "extended reality", and the other is the keyword set related to "landscape engineering".

Web of Science database and Scopus database, respectively, searched the literature within the scope of this review according to the following search methods:

TS = ("immersive*technology*" OR "extended reality" OR "virtual reality" OR "augmented reality" OR "mixed reality" OR "XR" OR "VR" OR "AR" OR "MR" OR "virtual prototype*" OR "virtual environment") AND TS = ("Arboretum" OR "Botanic garden*" OR "Botanical garden*" OR "Botanic Park" OR "Botanical Park" OR "plant" OR "landscape" OR "landscape engineering" OR "horticulture").

TITLE-ABS-KEY ("immersive* technology*" OR "extended reality" OR "virtual reality" OR "augmented reality" OR "mixed reality" OR "XR" OR "VR" OR "AR" OR "MR" OR "virtual prototype*" OR "virtual environment") AND TITLE-ABS-KEY ("Arboretum" OR "Botanic Garden*" OR "Botanical Garden*" OR "Botanic Park" OR "Botanical Park" OR "plant" OR "landscape" OR "landscape engineering" OR "horticulture").

3.2. Screening and Inclusion

3.2.1. Restrictions on the Period of Literature

In this study, the above search methods were used as the search keywords, the subject as the search item, and the research field as the search field. The literature was retrieved from the Web of Science database and Scopus database. Among them, the dashed lines in Figures 2 and 3 represent the trend line of the annual number of publications, which shows an upward trend. It shows a steady increase in the number of annual articles published in both databases. Since the turning point in 2012, the number of studies published in these two databases has consistently exceeded 180 and 500 since 2013, showing a clear upward trend. Therefore, to ensure the timeliness of literature retrieval, the period of the literature is finally limited to January 2013 to October 2023. Due to the time-limited search scope of this review, the annual total number of publications in 2023 were computed using the linear prediction function "Forecast" in Excel, and the connection between 2022 and 2023 was distinguished by the orange display.

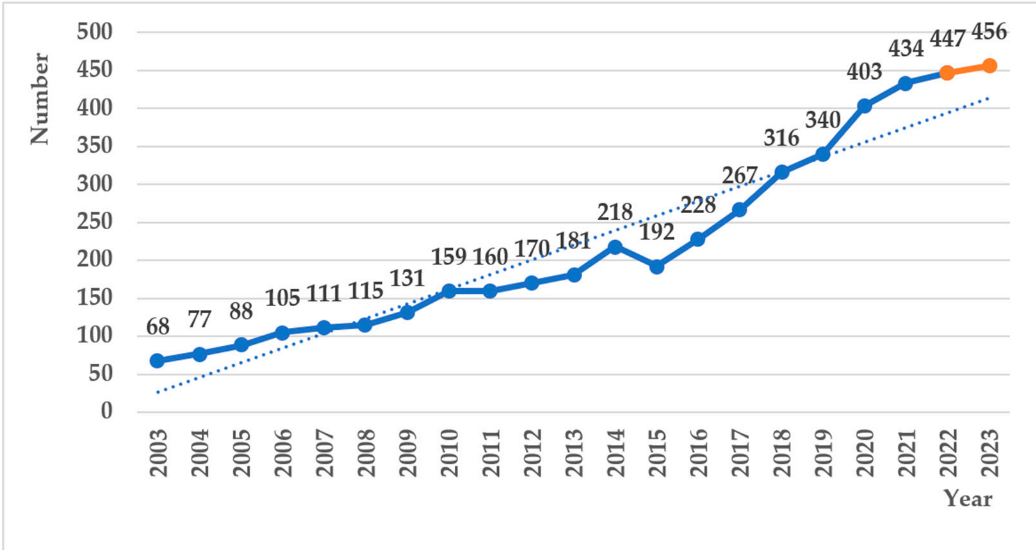

Figure 2. Annual number of publications in WoS database full-field retrieval from 2003 to 2023.

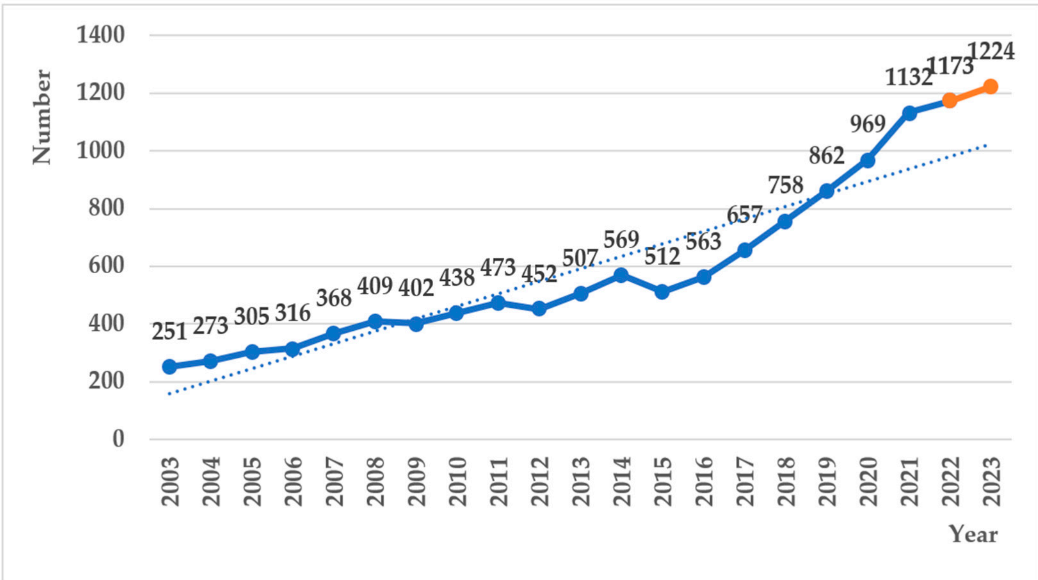

Figure 3. Annual number of publications in Scopus database full-field retrieval from 2003 to 2023.

3.2.2. Restrictions on the Type and Language of Documents

Papers of article type are the overall detailed elaboration of the latest research results by the researchers, and as journal papers, they will go through several rounds of strict review process. These types of papers provide high-quality academic information, so the literature used for this review is article-type papers. Meanwhile, papers from international journals retrieved from Web of Science databases and Scopus databases were selected for this review, so the language of the literature was limited to English.

3.3. Bias in Meta-Analysis

According to the actual situation of this paper, the bias analysis is explained. If there are system defects or limitations in the design stage and production stage of the system review, there will be bias, which will affect the authenticity and reliability of the results [78]. In meta-analyses, the different types of research literature have different quality evaluation criteria. In the stage of paper data retrieval, screening and inclusion, the bias in meta-analysis can be divided into two categories: literature search bias and literature screening and inclusion bias. According to the actual situation of this paper, the bias analysis of the specific literature is shown in Table 2.

This review did not impose strict limitations on research design to ensure that all relevant studies regarding the application of extended reality in landscape engineering construction and management were included. In terms of research design, following recommendations from the Cochrane Handbook [79,80], we utilized the Risk of Bias 2 (RoB2) tool, which is specifically tailored for randomized controlled trials (RCTs). RoB2 comprises five domains: (1) bias arising from the randomization process, (2) bias due to deviations from intended interventions, (3) bias due to missing outcome data, (4) bias in outcome measurement, and (5) bias in the selection of the reported result. Each domain is assessed at three levels: "low risk", "some concerns", and "high risk". The highest risk across the five domains is recorded as the overall risk level.

RoB2 evaluation results are detailed in Section 4.3.

Table 2. The bias in the meta-analysis of the specific literature.

Serial Number	Categories	Key Point	Specific Situation
1	Literature Search Bias	Publication Bias	The only way to control for publication bias is to collect as fully as possible all studies that meet the inclusion criteria [78]. In this paper, a full-field search was conducted in two databases, Web of Science and Scopus. The total number of articles was N = 20,209, and relevant data were collected according to the research purpose to reduce publication bias as much as possible.
2		Literature Database Bias	At present, there is no database that can comprehensively record all the published literature on the application of XR to landscape engineering, and the standards of literature collection vary from country to country, so the bias can be controlled by searching multiple authoritative databases [81]. This paper employs both Web of Science and Scopus databases for literature retrieval purposes.
4		Repeated Publication Bias	The results of the same group of subjects were divided into two or more papers published by the author, which may result in repeated publication bias of the subjects of the study [81]. In this study, the removal of duplicate data has been included as a screening criterion in the process of literature screening to reduce publication bias as much as possible.
5	Literature Screening and Inclusion Bias	Selector Bias	The authors of the meta-analysis are influenced by their subjective intention when screening and including literature reviews, which results in the bias caused by the inaccuracy of the included studies [78]. Two or more researchers can be selected to conduct the search at the same time, and if there are different opinions, it is necessary to discuss with experts to control bias. In this study, several authors were involved in literature screening to minimize the subjectivity and bias of the data.
6		Inclusion Criteria Bias	The inaccuracy of the selection criteria will lead to bias [78]. According to the purpose of the research, this paper strictly formulates the research object and research design type of literature retrieval and, on this basis, determines the keyword set of searches; criteria such as search period and language are limited to control bias.

