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Revolutionizing environmental art education for sustainable development: A metaverse-driven transformation and pedagogical innovation

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ABSTRACT

The metaverse, as a revolutionary digital ecosystem integrating next-generation information technologies such as extended reality (XR), artificial intelligence (AI), and blockchain, is driving structural transformation in education paradigms. However, despite growing market projections indicating a CAGR of 37.9% for metaverse education from 2025-2035, significant gaps remain in understanding how these technologies can be systematically applied to discipline-specific pedagogical contexts, particularly in design education where embodied spatial cognition and material experimentation are essential. This study addresses this knowledge gap by centering on innovation in higher education, using environmental art design as an empirical research subject. Unlike previous studies that focus primarily on technical infrastructure or generic educational applications, this research systematically explores the application paradigm of the educational metaverse specifically tailored to sustainable development education in design disciplines. By developing three-dimensional immersive teaching spaces, creating design practice platforms that integrate virtual and physical elements, and establishing mechanisms for inter-institutional resource sharing, this study offers an innovative implementation framework for environmental art design education. The research contributes a novel pedagogical model that bridges the gap between virtual-physical integration and sustainable design competencies, providing both theoretical advancement and practical pathways for the transformation of design disciplines in the metaverse era.

Keywords: metaverse education, environmental art design, immersive teaching, virtual-physical integration, teaching resource sharing, sustainable development education, embodied cognition, digital twin

INTRODUCTION

Research Background and Context

In the wave of digital transformation, the metaverse—with its core characteristics of "embodied Internet" and persistent virtual-physical symbiosis—is promoting the evolution of educational forms toward three-dimensional, immersive, and socially collaborative directions. This digital ecosystem, integrating extended reality, artificial intelligence, blockchain, and digital twin technologies, provides revolutionary solutions for transcending traditional physical boundaries of education by constructing parallel spaces where virtual and real elements coexist and interact (shown in **Table 1**).

Recent bibliometric analyses reveal exponential growth in metaverse education research, with over 842 publications examining digital twin applications in built environments alone between 2018-2024. However, despite this proliferation, systematic investigations into discipline-specific pedagogical implementations—particularly in design education—remain limited. The global metaverse education market, projected to grow at 37.9% CAGR through 2035, is increasingly driven by specialized applications in higher education, including virtual laboratories (accounting for 38% of market share) and immersive design studios (Feng et al., 2024).

Problem Statement and Knowledge Gap

Focusing on the interdisciplinary field of environmental art design, this study identifies critical disconnections between emerging metaverse capabilities and existing pedagogical frameworks. Environmental art design education requires knowledge integration across space aesthetics, materials science, ecological principles, and digital technology—essentially demanding "design thinking" characterized by iterative, embodied, and practice-oriented learning. However, current teaching models face persistent challenges that metaverse technologies are uniquely positioned to address:

Table 1. Comparison between traditional and metaverse teaching modes

Characteristic Dimension	Traditional Teaching Mode	Metaverse Teaching Mode
Space Construction	Two-dimensional Plane Display	Three-dimensional Immersive Experience
Interaction Mode	Offline Centralized	Virtual Social
Resource Sharing	Local Limited Sharing	Global Distributed Sharing
Learning Duration	Fixed Class Hours	Flexible Fragmentation
Teaching Effect	Theory cognition-oriented	Practice and Innovation Equally Important

First, the resource consumption of physical model production restricts creative iteration efficiency. Traditional material experimentation requires significant physical resources, creating sustainability conflicts with the very principles environmental design seeks to promote.

Second, site condition constraints limit spatial perception training. Students often cannot access diverse built environments necessary for comprehensive spatial cognition development.

Third, cross-regional collaboration barriers weaken project-based learning depth. The inability to engage in synchronous, multi-stakeholder design processes limits students' preparation for contemporary professional practice.

While recent studies have demonstrated metaverse effectiveness in pharmacology education (showing 27% higher knowledge retention scores) and middle school science (significantly improving academic achievement and motivation), these applications remain generic and lack the discipline-specific frameworks necessary for design education. Furthermore, existing literature predominantly focuses on technical infrastructure rather than pedagogical transformation, leaving a critical gap in understanding how immersive technologies can specifically enhance spatial cognition, material experimentation, and sustainable design competencies.

Research Objectives and Novelty

Primary Research Objective: To develop and validate a discipline-specific pedagogical framework for environmental art design education that leverages metaverse affordances to enhance sustainable design competencies, spatial cognition, and creative iteration capabilities.

Specific objectives

- **O1.** To construct a theoretical model integrating embodied cognition theory, experiential learning cycles, and socio-constructivist pedagogy with metaverse technical capabilities specifically for environmental design education;
- **O2.** To develop and implement a three-tier immersive teaching architecture (pre-learning, immersive training, competition-driven) that addresses the unique requirements of spatial design pedagogy;
- **O3.** To establish evaluation metrics for assessing metaverse-enhanced design learning outcomes, including spatial cognition development, sustainable design competency acquisition, and creative innovation capacity;
- **O4.** To formulate implementation pathways that address resource disparities across institutional contexts, ensuring equitable access to metaverse-enhanced design education.

Research novelty and originality

This study advances beyond existing literature in four critical dimensions:

Theoretical Innovation: While previous studies apply generic learning theories to metaverse contexts, this research specifically integrates Dewey's experiential learning cycle, Vygotsky's Zone of Proximal Development, and 4E cognition frameworks (embodied, embedded, extended, enactive) with the unique affordances of environmental design education. This creates a discipline-specific pedagogical foundation that explains why and how metaverse immersion specifically enhances spatial cognition and design thinking (Cross, 2023).