4. Analysis of the Application of XR in Landscape Engineering

4.1. Temporal Distribution

The annual publication volume of 68 articles included in the analysis was analyzed, as shown in Figure 4. According to the data in Figure 4, from 2013 to 2023, the research on the application of XR in the construction management of landscape engineering shows an overall growth trend, and the number of published documents reaches the highest in 2022.

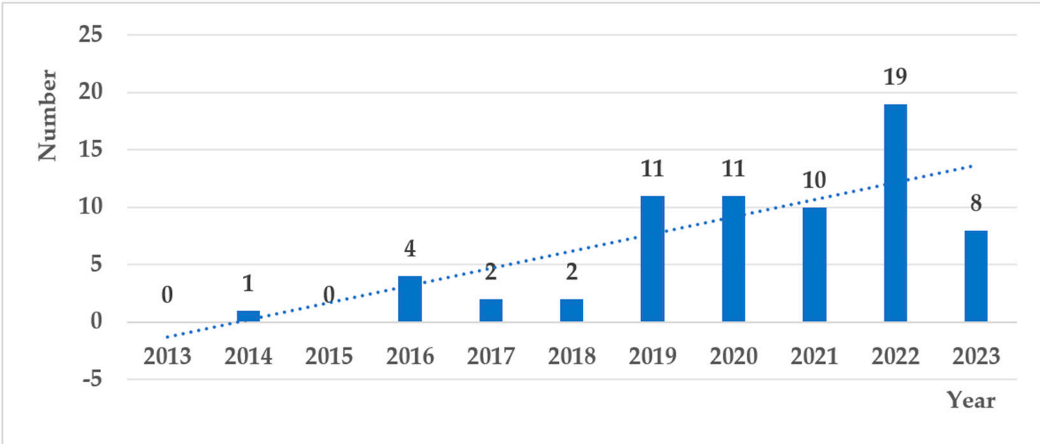

Figure 4. Analysis of annual publication volume among all articles included in the analysis from 2013 to 2023.

4.2. Spatial Distribution

4.2.1. Article Distribution

In this paper, the citations corresponding to Web of Science and Scopus of the papers included in the analysis will be sorted and counted, and the authors, publication years, journals, and other information of the top five most-cited papers was listed, as shown in Table 3.

Table 3. Top five papers cited most frequently in all the articles included in the analysis.

Serial Number	Author	Year	Title of Paper	Journal Title	Citation Count
1	Huang, T.C., et al. [51]	2016	Animating eco-education: To see, feel, and discover in an augmented reality-based experiential learning environment	Computers and Education	205
2	Huang, Q.Y., et al. [36]	2020	Trees, grass, or concrete? The effects of different types of environments on stress reduction	Landscape and Urban Planning	91
3	Wang, X.B., et al. [37]	2019	The Influence of Forest Resting Environments on Stress Using Virtual Reality	Environmental Research and Public Health	72
4	Gao, T., et al. [38]	2019	Comparisons of Landscape Preferences through Three Different Perceptual Approaches	Environmental Research and Public Health	28
5	Shi, J.Y., et al. [42]	2020	Using Virtual Reality to Assess Landscape: A Comparative Study Between On-Site Survey and Virtual Reality of Aesthetic Preference and Landscape Cognition	Sustainability	20

4.2.2. Journal Distribution

In this study, the papers included in the analysis will be sorted and counted in the corresponding journals of Web of Science and Scopus, and the information of the top five journals with the largest number of published articles will be listed, as shown in Table 4.

Table 4. Top five journals with the most published papers in all the articles included in the analysis.

Serial Number	Journal Title	Number of Papers	Proportion
1	IEEE ACCESS	3	4.41%
2	Landscape and Urban Planning	3	4.41%
3	Sustainability	3	4.41%
4	Wireless Communications and Mobile Computing	3	4.41%
5	Forests	2	2.94%

4.2.3. Regional Distribution

In this study, author information of the papers included in the analysis was sorted and counted, and information of the top five regions with the largest number of published articles was listed, as shown in Table 5.

Table 5. Top five countries with the highest number of papers published in all the articles included in the analysis.

Serial Number	Country	Number of Papers	Proportion
1	China	33	48.53%
2	Korea	7	10.29%
3 (1)	Germany	4	5.88%
3 (2)	USA	4	5.88%
3 (3)	Japan	4	5.88%
4	Italy	3	4.41%
5 (1)	India	2	2.94%
5 (2)	Portugal	2	2.94%

4.3. Risk of Bias Assessment

Resulting from the risk of bias assessment, 16 RCT studies were conducted using the RoB2. When evaluating studies using RoB2, two studies were categorized as 'low risk' of bias, eight studies were classified as 'some concerns', and six studies were rated as 'high risk' (Figure 5).

Regarding the randomized process, most studies demonstrated the adequacy of randomization through baseline analysis. In fourteen studies, there was potential for concealing interventions and assessment methods until participants were allocated to interventions, but this was not feasible in two studies. Therefore, in these two studies, the inability to conceal this method was assessed as 'high risk'. In two studies, there was potential for concealing intervention measures until they were allocated, which was deemed as 'some concerns'. Due to the small number of participants, it was challenging to determine homogeneity between groups.

Regarding deviations from intended interventions, in most studies, participants and researchers were aware of the designated intervention measures. Furthermore, in two studies, it was not demonstrated that the designated intervention measures were unrelated to the trial context. Therefore, the two studies that did not mention or consider this factor were identified as being at 'some concerns' risk level.

Regarding missing outcomes, no studies were assessed as 'high risk' because there were no instances of missing outcome data. However, most studies reported data for all or nearly all participants and were assessed as 'low risk' or 'some concerns'.

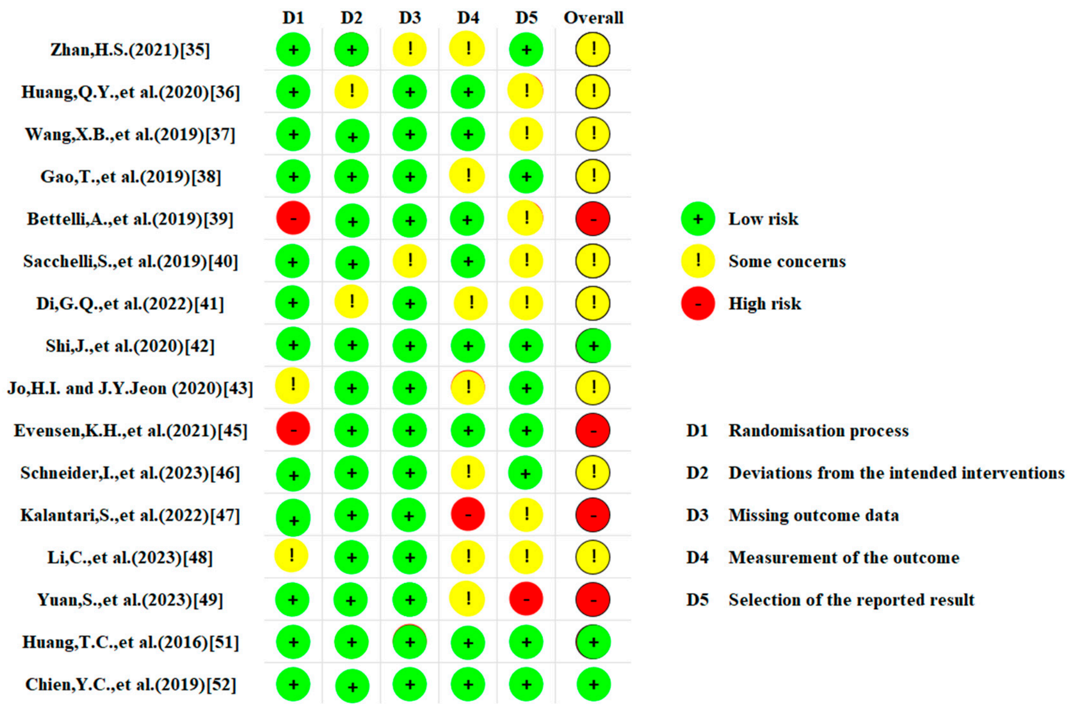

Figure 5. Risk of bias in randomized controlled trials using the RoB−2 tool.

Regarding the outcome measurements, 16 studies extensively utilized metrics and provided evidence. In most studies, assessors were aware of the intervention measures, but the likelihood of this prior knowledge influencing the outcomes was deemed low. Therefore, only one study with uncertain measurement was assessed as 'high risk'.

Regarding the selection of results, due to appropriate pre-specified protocols and clear reporting of outcomes, eight studies were rated as 'low risk'. Among the eight studies that did not mention protocols, seven were assessed as 'some concerns', and one was assessed as 'high risk' because it did not provide sufficient evidence for the choice of analytical methods.

4.4. Application Scenario Analysis

Through multidimensional retrieval and scrutiny of data sources, this study selected 68 research papers for a comprehensive bibliometric analysis. These articles were downloaded and exported in RefWorks format. Then, they were imported into Cite Space 6.2.R6 for keyword clustering analysis. Figure 6 shows the Cite Space 6.2.R6 keyword clustering map. The Log-Likelihood Ratio (LLR) is one of the clustered tag word extraction algorithms provided by Cite Space 6.2.R6 for extracting research terms at different locations in citing documents. Compared with other clustering algorithms, LLR emphasizes the research characteristics and is more suitable for the use requirements [2]. Utilizing the LLR algorithm within the clustering analysis, seven major research clusters (#0–#6) were identified. As depicted in Figure 6, the clustering keywords for these articles are "modeling ecosystem reference condition", "as-built model landscape architecture", "assessment", "media creation", "landscape management education", "feel", and "distribution". Each cluster is composed of closely related terms. The clustering results of Cite Space 6.2.R6 have provided a reference for the classification of XR application scenarios in this section. In particular, some words highlighted in black boxes in Figure 6 are more representative.

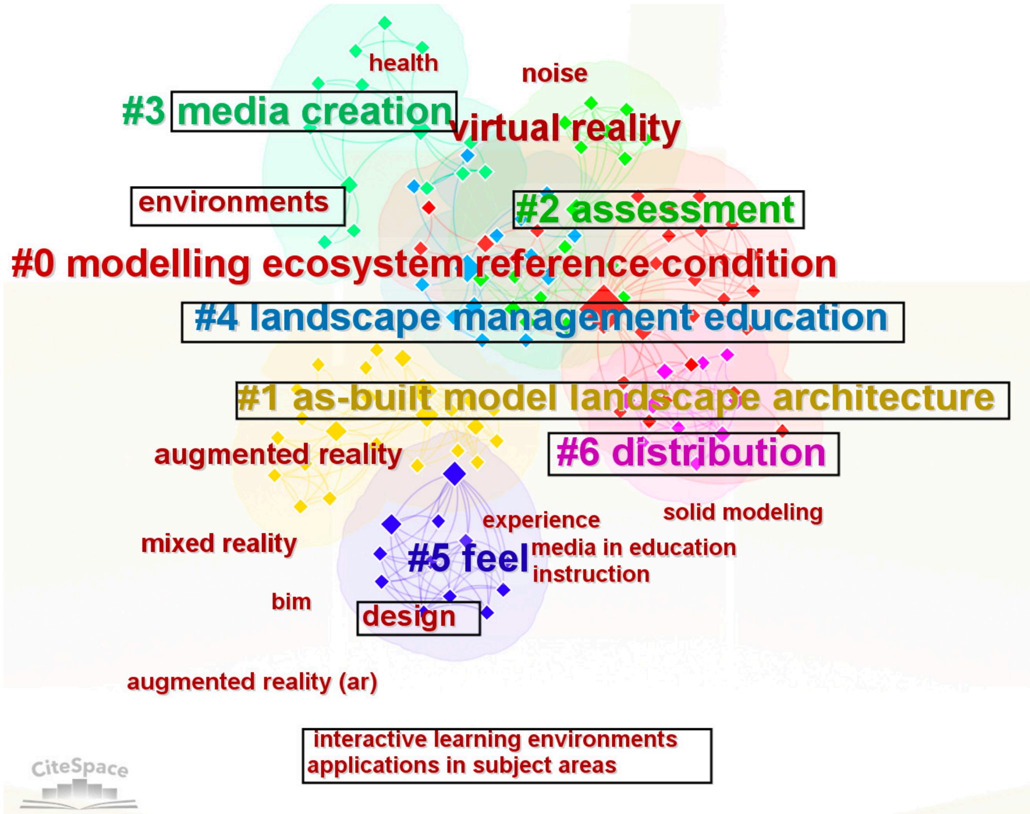

Figure 6. Cite Space 6.2.R6 keyword clustering map.

Firstly, XR achieves a three-dimensional visual simulation of garden landscapes and is applied across various scenarios in different stages of landscape engineering based on virtual model construction (see Section 4.4.1 for details).

Secondly, the key application scenarios of XR in this study are categorized into the following five aspects: (1) plant growth monitoring and maintenance, (2) landscape engineering management and maintenance, (3) landscape planning and design, (4) landscape perception and preference assessment, and (5) virtual natural experiences of garden landscapes (see Sections 4.4.2–4.4.6 for details).

Through a systematic analysis of the retrieved research outcomes, it is observed that each study is not confined to the development of a single technology (VR, AR, or MR) or a specific application scenario. In response, the authors created Venn diagrams illustrating different combinations of XR application scenarios, with each area assigned a distinct color for clarity. The intersecting regions display the number of literature studies exploring various combinations, as depicted in Figure 7.

As can be seen from the statistical results, the application of XR is most prominent in the realm of landscape planning and design, with relatively fewer instances in the field of landscape engineering management and maintenance. Analyzing the intersectional data points among these five application scenarios reveals that research within each scenario tends to be relatively independent.

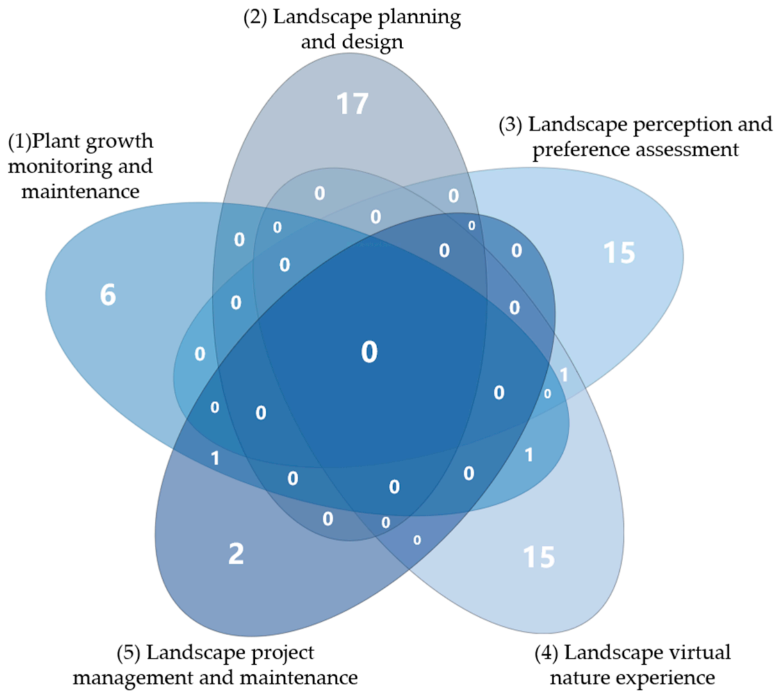

Figure 7. Combinatorial Venn diagrams for different application scenarios of XR.