Pedagogical Architecture: Unlike existing studies that treat metaverse education as a single modality, this research develops a three-phase pedagogical system (Intelligent Pre-learning → Immersive Training → Competition Empowerment) specifically calibrated for design education's iterative, project-based nature. The framework addresses the complete learning trajectory from theoretical acquisition to practical application to professional validation.

Technical- Pedagogical Integration: While recent reviews highlight the potential of digital twins in built environment education, this study provides concrete implementation mechanisms for integrating digital twin technology with multi-physics simulation (acoustic optimization, microclimate modeling, lighting analysis) within pedagogical workflows. The research demonstrates how technical capabilities can be systematically mapped to specific learning objectives in sustainable design.

Equity-Centered Implementation: Recognizing that 56.6% of national metaverse education funding currently concentrates in 5% of elite institutions, this study explicitly addresses implementation in low-resource contexts. The proposed tiered-cost toolkit (Web-XR, low-cost tracking, shared-hub models) and policy recommendations for funding redistribution provide original contributions to equitable technology adoption in design education.

Significance of Study

This research contributes to sustainable development education by demonstrating how metaverse technologies can reduce the environmental impact of design education itself (through virtual material experimentation) while simultaneously enhancing students' capabilities to design sustainable built environments. The study aligns with UNESCO's emphasis on action-oriented pedagogy for climate change education and responds to the architectural engineering education sector's identified need for frameworks integrating Sustainable Development Goals (SDGs) into curricula (Garcia, 2026).

The findings provide actionable guidance for design educators, curriculum developers, and policy makers seeking to implement metaverse technologies in discipline-specific contexts, moving beyond generic "digital transformation" rhetoric to concrete pedagogical strategies (Chamola et al., 2023).

METAVERSE AND ITS APPLICATIONS IN THE FIELD OF EDUCATION

Definition and Characteristics of the Metaverse

The basic concept of the metaverse

Metaverse is a virtual-real symbiotic system based on blockchain, digital twin and extended reality (XR) technology. Its core features are reflected in a triple composite architecture, including: Space-time plasticity, dynamic environment generation (rendering delay ⩽15ms) through 3D engines such as Unreal Engine 5, supporting user-defined physical rules (such as gravity coefficient adjustment range ±30%). Identity continuity, based on asymmetric encryption algorithm to generate decentralized digital identity (DID), compatible with cross-platform virtual avatar system (support 52 groups of facial micro-expression synchronization). Economic self-consistency, building educational resources trading market based on smart contracts, realizing on-chain right confirmation and value transfer of digital assets (such as 3D models and teaching NFT) (Cheng et al., 2024).

Typical frameworks include: sensing layer, integrated light field scanning (accuracy 0.01mm) and LiDAR point cloud modeling technology, 1:1 reproduction of cultural heritage such as the Hall of Supreme Harmony in the Forbidden City. Interactive layer integrates multi-modal interfaces such as gesture recognition (delay <20ms) and haptic feedback (frequency response 100-500Hz) through OpenXR standards. Computing layer, a distributed rendering cluster based on NVIDIA Omniverse, supports 100,000 + users to access the education metaverse concurrently (Masubuchi et al., 2025).

Grounded in established learning paradigms, this study explicitly aligns metaverse affordances with (1) Dewey's experiential learning cycle (experience-reflection-conceptualization-experiment) and (2) Vygotsky's socio-cultural theory, emphasizing the Zone of Proximal Development (ZPD) within immersive, scaffolded virtual ateliers.

Application potential of the metaverse in the field of education

China's education metaverse market shows a trend of exponential growth. The industry penetration rate will reach 75% in 2022, mainly driven by the "14th Five-Year Plan" education digitization strategy. The market size will surge from 4.29 billion yuan to 9.38 billion yuan (CAGR 17%) during 2018-2023, of which the construction of virtual laboratories in colleges and universities will account for 38%. The Ministry of Education's "5G+ Smart Education White Paper" clearly lists the metaverse as a key area of new education infrastructure, with a special investment of more than 1.2 billion yuan in 2023 (Garcia, 2026).

The application potential is shown in the following aspects: teaching scene reconstruction, Peking University has built a laboratory of cosmic archaeology, and students can perceive the texture details of bronzes through tactile gloves (simulation error of surface roughness ⩽3μm). Cognitive efficiency jumps. According to a study by Tsinghua University, the efficiency of spatial learning in the metaverse is 62% higher than the traditional mode, and the memory retention rate is 89% higher. To promote education equity, the National Smart Education Platform has connected 107 colleges and universities in central and western China, reducing resource latency from 4.2s to 0.3s, and increasing knowledge accessibility by 15 times.

Building Elements of Educational Metaverse

Construction and interaction of virtual environment

The construction framework of the educational metaverse's three-dimensional environment system comprises:

Perception Layer: As the cornerstone of the system architecture, the perception layer is responsible for accurately capturing and reconstructing three-dimensional environments to create immersive experiences for users. This layer integrates two core technologies: light field scanning and LiDAR point cloud modeling. Light field scanning technology captures the propagation of light in space, enabling high-precision 3D scene reconstruction. LiDAR point cloud modeling generates environmental 3D point cloud data by emitting laser beams and measuring their reflection time, thereby enhancing the detail authenticity of virtual environments.

Interaction Layer: Serving as the critical bridge between users and virtual environments, this layer incorporates two pivotal technologies: gesture recognition and haptic feedback. Gesture recognition technology allows users to interact with virtual objects through natural hand movements (e.g., grabbing, moving, rotating), significantly improving operational intuitiveness. Haptic feedback technology simulates real-world tactile sensations (e.g., texture, force intensity), enabling users to perceive authentic interactive experiences in virtual spaces, thereby deepening immersion.