4.4.1. Construction and Simulation of Landscape Models

Among the 68 publications analyzed, researchers have investigated different application scenarios focused on creating virtual three-dimensional landscape models. The creation of virtual scenes for three-dimensional landscape models primarily involves the generation of models for landscape topography, trees, flowers, plants, and other elements. Additionally, it encompasses the realization of fitting three-dimensional topography to landscape models. This process includes designing environmental effects, connecting to databases, incorporating special effects, and enabling real-time rendering. These efforts collectively facilitate dynamic queries, interactive roaming, and user-defined exploration functionalities within the landscape [3]. As a foundational element across various XR application scenarios, the establishment of virtual landscape models assumes particular significance. These models serve the purpose of simulating, analyzing, interpreting, and predicting real-world botanical data, aiding in the comprehension of intricate plant growth phenomena. Furthermore, they provide support for landscape engineering planning, decision-making, and regulation [4]. However, due to the unique and intricate structure of plant models, traditional landscape modeling and simulation methods are rather time-consuming. Efficiently and accurately representing diverse digital plants poses a significant challenge [5]. Moreover, garden landscapes exhibit temporal variations with changing seasons and day-night cycles, along with complex responses to environmental factors such as climate and soil conditions. Achieving comprehensive three-dimensional visualization and simulation of the overall landscape presents a challenge [6]. To address the challenges, various scholars have proposed multiple optimization algorithms or methods for achieving three-dimensional reconstruction of models. Concurrently, the application of XR can be employed to present virtual landscapes as immersive experiences, efficiently conveying the dynamic changes within garden landscapes to users.

- Optimization of garden landscape model construction method

Among the sixty-eight studies included in the analysis, nine focus on the optimization of landscape model construction methods [5–14]. The above studies all revolve around the construction and simulation of three-dimensional models based on VR. To enhance the quality, speed, and precision of modeling, some scholars have undertaken optimization efforts specifically targeting the construction of three-dimensional plant models and related algorithms. For instance, Wang et al. [8] proposed an optimization strategy for the three-dimensional model of landscape space based on VR and big data analysis. The improved edge folding region algorithm reduces errors while ensuring image quality, and the adaptive search algorithm shortens modeling time, thereby enhancing compression rates. Additionally, some scholars have put forth different optimization strategies for the overall construction of landscape models. Tabrizian et al. [11] introduced a landscape modeling and improved vegetation modeling approach based on high-resolution spatial data, effectively quantifying the composition and configuration of visible landscape elements.

- Visual simulation of multi-scale time-varying virtual landscape model

The visual simulation of the virtual garden landscape model is not limited by time and space, and can reverse the past, reproduce reality, and predict the entire process of future garden growth [4]. Among the literature reviews included in the analysis, four papers focused on how to simulate the time-varying process of landscape architecture by creating multi-scale virtual models [4,6,10,15]. For example, Chandler et al. [6] created 3D animated models of 14 key plant species alternating between seasons as well as renderings of the surrounding environment, simulating the soundscape changes that occur throughout the day. Yang et al. [4] constructed three-dimensional forest landscapes based on forestry spatial data and VR to express complex forest phenomena. According to the spatio-temporal range of the virtual forest environment and the different simulated objects, the virtual objects are divided into three levels: landscape (whole stand), single stand, and single plant. The species information and topographic distribution of local trees were obtained through field investigation and remote sensing analysis. VR is used to simulate the form of single trees, generate stands on digital terrain, and add environmental factors such as wind, frost, rain, and snow to generate a multi-scale time-varying virtual forest environment such as interdiurnal, seasonal, and annual. The above research is based on VR.

4.4.2. Plant Growth Monitoring and Maintenance

Of the sixty-eight studies included in the analysis, eight studies are related to research topics in plant growth monitoring and maintenance. Of the eight XR systems developed in these studies, two are VR systems, five are AR systems, and one is an MR system. Overall, these related studies apply XR in combination with other advanced technologies in plant growth monitoring and maintenance, enabling managers to understand plant nutritional requirements and pest and disease risks more accurately, optimize plant management strategies, adjust maintenance schedules, and take timely measures to prevent and deal with problems, increase plant survival rates, and improve the eco-efficiency of the gardens.

- Plant growth monitoring and simulation

Among the relevant studies included in the analysis, there are six articles focused on plant growth monitoring and simulation [16–21]. In some studies, XR is combined with other advanced technologies to obtain information such as the growth and health status of plants in gardens in real time to monitor the growth status of plants and environmental risks and to simulate the future growth of plants virtually. For example, Wang et al. [16] applied the Internet of Things (IoT) and AR to the plant management control system, using IoT to integrate environmental parameters and the state of various equipment into the control parameters and AR to provide real-time interactive information, directly integrating various information intuitively to the manager. Some scholars have improved the methods or algorithms of virtual simulation of plant growth. Xing et al. [19] proposed a method based on AR to quickly and efficiently build a large-scale field plant dataset matching the actual inspection environment, and it can be combined with the dataset of the virtual space imaging environment for automatic annotation, significantly improving the average accuracy of the trained model. In addition, in terms of plant growth monitoring and maintenance, a variety of mobile devices or programs based on XR are also being developed. Prasad et al. [28] proposed a mobile MR Penetration system that utilizes a simple camera-based interactive and powerful mobile interface to monitor and control plant leaf disease.

- Vegetation fire simulation and mechanism exploration

Among the literature included in the analysis, there are three articles [4,6,21] mainly studying the fire simulation of vegetation and exploring the destruction mechanism. The construction and management of garden landscapes is not only the construction of new gardens but also the protection of garden ecological heritage caused by the destruction of natural and human factors in the past. XR can be used to explore or verify its external destructive factors, such as fire mechanisms, invasive species, etc. For instance, Chandler et al. [6] employed VR to simulate an endangered eucalyptus forest ecosystem, utilizing virtual landscape visualization to recreate and simulate the impact of destructive factors. This analysis facilitated managers in comprehending the dynamic changes within the ecological community and aided in crisis management for biodiversity. Simultaneously, in the context of forest fire prediction, a virtual forest environment platform considered factors such as terrain slope, wind direction, temperature, humidity, and weather. This in-depth understanding of fire model analysis mechanisms, coupled with the establishment of a three-dimensional model for forest fire spread, effectively supported decision-making in firefighting efforts. It represents a crucial approach to mitigate forest losses [4].

4.4.3. Landscape Planning and Design

Ecological landscape design requires reasonable collocation and planning of landscape elements and pays more attention to the allocation and relationship between plants and non-plants in landscape architecture [22]. The traditional garden design method depends on the knowledge, experience, and aesthetic ability of the designer, which makes it difficult to meet the increasingly complex element distribution and spatial planning requirements of urban gardens, and it is urgent to create a perfect smart garden design method with vitality and innovation [9]. With the rapid development of information-based technology, the research of XR-assisted landscape planning and design is being carried out gradually. Powerful 3D modeling, solid rendering, and animation capabilities create a good environment for landscape design [22]. Among the 68 studies included in the analysis, 17 are related to the research topic of landscape planning and design. In general, these related research studies mainly focus on the realization of visualization in landscape design and interactivity in the planning process. Of the seventeen XR systems developed in these studies, there are fifteen VR systems, one AR system, and one MR System.

- Virtual design exhibition of multi-scale garden landscape scheme

Among the literature included in the analysis, 12 articles are related to the multi-scale display of virtual landscape design schemes [13,14,22–31]. In the context of constructing garden landscape models, XR enables the flexible and systematic arrangement of landscape elements, enhancing the intuitive and immersive presentation of design schemes. Additionally, the integration of XR facilitates the in-depth analysis, deduction, and refinement of designers' works, enabling the timely identification of issues and the mitigation of design defects. For example, the virtual garden system developed by Zhang et al. [14] realizes the spatial layout of various types of landscapes with parameter control through the digital vector layer, flexibly manages and organizes various garden elements, and reasonably organizes the spatial topological relationship between various types of landscapes in three-dimensional space. Yuan et al. [31] proposed a general process of applying 3D virtual reality interactive technology to Marine urban plant greening. Through the demonstration on computers and mobile devices, designers can observe design schemes in a multidimensional virtual environment, which greatly expands the channels for displaying and communicating design schemes.

- Virtual simulation of multimodal landscape effect simulation

Among the literature included in the analysis, 10 articles focus on virtual simulation of multimodal landscape effects [13,14,22,27,29,31–35]. When XR is applied to landscape planning and design, designers can transcend the constraints of two-dimensional thinking and engage in a three-dimensional, multimodal immersive observation of landscape works. This facilitates a more intuitive comprehension of design schemes, aiding decision-makers in the thorough evaluation of such schemes. Moreover, it enables the rational allocation of plant density and the formulation of design schemes pertaining to the distribution of garden elements. Simultaneously, it enhances the comprehension of spatial dynamics, thereby imparting a more artistic dimension to the garden landscape. For example, Li et al. [33] proposed a reasonable analysis method of landscape garden distribution based on 3D images. The outcomes of 3D image reconstruction and VR were leveraged, leading to a comprehensive analysis of the rationality of landscape distribution in 3D images. The findings substantiated the efficacy of the technology implemented for rational landscape garden layout.