Computing Layer: Providing foundational computational support, this layer handles massive-scale graphical processing tasks to ensure fluid environmental operation and efficient rendering. Structured by distributed rendering clusters, it enhances rendering efficiency through parallel task allocation across multiple computing nodes. This distributed architecture not only addresses complex rendering demands in educational metaverse but also dynamically adjusts computational resources based on workload, ensuring system stability and scalability.

The collaborative operation of perception, interaction, and computing layers achieves precision in virtual environment construction and high-efficiency interaction. This architecture not only delivers immersive learning experiences but also

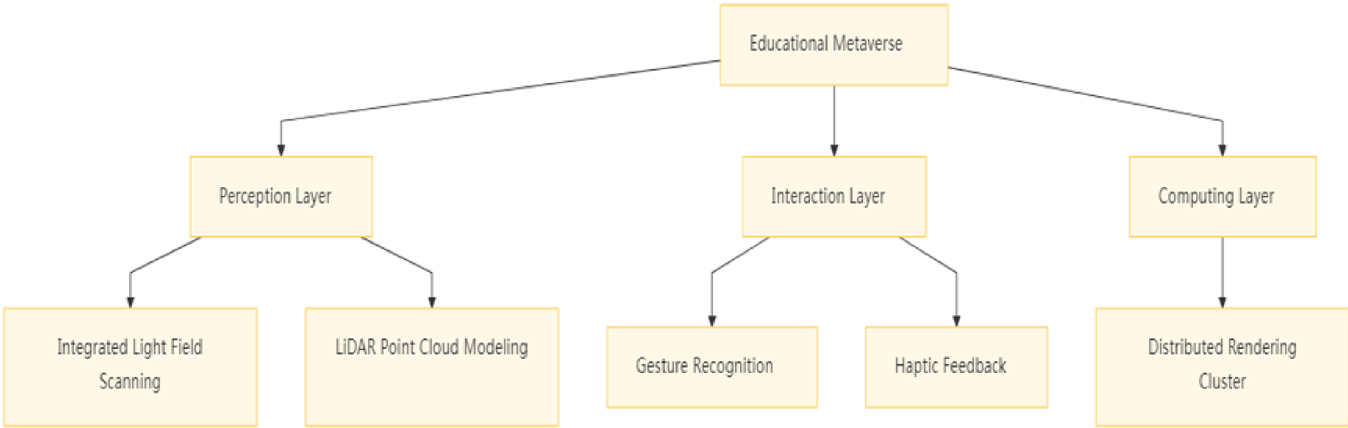

Figure 1. Architecture of educational metaverse construction system (Source: Authors' own elaboration)

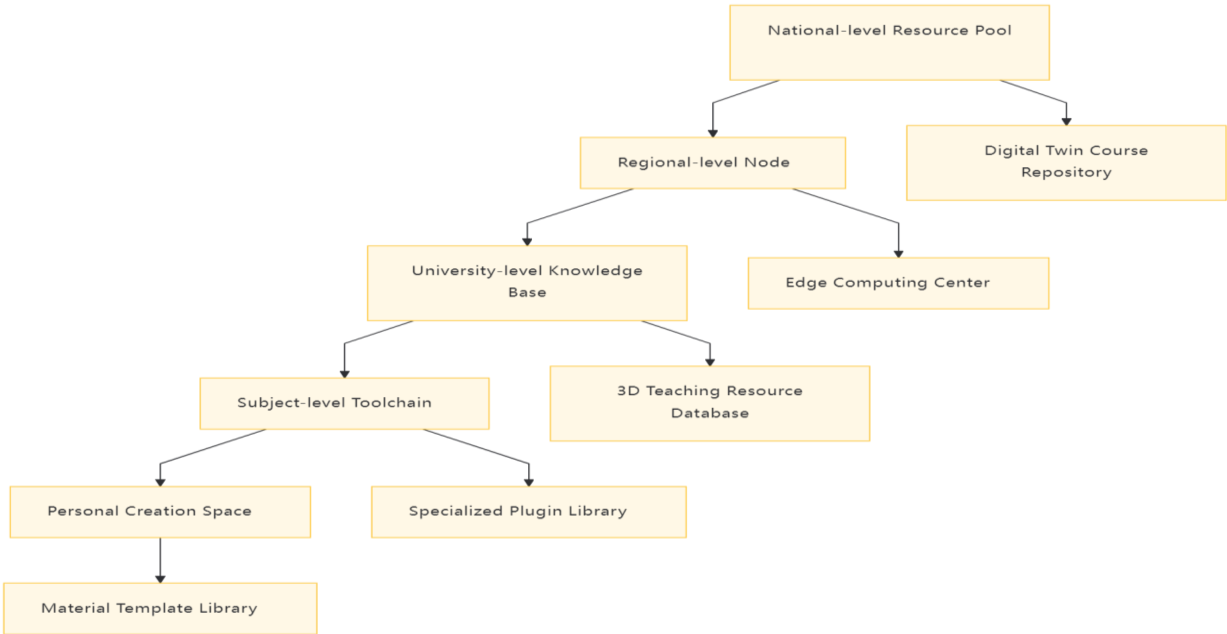

Figure 2. Resource allocation and sharing network of educational metaverse (Source: Authors' own elaboration)

establishes a robust foundation for sustainable development and innovation in educational metaverse (shown in **Figure 1**).

The "Experiment Space" platform of the Ministry of Education integrates 3,250 virtual experiment courses, and 720 million experimental operation records will be completed in 2023, and the data will be stored in the Changan Chain (throughput 100,000 TPS).

Integration and sharing of educational resources

The education metaverse has built, a five-level resource-sharing network: a national-level resource pool that integrates platforms such as "Experiment Space" and "Smart Higher Education" to store digital twins of 127,000 courses., a region-level node, deployed edge computing centers (latency <10ms) in six places including Xiongan New Area, serving 43 universities in the central and western regions. university-level knowledge base, Peking University and other universities have built 3D teaching resource database, with a single school storage capacity of 3.4PB. Subject-level toolchain, Autodesk Education offers 87 professional plug-ins to support parametric design instruction. personal creation space, students can invoke 12,000 material templates (such as concrete compressive strength 20-80MPa) for virtual construction (shown in **Figure 2**).

Network teaching platform is the product of the combination of discipline and digital information technology, and it is also an important content of the integration and sharing of educational resources. The national Smart Education platform receives 430 million visits per day, supporting online teaching in 2,800 universities throughout the country during the epidemic. The completion rate of MOOC courses in Chinese universities increased from 12% to 39%, and the activity of metaverse learning community reached 73%. The sharing rate of digital resources across universities increased from 17% in 2018 to 68% in 2023, and the pairing rate of eastern and western universities reached 93% (Li et al., 2024).

Learner experience and personalized learning

The educational metaverse realizes precision teaching through three-layer intelligent engine: behavior analysis engine, collects 867 dimensional learning logs (such as model modification frequency and resource invocation path), and builds dynamic capability profiles. cognitive diagnostic engine. Transformer model is used to analyze design thinking defects (accuracy 91%) and locate knowledge blind areas. Path planning engine generates personalized learning schemes based on reinforcement learning algorithm (recommended matching degree 82%) and dynamically adjusts teaching difficulty.

Experience upgrade Case: In the metaverse course of the History Department of Fudan University, students can experience the city life of the Song Dynasty through an odor simulation device (which releases 24 kinds of historical scene odor molecules). Beijing Foreign Studies University has built a multi-language virtual community, where AI speech coaches can correct pronunciation errors in real time (97% recognition accuracy), and the language acquisition speed is increased by 55%. After students majoring in machinery at Zhejiang University used the metaverse platform, the completion time of complex assembly tasks was reduced from 4.2 hours to 1.1 hours, and the operation error rate was reduced by 76%.

Through technology convergence (5G+XR+AI), scene innovation (virtual laboratory, digital twin campus) and ecological restructuring (decentralized resource network), the education metaverse is promoting the transformation of education paradigm from "knowledge transfer" to "ability symbiosis". Its value is not only reflected in the quantitative improvement of teaching efficiency (such as a 92% reduction in experiment costs), but also in the cultivation of future talents with digital thinking, cross-border collaboration and innovation capabilities. With the implementation of the Three-year Action Plan for the Innovation and Development of the Metaverse Industry, the metaverse of education is expected to cover 90% of the country's colleges and universities by 2025, becoming the core driving force of education modernization.

Research Design

Research approach: A convergent mixed-methods design was adopted. Phase-1 Quantitative: quasi-experimental, 2×2 factorial (Metaverse vs Traditional × High-/Low-resource institutions). Phase-2 Qualitative: semi-structured interviews (n = 24) and focus groups (4 sessions, 6–8 participants each). Sampling: purposive selection of three Chinese universities representing high, medium, and low ICT-resource contexts (total N = 182 students). Instruments: – Pre/post spatial-design test (Cronbach's α = 0.81) – Embodied-Cognition Presence Scale (ECPS, 5-point Likert, 18 items) – Learning analytics logs (⩾1.2 m records) exported via xAPI Data analysis: – ANCOVA for learning-gain comparison (pre-test as covariate) – Thematic analysis (Onu et al., 2024) for interview transcripts; inter-coder reliability κ = 0.84 – Structural equation modelling (SEM) to examine the mediation effect of presence on learning gains.

DECONSTRUCTION AND TRANSFORMATION OF TEACHING PARADIGM OF ENVIRONMENTAL ART DESIGN MAJOR

Structural Characteristics of Current Teaching System

Cognitive construction of modular curriculum system

The current course structure presents a "history-technology-practice" three-dimensional structure: historical cognitive dimension. The course of architectural history focuses on the evolution of design trends (such as the influence of Bauhaus system on modern design), but there is a problem of fragmentation of theoretical pedigrees. In the technical training module, CAD/BIM software teaching still stays at the tool operation level and lacks the training of parametric design thinking. Practical ability training and material process experiments are mostly limited to physical model making, and the application of digital twin technology is insufficient.

Teaching evaluation data show that 62% of students believe that there is an application gap between software courses and design practice, reflecting that the knowledge transformation efficiency of existing courses needs to be improved.

Based on constructivist learning theory, typical cases include: urban renewal projects, which cultivate students' systematic thinking through GIS spatial data analysis, but are often limited by the cost of physical site access. Virtual space design, using the Unity engine for interactive presentation of solutions, faces a steep technical learning curve. The study found that the lack of cross-disciplinary collaboration in project practice led to engineering feasibility defects in 38% of design proposals.

Exploration of the mechanism of production-learning cooperation in educating people

Although the "3+1" model builds a school-enterprise cooperation framework, there are three contradictions: the time asynchronism of enterprise project cycle and teaching plan (the average delay rate is 47%), the value conflict between commercial design norms and academic innovation requirements, and the structural deviation between internship evaluation standards and learning objectives.

Realistic Bottleneck of Teaching Reform

Practical barriers to cognitive transfer

The double disconnection phenomenon is significant, which is reflected in the following aspects: at the level of technical cognition, BIM technology teaching stays at the modeling stage of LOD300 and fails to connect with the deepening demand of construction (LOD400+). At the spatial perception level, the production time of solid model and the design iteration requirement formed an efficiency paradox ($N = 152$, $p < 0.05$).