4.4.4. Landscape Perception and Preference Assessment

Visitors to gardens, urban parks, or botanical gardens are heterogeneous groups with different age, occupation, other attribute types, and feelings and preferences for garden landscapes. Therefore, it is very important to customize and adjust user experience for heterogeneous audiences for the early design and later operation management of garden projects [39]. XR can interact and remotely collaborate with designers and other stakeholders to provide real-time feedback and evaluation in the process of landscape visualization, promoting participation and decision-making sharing. These feedback and evaluations mainly include soundscape, emotion, behavior, safety, landscape beauty, satisfaction, and other aspects of evaluation. Of the 68 studies included in the analysis, 16 are related to research topics on landscape perception and preference assessment. In general, these related studies mainly focus on people's sensory perception, emotions, and aesthetic preferences. In addition, of the sixteen articles, fifteen are VR systems, two are AR systems, and one is an MR System.

- Soundscape perception

A park or botanical garden is an important public place, and the quality of its sound landscape directly affects the public's satisfaction with the garden. Soundscape consists of two elements, sound and landscape, which influence the public's perceptual experience through hearing and sight, respectively. The research shows that sound pressure level, sharpness, loudness, and roughness are important sound factors that affect the auditory perception of parks, and the local landscape composition of roads, water, vegetation, and buildings is closely related to visual perception. Among the literature included in the analysis, there are five articles [40–44] on the application of XR in garden soundscape perception. Using XR to reproduce soundscape is a reliable method to evaluate soundscape perception, which can effectively replace soundscape surveys. Sacchelli et al. [40] used an analytical method based on the integrated perception of urban forest visual landscape and sound landscape to classify recreational suitability at the spatial level. VR allows respondents to be fully immersed in a specific environment, and the test highlights the link between natural visualizations, natural sounds, and stress recovery.

- Landscape emotion preference and cognition

Among the literature included in the analysis, there are seven articles [11,36,37,45–48] on the application of XR in landscape emotional preference and cognition. The forest environment provides individuals with multiple health benefits, such as physical relaxation and psychological relief, by stimulating multiple senses, such as sight, hearing, and smell. XR is applied to the study of forest multisensory preference, which is an extension of previous research on virtual forest environments in terms of mood improvement, stress recovery, and psychological recovery. For example, Evensen et al. [45] studied the impact of security enhancement landscape design measures on the visitor experience of urban parks.

Through a questionnaire survey, Li et al. [48] collected visual perception data from users watching virtual forest videos and verified the effectiveness of virtual reality eye-tracking technology in a virtual reality forest environment, which is conducive to the maintenance and management of forest parks.

- Landscape aesthetic preference and cognition

Among the literature included in the analysis, there are five articles [38,39,42,49,50] on the application of XR in landscape aesthetic preference and cognition. Understanding preferences for natural landscapes is crucial for creating attractive green spaces and promoting the benefits individuals derive from nature. Previous research on landscape preferences has predominantly relied on quantitative, theory-driven methods that may overlook intricate human emotions and thoughts. Additionally, past studies often used static images, potentially failing to accurately represent the experiential and perceptual aspects of the real world. In addressing these issues, Yuan et al. [49] endeavored to unveil the key factors influencing landscape preferences through a VR-based approach utilizing 360° videos and interview questions. To determine the effects and differences of different landscape perception methods on landscape preferences, Gao et al. [38] investigated people's preferences for urban green spaces with different vegetation structures in early spring using three methods: field investigation, light excitation, and VR.

4.4.5. Landscape Virtual Nature Experience

Due to the temporal variations in seasonal changes of landscape and the extended growth cycles of plants, challenges arise in leveraging the social values of natural education and environmental conservation in landscape engineering. Simultaneously, unavoidable factors and geographic constraints sometimes prevent individuals from experiencing nature on-site in gardens [39]. Of the 68 studies included in the analysis, 17 articles are related to the research topic of virtual nature experience in landscape architecture. In general, these related studies apply XR to educational activities, interpretations, and interactive experiences [6] and provide richer and more lively and immersive ways of learning and engagement [18], realizing real-time interaction and information exchange with users, including voice, gesture, and image recognition [59]. In addition, of the fifteen XR systems developed in these studies, eight are VR systems, ten of them are AR systems, and two of them are MR systems.

- Immersive interactive experience

Nine of the articles [53–61] included in the analysis focused on providing an immersive, interactive experience. VR and AR enable visitors to experience natural environments in an engaging and educational manner. Some scholars have employed XR to simulate sensory environments, incorporating elements such as sound, vision, and touch, among others. This approach establishes a multimodal interactive virtual natural system, offering visitors an immersive experience during their visit. This utilization of XR contributes to a more comprehensive and sophisticated exploration of sensory engagement within virtual environments. For instance, Bettelli et al. [39] have developed an advanced system utilizing VR and AR, allowing visitors to engage more closely with the interaction between humans and animals. Paar et al. [58] described a story-centric virtual giant plant greenhouse VR exhibition, transforming botanical garden visitors from passive observers and readers into active participants through VR.

- Classroom education

Four of the articles [51,52,61,62] included in the analysis focused on classroom education. After the completion of landscape engineering construction, during the maintenance and operation phase, the gardens, with their living characteristics, provide users with social values such as natural education. XR can also be employed in specialized classroom education, such as landscape architecture or environmental studies and environmental awareness campaigns. It supports learners in actively engaging with plant observations, fostering higher cognitive processes, enhancing student interest, and promoting education that embodies creativity, environmental consciousness, teamwork, and digital learning experiences. For instance, Yang et al. [62] conducted research on a practical teaching approach for environmental landscape design based on IoT and VR. After guiding students through the cognitive construction of environmental landscape design, they established a virtual teaching environment. The system utilized gesture recognition technology to identify students' landscape design operations, allowing them to better grasp essential design information. In comparison to traditional learning methods involving plant observations, Chien et al. [52] presented an AR-based learning material that offered multiple perspectives of the studied plants. This approach significantly enhances students' higher-order cognitive abilities during classroom education, enabling them to construct knowledge more effectively about the target plants during observational learning activities.

- Plant education learning software

Four of the articles [18,59,63,64] included in the analysis focused on developing an application or system related to plant information education. XR facilitates a more scientific, intuitive, and vivid learning experience for fundamental plant information and pathological details. By creating educational software tailored to plant studies, it addresses the needs of students, botanists, biologists, medical professionals, and others working in the field who seek intelligent plant identification. For instance, Angeles et al. [64] developed an augmented reality mobile application for herbal plants. Integrating image recognition technology, the application presents three-dimensional models of herbaceous plants along with enhanced information, such as their characteristics, scientific names, vitamin content, and uses.

4.4.6. Landscape Project Management and Maintenance

Among the literature included in the analysis, there are three articles [16,65,66] focusing on the application of XR in the management of the operation and maintenance phase of landscape engineering. Among them, one is based on VR, one is based on AR, and one is based on MR. For example, Zhao et al. [65] proposed an intelligent construction and management framework to establish detailed plant models through BIM+MR, capture the dynamic updates of plant models with seasonal variability, and establish real-time data transmission methods to effectively achieve remote project coordination and plant maintenance. Wang et al. [16] applied IoT and AR to the plant management control system to reduce manpower requirements and improve the control performance of plant factories. The AR navigation information system, facilitated through a dedicated mobile application, delivers real-time interactive information. It allows for the live querying of the growth status and relevant details of various crops within the plant facility, providing direct feedback and integration of diverse information to the administrators. In this process, the paramount significance lies in the immersive interactive experience, which serves to heighten the interest of visitors.

4.5. Applied Technical Analysis

4.5.1. Analysis of XR Application Technical Hierarchy

In Figure 8, the numbers on each block represent the number of papers involving different XR techniques across all the studies included in the analysis, and the crossing areas indicate that multiple XR techniques may be involved in a single paper. Among the 68 literature studies identified in this study, combined with Table 6 and Figure 8, it can be concluded that (1) although the application of MR is involved in different aspects, the application proportion of MR In the construction and management of landscape engineering is the lowest; the use of AR is also relatively rare; VR accounted for the highest proportion of applications; (2) the application of VR, AR, and MR in the field of landscape architecture is relatively comprehensive at various stages; that is, the application of XR is involved in different aspects of application research.