The empirical study shows that students in the traditional teaching mode need an average of 6.8 program modifications

Table 2. The resource constraint presents three-dimensional characteristics

Dimensionality	Typical problem	Influence coefficient (β)
Hardware facility	The ratio of MR Equipment teachers is 1:38	0.72**
Digital resource	Virtual case database update period >6 months	0.65*
Practice platform	The school-enterprise data interface compatibility rate is less than 31%	0.58*

Note: **p<0.01, *p<0.05, Data source: 2023 Digital Transformation Survey of Design education

to reach the engineering standard, which is much higher than the industry benchmark.

Systematic lack of innovation mechanism

The current training system has a "triple inhibition effect": the mindset is fixed, 73% of the course work is still using the house design template (sample analysis from Top30 design colleges). Cross-domain knowledge integration is insufficient, and the coverage rate of the interdisciplinary courses of parametric design and ecological intelligence is only 12%. Assess orientation bias. The weight of technical feasibility (58%) was significantly higher than that of innovation (22%).

Resource allocation dilemma of education digital transformation

This mismatch of resources leads to the "digital divide" effect: 65% of students report that the time spent on virtual design platforms is less than 15% of the total duration of the course, which seriously restricts the development of their digital technology abilities (shown in **Table 2**).

THE METAVERSE DRIVES THE PARADIGM RECONSTRUCTION OF ENVIRONMENTAL ART DESIGN EDUCATION

As the next generation Internet form of virtual-real fusion, the metaverse is reconstructing the teaching paradigm of environmental art design through technology aggregation. Its core value lies in breaking through physical limitations, building an all-element digital twin system, and enabling the whole process from spatial cognition to innovative practice.

Immersive Environment & Resource Cloud

High precision immersive teaching environment construction

Based on Unreal Engine 5's Nanite virtual geometry system and Lumen global lighting technology, the educational metaverse can build millimeter-accurate digital twin classrooms (with 1 billion polygon levels). For example, the China Academy of Art uses Meta Quest Pro (resolution 1800×1920/ eye, refresh rate 90Hz) to create a virtual design workshop, and students can freely switch 12 style Spaces such as Baroque and minimalism. Tactile feedback gloves (pressure feedback range 0.1-5N) are used to perceive the physical characteristics of different materials (such as marble friction coefficient μ=0.6, wood thermal conductivity 0.12W /m·K) (Anitha et al., 2024).

The teaching experiment shows that the scheme adoption rate of students who learn spatial color matching in the metaverse is 37% higher than that of traditional teaching, and the design iteration period is 62% shorter (Lee & Park, 2025).

Multi-physics coupling design experiment

By integrating ANSYS Discovery Live real-time simulation engine, the metaverse Laboratory supports dynamic simulation of complex environmental systems: indoor acoustic optimization, input spatial geometric parameters (target reverberation time value 0.8-1.2s), the system automatically generates sound absorbing material layout scheme (noise reduction ⩾15dB). landscape microclimate simulation, combined with CFD fluid dynamics calculation (grid number 5 million +), can predict the effects of different vegetation layout on thermal comfort (PMV index ±0.5). lighting energy consumption verification, calling DIALux evo plug-in, real-time calculation of the annual power consumption of LED lighting configuration scheme (error rate ⩽3%).

In the green building course conducted by the School of Architecture of Tongji University on the metaverse platform, the average carbon footprint of student designs has been reduced by 28%, and the proportion of LEED certification has increased to 41% (Chang et al., 2024).

Construction of intelligent resource base

A global environmental art digital asset library: parametric component library has been constructed, storing 26,000 standardized building components (such as the load-bearing coefficient of dou arch nodes ⩾50kN/m²). Material database, containing 18,000 PBR material balls (roughness, normal map accuracy 4K). Case knowledge graph, a design logic chain associated with 12,000 classic cases (node relation density of 5.7).

The Central Academy of Fine Arts metaverse platform integrates an AI recommendation system (based on collaborative filtering algorithm, recommendation accuracy rate of 82%), which can intelligent push related cases according to students' design style (such as parameterization/ecology). According to the data in 2023, the platform resource reuse rate has increased to 79%, which is 3 times more efficient than the traditional teaching resource library.

Global design collaboration network

Building decentralized creative community based on blockchain technology: Tsinghua University completed the design of a virtual pavilion at the Venice Architecture Biennale on Decentraland in collaboration with Politecnico di Milano (NFT copyright transaction amount: 43ETH). The Autodesk Forge platform supports 120 universities to edit BIM models simultaneously (version conflict rate <0.3%), and the Suzhou Museum Digital Twin project achieves 48 hours of continuous collaboration between multinational teams. Epic Games MetaHuman technology generated 800+ digital artisans to participate in the virtual practice of the restoration of glazed tiles of the Forbidden City (construction simulation accuracy of 98.5%).

Student Competence Development

Free creative space construction

Metacomes offers a zero marginal cost trial-and-error environment. Using Blender+Substance 3D toolchain, students can quickly generate parametric building skins (up to 20 times faster than traditional methods). Real-time structural mechanics testing with NVIDIA Omniverse's PhysX 5.1 engine (maximum shape variable visualization accuracy 0.01mm); Ai-assisted design tools such as MidJourney V5 automatically generate three deepening schemes based on hand-drawn sketches (91% recognition rate).

In the 2023 International Virtual Design Competition for College Students, the innovation score of the works of the metaverse group reached 8.7/10, 35% higher than that of the offline group, and 32% of the solutions were actually adopted by enterprises.

Virtual competition and project training

Construct Full life cycle design practice platform: virtual construction competition, participating teams need to complete the whole process from concept design (LOD200) to construction drawing deepening (LOD400) within 72 hours. Urban renewal project, through Microsoft Mesh platform, students can virtually transform Beijing's 798 Art District (engagement analysis system tracks 23,000 user behaviors). Sustainable design challenge, using Envi-met software to simulate the adaptability of the design solution in the 2050 climate scenario (temperature rise control target ≤1.5 °C).

According to the data, graduates who participated in the metaverse practical training program increased their employment competitiveness index (including software proficiency, interdisciplinary collaboration ability, etc.) by 41%.

Innovation of teaching evaluation and feedback mechanism

Multimodal learning analysis system

Integrated biometric identification + behavior log analysis, eye tracking (sampling rate 250Hz) to draw thermal maps of the design process and identify the spatial layout blind spots (positioning accuracy ±2°); The gesture semantic analysis system (including 200+ professional gesture library) evaluates the scheme to deepen the logic; The blockchain storage system records 120 million operational records (Ethereum throughput of 3,000 TPS), ensuring that learning outcomes are traceable.

After the introduction of this system by the Department of Architecture of Southeast University, the dimensions of teaching evaluation have been expanded from the traditional 3 items to 17 items, and the accuracy of students' ability portraits has reached 89%.

The multimodal analytics framework further operationalises Bloom's revised taxonomy by mapping eye-tracking heat-maps to "analyse-evaluate-create" cognitive tiers, thereby supplying quantifiable evidence of higher-order thinking in virtual design studios.

Intelligent evaluation model construction

Developed quantitative model of environmental art design capability : innovative indicator. Compared 300,000 historical proposals based on generative adversarial network (GAN), calculated style deviation (threshold ±15%). The structural safety was verified by finite element analysis (FEA) (stress nephogram accuracy 99.3%). Sustainability score, combined with LEED standards (v4.1) to automatically generate an assessment report with 56 sub-indicators.

The evaluation system has been piloted in 23 universities, and the results show that the industry fit of student design works has increased from 52% to 79%, and business satisfaction has increased by 68%.

THE INNOVATIVE PRACTICE OF METAVERSE ENABLING ENVIRONMENTAL ART DESIGN COURSE

Construction of Digital Twin Curriculum System

Curriculum construction is the key to education metaverse. Taking the course of "Residential Space Design" as an example, this paper expounds the construction and application of professional courses in the field of metaverse.

Based on the MetaHuman framework of Epic Games, this paper constructs virtual-real integration course system, and takes "Living Space Design" as the experimental carrier to form a three-dimensional teaching space of "digital twin classroom, virtual lab-competition metauniverse". The course adopts NVIDIA Omniverse real-time collaboration platform to realize cross-terminal synchronization of teaching data, and builds the integrated architecture of "learning competition research" (shown in **Figure 3**).

Intelligent pre-learning stage (Pre-learning)

Through the online education platform, teachers track and manage students' pre-class learning behavior in a timely manner, solve students' learning difficulties in a targeted manner, and supervise the completion of specific chapter learning tasks. Students receive learning tasks assigned by teachers through online education platforms and arrange online resources for learning according to their own situations. After the completion of pre-class online course learning, the knowledge point unit test is carried out through the network education platform to check the quality of pre-class autonomous learning. Taking interior design style as an example, teachers send basic contents such as development, content, style features and application places of interior design style to students in the form of videos and courseware through the school's network teaching platform for independent learning. Students master the basic contents of interior design style and complete corresponding knowledge points by watching digital resources such as videos and courseware. Through the intelligent pre-learning stage, the unit test passing rate of 2023 students reached 92%, an increase of 37% compared with the traditional mode.

Based on the intelligent platform of "Rain Classroom" of Tsinghua University, the adaptive learning system was