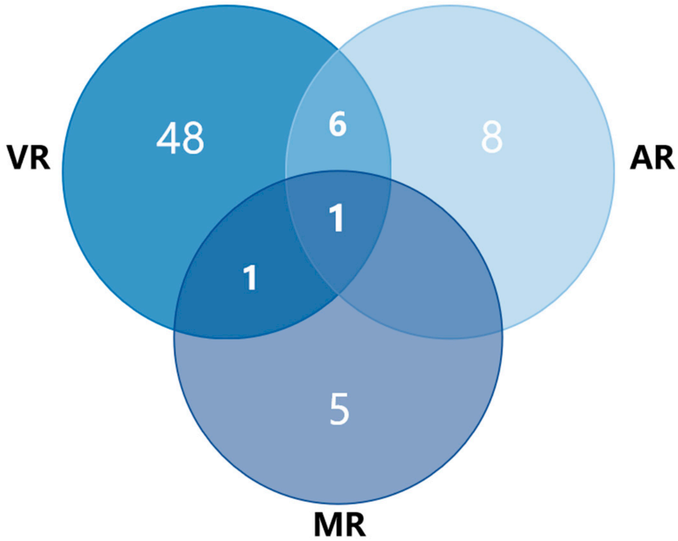

Figure 8. Venn diagram of various combinations of XR applications.

Table 6. Distribution of XR advantages and applications.

XR	Advantages	Number of Papers	Reference
VR	Fully immersive experiences, panoramic roaming, virtual simulation.	56	[3–15,22–43,45–50,53,54,58–63,66–70,82,83]
AR	Environment perception integration of virtual and real, enhanced interactive experience.	15	[16–19,21,39,46,51,52,54,57,61,63,64,69]
MR	Virtual and real seamless integration, multi-mode real-time interaction.	7	[20,30,44,55,56,61,65]

At the conceptual level of technology, extended reality is defined as the "Five Horizontals and Two Verticals" top-level technical framework. The "Five Horizontals" encompass near-eye display, perceptual interaction, network transmission, rendering processing, and content creation—constituting the five major technological domains. The "Two Verticals" refer to the crucial devices or equipment supporting XR development and content development tools or platforms. Despite substantial experiential differences between AR and VR, they share a common technological foundation characterized by multiple intersections across diverse technological domains. MR is generally understood as an augmentation of AR capabilities, representing a highly integrated stack within the AR technological framework [70,82].

- Application of VR in landscape engineering

Among the 68 articles included in this paper, 56 studies pertaining to the application of VR in landscape engineering construction and management. VR represents a comprehensive fusion of various technologies, including computer graphics, image processing, pattern recognition, intelligent interfaces, multi-sensor systems, speech processing, and audio–visual technologies. It constitutes a highly sophisticated and all-encompassing information technology [67]. At the technical application level, VR can afford users a futuristic panoramic virtual landscape and an immersive experience, finding extensive applications in landscape planning and design, as well as perception and preference assessments of landscape scenes. VR, employing intelligent mapping and panoramic displays, delivers realistic information simulation for designers, significantly enhancing design efficiency and effectively improving design quality [25]. VR can transcend temporal and spatial constraints, presenting changes that may take decades or even centuries to observe within a very short period. Integrating interactive experiences or novel display methods such as holographic videos allows for the scientific and artistic observation and appreciation of overall landscape schemes. VR addresses shortcomings in traditional 3D landscape presentations by capturing intricate details, including shadows between vegetation landscapes, the permeability of overall spatial layouts, and the sensory impact of terrain fluctuations on the landscape. It provides a high-information-density virtual display of landscape architecture [14].

- Application of AR in landscape engineering

Among the 68 documents included in this study, 15 articles delve into the application of augmented reality (AR) in landscape engineering construction and management. AR involves overlaying computer-generated virtual objects and information onto scenes in the real world, requiring perception of virtual objects in the real-world environment, achieving three-dimensional registration and facilitating interactive responses. AR finds extensive application in creating virtual natural experiences within landscape scenery. Particularly in leveraging the educational value of landscape environments, AR achieves a fusion of the virtual and real, enriching learning materials with more comprehensive content and vivid information. By providing a more realistic learning environment, it enhances the learning experience, enabling learners to interact with virtual objects effectively. Consequently, learners can explore and observe landscape environments more efficiently [52]. AR-supported learning activities often involve scientific observation of phenomena or objects, where mobile devices are more prevalent than head-mounted displays or other technologies [69].

Web XR comprises a set of standards supporting the rendering of 3D scenes for presenting virtual worlds (VR) or augmenting graphic images into the real world (AR). This API facilitates access to VR or AR virtual devices and tracks user pose movements [84]. Taking the example of the Rostock Botanical Garden, Westphal et al. [54] proposed a research approach utilizing Web XR based on mono panorama and stereo panorama. To ensure a high level of accessibility, the Web stack was transitioned from Web VR to the new Web XR standards. However, one drawback of Web XR is that complex 3D models and dense point clouds often require substantial optimization efforts for display.

- Application of MR in landscape engineering

Among the sixty-eight articles included in this paper, seven articles are related to the application of MR in the construction and management of landscape engineering. MR builds an interactive feedback information loop between the real world, the virtual world, and the user, which can achieve the integration of the virtual and real-time interactions, and its application in the field of landscape engineering is still in the preliminary stage of development, but it has greater development potential. MR has been applied in the fields of plant growth, plant growth monitoring and maintenance, landscape planning and design, landscape perception and preference assessment, landscape virtual nature experience, and landscape engineering management and maintenance. One of the technical challenges of MR-based landscape visualization is occlusion, a phenomenon that occurs when real objects in the foreground are obscured by superimposed 3D models. Dealing with occlusion in real time is crucial for landscape visualization during the planning and design phase when decision-makers and stakeholders evaluate landscape images before and during construction. Kido et al. [30] developed a future landscape evaluation system based on MR, which used semantic segmentation to evaluate landscape index and realized dynamic occlusion processing and landscape index estimation for landscape evaluation. In the process of virtual nature experience in natural museums, botanical gardens, and similar landscapes, the interactive application of MR has also played a huge advantage. By integrating features such as spatial mapping, virtual character animation, speech recognition, and visual tracking, Ali et al. [55] implemented a seamless multimodal interaction framework for intelligent virtual agents. In the realm of landscape engineering management and maintenance, Zhao et al. [65] have integrated Building Information Modeling (BIM) with MR. This integration further elucidates the temporal and spatial aspects of various information expressions related to landscape plants in a mixed-reality visual interactive environment.

This approach proves beneficial for collaborative design, retrospective tracking of landscape plant maintenance information, and scientifically effective landscape management.

4.5.2. Discussion of Virtual Engines for Creating XR Scenarios

The engines used to create XR application scenarios typically belong to a category of graphic engines, which provide developers with the necessary tools and functionalities to construct immersive and interactive virtual environments. Among the 68 articles included in this study, the majority of them involve the use of general-purpose graphic engines to create XR application scenarios, which serve as fundamental technological support. Additionally, some studies utilize specialized VR/AR/MR engines for their research purposes. The graphics engines or add-ons used to create XR application scenarios in all studies included in this analysis are shown in Table 7.

Table 7. The graphics engines or add-ons used to create XR application scenarios.

XR Technology	Graphics Engines	Number of Papers	Reference
Universal graphics engine	Unity 3D	10	[5,18,23,30,33,46,56,60,64,65]
	UE4	3	[19,36,58]
	Open Scene Graph (OSG)	1	[14]
VR	Oculus SDK	4	[28,36,43,49]
	Converse 3D	1	[3]
	Virtools	1	[3]
	Quest 3D	4	[3,14,29,66]
	VR-Platform	1	[3]
	KRETZLER 2006	1	[58]
AR	Vuforia	7	[18,20,21,57,63,64,69]
	Zappar	1	[41]
	ARKit or ARCore	5	[16,18,21,59,69]
MR	Microsoft Mixed Reality Toolkit	5	[30,44,55,56,65]
	Magic Leap SDK	1	[55]
Add-on applications	Adobe Photoshop CS6, Sketch Master, Sketch Up, Blender, 3ds Max, Rhino, Speed Tree, Onyx, Marlin Studios, Plant Factory, Android Studio SDK, Lumion	15	[3,4,9,13,18,22,24–28,32,36,53,59]
Not specified	There is no statement or description of the graphics engines or add-ons used to create XR application scenarios	29	[6–8,10–12,15,16,31,34,35,37–42,45,47,48,50–52,54,61,62,67,68,70]

- Universal graphics engine

Developers can effectively construct various types of virtual environments and interactive experiences utilizing graphic engines. As a general-purpose graphic engine, Unity 3D is widely employed in creating diverse cross-platform applications, including VR, AR, and MR scenarios, boasting robust tools, resources, and extensive community support [5,23]. Similarly, Unreal Engine offers advanced graphic rendering and physics simulation capabilities, suitable for applications requiring high fidelity [19,36]. Based on the Open Scene Graph (OSG) graphics rendering engine, the visualization of various types of 3D landscape models is realized, and the spatial layout of various types of landscape with parametric control is realized through digital vector layers, which flexibly manage and organize various garden elements and reasonably organize the spatial topological relationship between various types of landscape in 3D space [14].

- VR engine

At present, the virtual reality software used at home and abroad mainly includes Virtools, Quest 3D, Converse 3D, VR-Platform, and so on. Through the combination of 3D modeling technology and virtual simulation technology, the modeling and scene planning of urban 3D art landscape are carried out [3]. Oculus provides a software development kit (SDK) for developing VR applications, supporting the creation of applications compatible with Oculus VR devices [36].

- AR engine

Vuforia is an engine specifically designed for AR application scenarios, capable of overlaying virtual architectural models onto real-world environments at construction sites for real-time navigation and visualization [18,57]. Native AR development frameworks, such as ARKit and ARCore, are suitable for creating high-quality AR applications running on mobile devices, enabling the presentation of virtual landscape models and design schemes within real-world environments [16,21].

- MR engine

Microsoft Mixed Reality Toolkit is a development toolkit for creating MR applications, supporting devices such as Microsoft HoloLens. It enables the fusion of virtual architectural models with real-world environments, providing interactive experiences [30,55]. Additionally, Magic Leap offers an SDK for developing MR applications compatible with its head-mounted display device, facilitating the creation of virtual landscapes and interactive design experiences in landscape architecture [55].

- Add-on applications

In addition to graphic engines, various add-on applications are utilized in the development of VR, AR, and MR applications. Leveraging these tools, developers can craft high-quality software packages compatible with a range of XR devices and platforms, offering users rich and immersive experiences. For instance, applications such as Sketch Master [22] and Adobe Photoshop [36] are employed for creating and editing diverse 3D models, textures, and images. Many 3D forest scenes are created through specialized vegetation 3D modelling software, such as Speed Tree, Onyx, Marlin Studios, and Plant Factory [4]. Additionally, professional 3D modeling and animation software. like 3ds Max [3], Rhino [9], Blender [18], and Sketch Up [24] are utilized to produce high-fidelity virtual environments and characters, enhancing the realism and visual effects of XR applications, rendering via 3D visualization platforms such as Lumion [22].

4.5.3. Discussion of Technology Devices for XR

XR devices provide crucial support for XR applications in the field of landscape engineering, enabling designers, engineers, and stakeholders to experience more intuitive and interactive design and visualization experiences. These hardware devices mainly include head-mounted displays (HMDs) and other auxiliary computing devices, including PC devices and mobile devices. The hardware devices used to support XR in all studies included in this analysis are shown in Table 8. Among them, the most critical device is the HMD, a compact display or projection system integrated into eyewear or affixed to headgear such as helmets, visors, or optical lenses. It facilitates the streaming of data, images, videos, and other pertinent information directly into the user's field of view. There exist primarily two types of head-mounted displays: VR headsets, which exclusively render virtual imagery, and AR or MR headsets, which augment computer-generated images onto the real-world environment [44]. Both variants are proficient in processing three-dimensional virtual environments and projecting the outcomes onto stereoscopic displays [11,69]. Additionally, HMDs commonly incorporate motion sensors to ascertain orientation and movement, thereby facilitating user interaction within immersive virtual reality applications. A salient feature of HMDs lies in their ability to track the wearer's head and ocular movements [48,52]. Consequently, the visual content displayed on the screen dynamically adjusts based on the wearer's head positioning and focal fixation [5,11].

Table 8. The hardware devices used to support XR.

Devices	Inclusion	Number of Papers	Reference
HMDs	HTC Vive, Microsoft HoloLens, Microsoft HoloLens2, the second-generation VR glasses of the illusion mirror type, Oculus DK2, Oculus rift, Oculus Go.	33	[3,5,6,11,17,28,30,34,36–50,52,55–58,60,61,65,66,69]
PC devices	Fixed computing devices, mainly including desktop computers, projectors, cameras, LED large screens, and digital interpretation machines installed in landscape engineering sites.	34	[3,4,6–13,17,19,22,25–27,29,31,33,34,36,37,41,42,44,49–54,61,65,69]
Mobile devices	Handheld, wireless computing devices, including mobile phones and tablets.	15	[15,16,18,20,21,28,30,36,39,40,51,59,63,64,69]
Not specified	There is no statement or description of XR devices.	9	[23,24,35,43,45,62,67,68,70]

4.5.4. Analysis of XR Combined with Other Technologies

XR can be integrated with various other technologies in the processes of landscape engineering construction and management, encompassing fields such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data Analytics, and 3D Geographic Information Systems (GISs). Table 9 shows the advantages and applications distribution of XR combined with other technologies.

Table 9. Distribution of XR advantages and applications.

Other Technologies	Advantages	Number of Papers	Reference
IoT	Remote monitoring and control.	6	[16,26,27,29,57,62]
AI	Real-time image processing, object recognition and tracking, multimodal sensory interaction.	20	[7,10,12,14,17,19,21,23,27,30–35,50,53,55,63,67]
Big Data Analytics	Deep data mining, multi-source data fusion.	5	[8,9,24,27,35]
3D GIS	Real-time geographic information data acquisition, accurate generation of 3D point cloud data models.	3	[13,40,60]

- XR and IoT

Among the sixty-eight articles included in this paper, six articles are related to the combination and application of IoT and XR in landscape engineering construction and management. IoT involves connecting sensors and other devices to collect data on plants and other environmental factors, facilitating real-time data acquisition, transmission, and sharing. XR typically integrates cameras, sensors, and display devices to capture and present virtual elements in real time. For example, Wang et al. [16] integrated IoT with AR in a plant management control system. In this context, IoT is employed to sense environmental parameters, control device units, utilize Wi-Fi wireless methods for data transmission, and employ cloud databases for reception, storage, computation, and monitoring. Zarraonandia et al. [57] proposed a pervasive AR game where the AR garden presented incorporates physical elements such as pots with sensors and RFID tags containing plant information. These physical elements are combined with virtual elements represented through AR, including plant models and information. This integration helps determine the health status and growth rate of plants, ultimately selecting virtual plant models that best represent their current stage and condition.

- XR and AI

Among the 68 articles included in this study, 20 articles specifically explore the integration and application of AI and XR in landscape engineering construction and management. These studies primarily encompass various research directions, such as natural language processing, machine learning, and computer vision.

Due to the complexity and morphological diversity of forest plant structures, the three-dimensional reconstruction of green plants in real environments poses a challenging problem in computer graphics and virtual visualization research [7,10]. XR captures the real world through cameras and sensors, overlaying virtual information into the user's field of view through computer graphics. Leveraging natural language processing, computers can comprehend, interpret, and generate human language, incorporating techniques like text analysis and speech recognition. XR responds to user queries in a virtual manner [17,55], providing information on plants, landscapes, history, etc. Designers utilize voice commands to adjust virtual landscape designs, with real-time feedback reflected in the XR interface. Addressing challenges in exploring generative design, users can navigate simulated, instantiate, introspect, and configure simulated elements, allowing coordination of more simulation agents in real-time interaction between users [17].

Machine learning facilitates system learning and adaptation to various plant information and landscape data through model training [12] and algorithm optimization [27]. It can be employed to enhance XR experiences, allowing managers in landscape engineering planning and design to make predictions or decisions more scientifically and efficiently. Currently, target detection networks in deep learning are widely used for detecting plant growth states. However, existing methods face challenges in constructing high-quality, large-scale plant datasets for plants in complex growth environments with difficult image capture. Addressing this issue, Xing et al. [19] proposed an AR-based method for constructing datasets for plant growth state detection tasks. This approach rapidly and efficiently constructs large-scale field datasets matching real inspection environments, significantly contributing to improving model detection accuracy and generalization ability. XR, through human–computer interactions, provides crucial insights into understanding the human visual perception process [53]. Additionally, deep learning in the field of view offers analytical approaches for image classification, processing, and segmentation [50]. For instance, Kido et al. [30] developed an MR-based future landscape assessment system capable of recognizing the surrounding environment and estimating landscape indices using deep learning semantic segmentation.