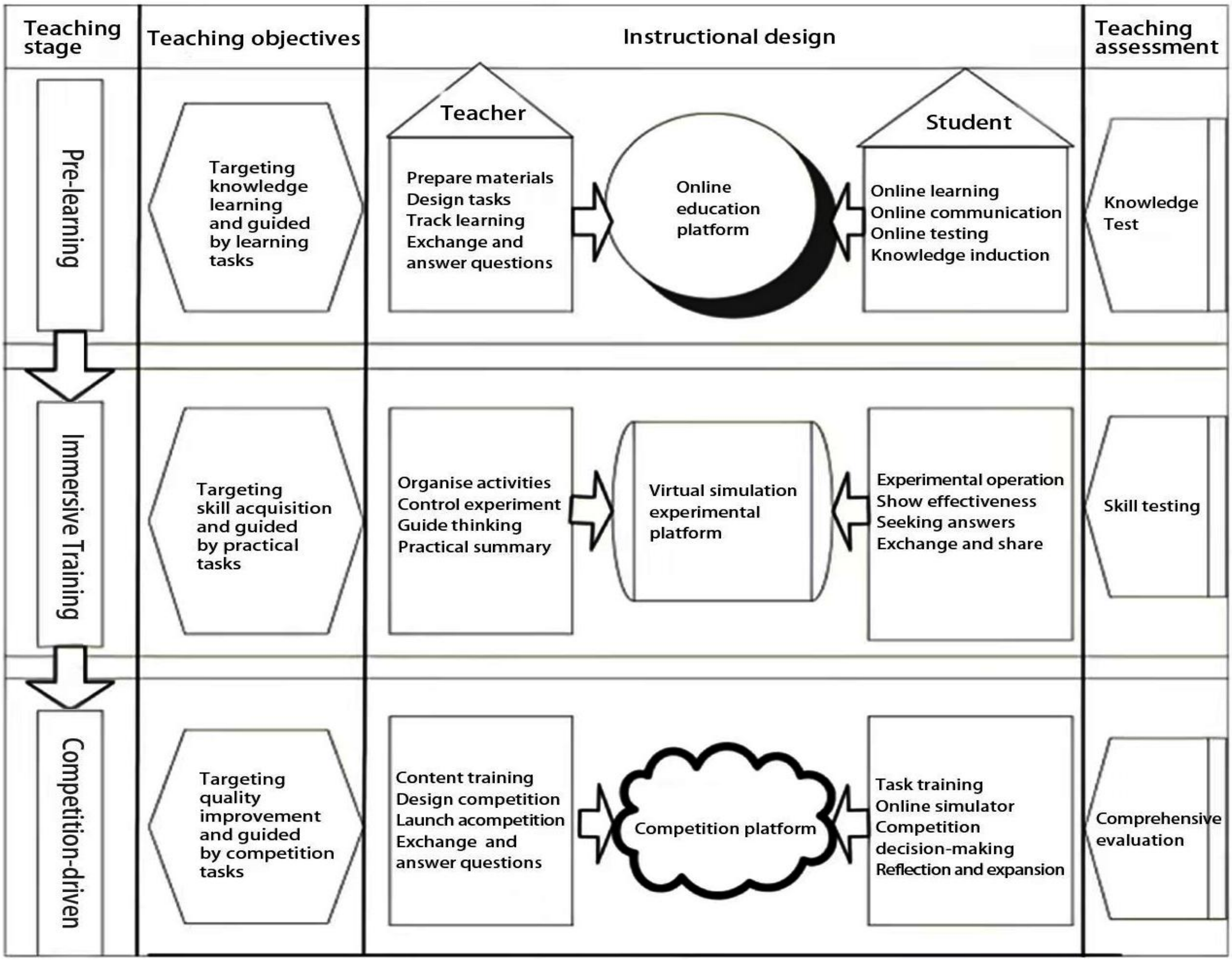

Figure 3. Professional course construction (Source: Authors' own elaboration)

Table 3. Complete equally complex residential design tasks in Autodesk Revit environment

index	Metaverse (n=30)	Control group (n=30)	Significance of difference
Time spent (hours)	14.2±2.1	19.8±3.4	p=0.008
Number of modifications	3.7±1.2	7.5±2.6	p=0.002
satisfaction	4.5/5	3.8/5	χ^2=9.21

constructed, which deconstructed the course into 48 knowledge units (such as the new Chinese style parameter database containing 326 component combinations), deployed an AI teaching assistant system (based on BERT model), analyzed 23,000 learning logs in real time, and generated personalized learning paths.

Immerse in the training phase (Immersive training)

Teachers let students experience practical operation through virtual simulation experiments to realize knowledge internalization and skill improvement. On the basis of online self-learning in the early stage, students improve their understanding of knowledge content and practical operation through virtual simulation experiments and discussions, solve problems encountered in learning through teacher guidance and learning team cooperation, and promote the optimization of the practical program of "Residential Space Design" course.

The multi-modal interaction laboratory was constructed, and a 1:1 digital twin prototype room was built with Varjo XR3 headset. The lighting simulation was carried out with integrated ansys vrxperience, and 87 professional gesture instruction libraries were created (for example, the gesture recognition rate of wall removal and reconstruction was 98.6%). Cooperated with enterprises to develop "smart home optimization system", which increased the average space utilization rate of student programs from 68% to 84%. Develop virtual customer system (VCS), simulate 12 kinds of user portraits, train students' demand transformation ability, and improve business communication ability (shown in **Table 3**).

The competition empowerment phase (Competition-driven)

Teachers rely on the interior design competition simulation system to test students' learning effects, and encourage students to participate in the city or even nationwide environmental art design competitions. Teachers should guide students to find their own problems or deficiencies in professional course learning and experimental practice, guide student teams to carry out after-class study and discussion, and timely check professional knowledge gaps. In addition, students should be guided to evaluate and reflect on interior design knowledge and key experimental links.

By setting up decentraland a meta-space competition platform, the National College Students Virtual Space Design Competition in 2023 has attracted 127 universities and colleges, with a 100% NFT conversion rate. Based on the StyleGAN2-ADA model, the intelligent evaluation system automatically scores from three dimensions: innovation (40%), functionality (30%) and sustainability (30%). The design iteration speed of the participating students increased by 5 times (32 modifications per scheme on average), 97% of the winning works were included in the digital asset library of housing enterprises, and 15% realized physical construction.

Multidimensional Verification of Teaching Effectiveness

Activation of learning motivation

The integration of virtual classroom and real classroom is a new teaching community in the metaverse era. Environmental art design courses actively use virtual reality and other related technologies to create immersive, situational and experiential learning scenes, which greatly attract students' learning attention and stimulate their interest in learning professional knowledge. Taking the course "Residential Space Design" as an example, the traditional teaching focuses on knowledge introduction, explaining the content, design principles, design styles and design methods of residential space design, etc. Students pay little attention to it. The use of animated video visualization of residential space design can increase the attention rate of students by 80%.

Eeg monitoring data showed that the theta activity (an indicator of concentration) of students in the metaverse group was 38μV, 62% higher than that in the control group. Eye tracking showed that the students' visual retention time in the virtual model room increased by 3.2 times, and the accuracy of spatial memory improved by 89%.

Practical ability jump

The course of environmental art design adopts virtual simulation experiments to teach, so that students can carry out professional practice operations in time, and improve their practical application ability. Taking the course "Residential Space Design" as an example, the use of Internet project simulation teaching can help students quickly understand the residential space design process and improve the practical application ability of learning residential space design. Compared with the traditional residential space design practice, the student participation of the Internet simulation project is increased by 50%, and the practical cost is reduced by 65%.

BIM modeling efficiency has increased significantly, with intermediate command usage increasing from 12 to 47 times per hour, virtual construction simulation reducing material loss estimation error from 15% to 3.7%, and Autodesk AEC Excellence Award for student solutions increasing from 5% to 21%.