The combined application of computer vision and XR enables computers to comprehend, analyze, and extract information regarding images and video content. This integration goes beyond traditional two-dimensional plant configuration designs, providing a multisensory, multi-environmental, and temporally immersive experience for landscape design. The system can actively perceive and respond to the user's surrounding real environment, recognizing plants or landscape elements in real time [14,23,31–34]. For instance, Li et al. [33] utilized three-dimensional images for image recognition, capturing real-time landscape images and reconstructing three-dimensional landscape images using SURF feature matching technology. They proposed a novel simulation technique for the rational distribution of landscapes based on three-dimensional images and VR. Computer vision methods automate the analysis of traditional landscape images, reducing the need for researcher intervention. Coupled with algorithms based on deep learning, these methods minimize time and human resource inputs, garnering attention in areas such as plant growth health monitoring, landscape preference assessment, and plant education learning [21,30,35,50,63,67].

- XR and Big Data Analytics

Among the sixty-eight literature studies included in this paper, five articles are related to the combination of big data analysis and XR and its application in the construction and management of landscape engineering. By using data mining [27], data fusion [35], and other technologies, big data analysis methods, such as association rule mining, cluster analysis, principal component analysis, anomaly detection, classification, and prediction model, are explored to deeply mine big data of landscape architecture and quickly and accurately discover, refine, and analyze valuable information in trajectory data [8,9]. The combination of data fusion and VR in landscape design has demonstrated significant effectiveness in modeling, design capabilities, innovation, and expressive abilities [24]. For instance, Zhan et al. [35] achieved notable results by employing a landscape information fusion model based on genetic neural networks to integrate three-dimensional landscape generation data with modular data, providing a clear and intuitive representation of the overall structure of the landscape.

- XR and 3D GIS

Among the sixty-eight articles included in this paper, three articles specifically address the application of 3D GIS in landscape engineering construction and management. 3D GIS serves as a valuable tool for visualizing the green space management process. By utilizing real-time geographic data captured through 3D GIS and integrating it with XR, the data are overlaid in the user's field of view, providing a real-time display of changes in terrain, architectural design, and other information within the real-world scene [13,40]. In their research on the comprehensive perception assessment of urban forest soundscapes, Sacchelli et al. [40] integrated the visual effects presented by Google Maps' Street view with the auditory stimuli presented through headphones integrated into VR headsets. This integration enabled the possibility of conducting landscape preference assessment surveys based on immersive VR. Three-dimensional point cloud data obtained through 3D laser scanning can be integrated into a 3D GIS environment to enhance the realism and accuracy of geographic information. Through method refinement and optimization, high-density and accurate three-dimensional point cloud data models are generated for better integration into virtual reality development environments [60]. To address technical accuracy challenges in complex landscape and garden terrain planning, Huang et al. [13] accurately obtained three-dimensional point cloud data of the landscape using 3D laser scanning. They established a three-dimensional model based on point cloud data to create a three-dimensional stereoscopic image of the landscape, thereby enhancing the realism of the three-dimensional virtual landscape.

5. Future Research Agenda on the Application of XR in Landscape Engineering

5.1. Challenges in the Application of XR in Landscape Engineering

This study provides a comprehensive overview of the challenges faced by XR in various application scenarios and highlights the unresolved technical limitations. Table 10 summarizes the application challenges of XR software development and XR hardware devices.

- XR software development

As all studies are fundamentally based on constructing virtual three-dimensional landscape models, a significant limitation in this process is the challenge of preparing resources to match real-world virtual three-dimensional models and soundscapes, namely the difficulty in establishing a library of landscape element models. Furthermore, the authenticity of virtual scene simulation and the applicability of application scenarios require improvement [4–15]. As a tool for visual simulation, XR has certain limitations compared to other visualization techniques. For instance, Gao et al. [38] conducted a comparative study using on-site surveys, light stimulation, and VR to investigate people's preferences for urban green spaces with different vegetation structures in early spring. Based on the research results, they suggested caution in the use of VR for sites characterized by strong vegetation heterogeneity, complex elements, and diverse spatial structures.

Table 10. Challenges in the application of XR in landscape engineering.

Type	Challenges	Reference
XR software development	The establishment of a landscape element model library encounters challenges.	[4–15]
	The authenticity and applicability of virtual scenes are constrained.	[3–14,38]
XR hardware devices	XR devices pose discomfort issues such as motion sickness.	[2,66,82,83]
	XR devices experience high network latency and low frame rates.	[2,58,82,83]

- XR hardware devices

Considerations regarding the head-mounted design of XR devices encompass aspects such as weight distribution, headband material, and the overall helmet design. Some scholars have pointed out potential design flaws in current XR devices, such as devices being excessively heavy or unbalanced, leading to discomfort during prolonged usage. For example, the study presented by Slob et al. [66] aims to explore the potential obstacles of integrating VR with 3D digital twins in greenhouse horticulture or agriculture, with a specific focus on the human–machine interaction aspects of digital twins and the subfield of motion sickness. Technical limitations such as high latency and low frame rates may also be present in XR devices during usage [58].

5.2. Potential Application Scenario of XR in Landscape Engineering

For future endeavors to overcome the challenges, numerous scholars have proposed corresponding solutions tailored to their own research. For instance, Paar et al. [58] suggested the necessity of a cloud database to handle vast amounts of data related to landscape elements. They proposed the establishment of a globally or nationally collaborative, visually compatible open-source library for 3D models of flora and fauna, including sound recordings, particularly those of birds, insects, and mammals. This study consolidates commonalities found in most research, addressing the challenge of establishing a library for landscape element models. The following developmental prospects are proposed:

1. Automated Model Generation: Undertake research to achieve automated modeling of landscape elements. Utilizing technologies such as computer vision and deep learning to develop algorithms capable of extracting data from real-world scenarios and generating virtual models to alleviate the manual workload in modeling;
2. Open Data Sharing: Advocate for the establishment of an open-access database for landscape elements, enabling researchers and developers to share and access standardized models. This can facilitate broader collaboration and enhance the quality of virtual scene simulations;
3. Crowdsourcing and Collaborative Modeling: Employ crowdsourcing and collaborative modeling approaches to involve the community in model creation, leveraging collective intelligence to collect, organize, and optimize landscape element models.

6. Conclusions

This study provides a comprehensive review of XR applications in landscape engineering construction and management. Initially, an analysis of annual publication volumes, citation counts, journal distribution, geographical distribution, and other bibliometric statistics was conducted to gain a general understanding of XR applications in the field of landscape engineering. The focus was then placed on a detailed analysis and summary of the integration of XR in various application scenarios. Additionally, the study analyzed the advancement of XR technology itself, along with its integration with other technologies. This approach allowed for an in-depth analysis of the challenges faced by XR in the application process within landscape engineering, leading to the formulation of potential XR technology applications and future research directions in landscape engineering construction and management. Despite the immense potential of XR technology, its widespread adoption in the landscape industry is currently hindered by issues such as discomfort from prolonged use of bulky XR headsets, sensitivity to on-site environmental conditions, and network transmission challenges.

In conclusion, the research findings of this paper aim to facilitate the broader application of XR in landscape engineering construction and management. However, it is essential to acknowledge the limitations of this study. The effectiveness of the literature review is most significantly compromised by the retrieval of data from the database. The databases used in this study were selected based on their relevance to the field of landscape engineering. To the best of the authors' knowledge, these databases cover a substantial number of published articles. Nevertheless, the exclusion of certain databases may result in the omission of other types of literature in this review. Furthermore, the specified search terms may fail to consider pertinent research articles.

Author Contributions: Conceptualization, X.Z. and S.L.; methodology, X.Z. and S.L.; software, X.Z. and S.L.; validation, X.M., X.Z. and S.L.; formal analysis, X.Z. and S.L.; investigation, X.Z. and S.L.; resources, X.M., X.Z. and S.L.; data curation, X.Z. and S.L.; writing—original draft preparation, X.Z. and S.L.; writing—review and editing, W.J., L.L. and S.L.; visualization, S.L., X.Z., X.M., W.J., L.L., W.L., Y.T., Y.P. and Q.Y.; supervision, X.M. and X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to thank Beijing University of Technology, Beijing, China.

Conflicts of Interest: The authors declare no conflicts of interest.

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