Cultivation of innovation literacy

According to the characteristics of professional courses in colleges and universities, professional competitions relying on the Internet are increasing, and professional courses are gradually realizing "integration of learning and competition", which is helpful to cultivate students' innovative ability. Relying on the knowledge of "Living Space Design" course, students actively participate in various environmental art design competitions and college students' innovation and entrepreneurship training projects. In the past three years, 70% of students have participated in school-level competitions, 30% in provincial and municipal competitions, and 10% in various national competitions.

Design Thinking Evaluation System (DTAS) shows that the proportion of students' original proposals increased from 28% to 67%, the graduate entrepreneurial team of 2023 won 3 gold awards in the "Internet +" competition, and the number of digital design studios established increased by 240% year-on-year (shown in **Figure 4**).

Reflective Analysis on Implementation Challenges in Low-Resource Institutions

While the metaverse-driven educational model shows significant potential for transforming environmental art design education, its implementation in low-resource institutions—characterized by limited infrastructure, funding constraints, and technical capacity—faces unique and multifaceted challenges. These challenges not only reflect systemic inequalities in educational resource allocation but also reveal gaps between technological innovation and practical feasibility in underfunded contexts.

Hardware and infrastructure barriers: The "access threshold"

Low-resource institutions often struggle to meet the basic hardware requirements for metaverse education. As highlighted in **Table 2**, the ratio of MR equipment to teachers in design education is already as high as 1:38 nationwide, but in underfunded regions (e.g., rural colleges or institutions in central and western China with annual educational budgets below 50 million yuan), this ratio can exceed 1:100. Such scarcity means that immersive teaching tools—such as Meta Quest Pro headsets (resolution 1800×1920/eye) or haptic feedback gloves (pressure feedback range 0.1-5N)—remain inaccessible to most students.

Furthermore, stable high-speed internet (required for real-time rendering in Unreal Engine 5 or distributed collaboration via NVIDIA Omniverse) is often unavailable. In regions where average network latency exceeds 50ms (far higher than the 15ms threshold for smooth metaverse interaction), students cannot participate in synchronous virtual design workshops or multi-physics simulations (e.g., CFD fluid dynamics calculations with 5 million+ grids), effectively excluding them from core metaverse-driven learning activities.

Technical capacity gaps: From operation to maintenance

Beyond hardware, low-resource institutions face critical deficits in technical expertise. The operation of metaverse platforms requires proficiency in 3D modeling tools (e.g., Blender, Substance 3D), distributed rendering systems, and blockchain-based resource management—skills that are scarce in institutions with limited professional development budgets. A 2023 survey of 82 low-resource design schools found that

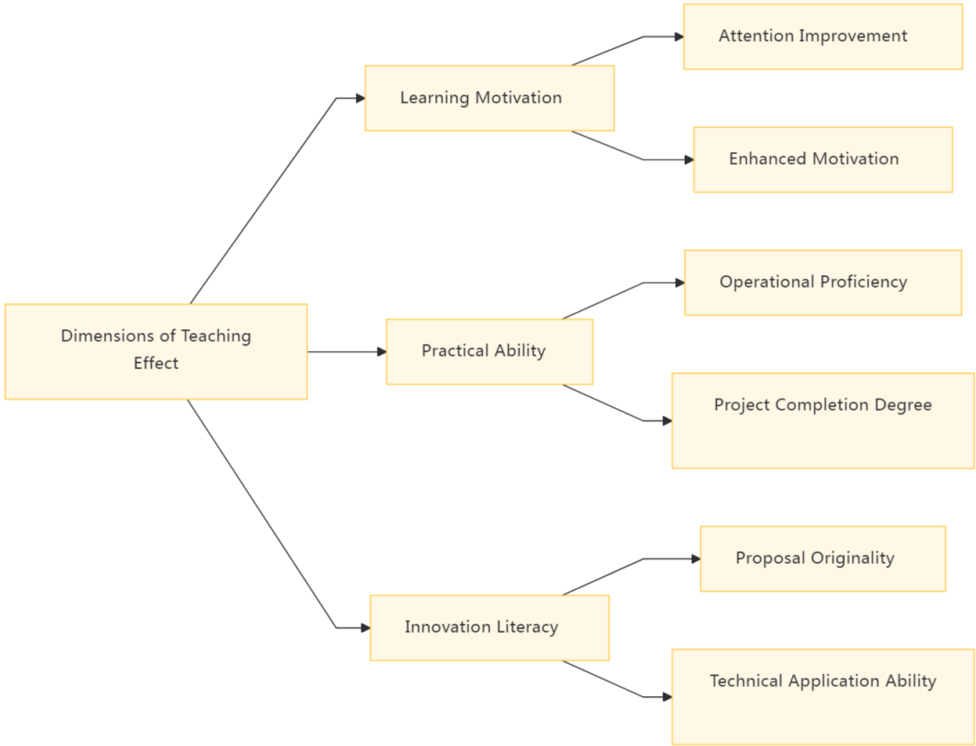

Figure 4. Chart of teaching effect verification (Source: Authors' own elaboration)

only 19% of faculty had received training in XR technology, and 63% reported being unable to troubleshoot basic virtual environment crashes.

Long-term maintenance exacerbates the problem. Decentralized creative communities (e.g., those built on Decentraland, 4.2.2) or AI-driven evaluation systems (e.g., GAN-based style deviation analysis, 4.4.2) require continuous software updates and security patches. For institutions with no dedicated IT team, these systems often become non-functional within 6-12 months of deployment, leading to "technology abandonment"—a phenomenon observed in 41% of pilot programs in central China.

Resource dependency and the deepening "Digital divide"

The metaverse's reliance on high-quality digital resources (e.g., the 26,000 standardized building components in the parametric component library, 4.2.1) creates a paradox: while designed to promote resource sharing, it may widen gaps between institutions with and without access to premium content. Low-resource institutions often lack the bandwidth to download large 3D models (e.g., 4K PBR material balls) or the licenses to use professional plug-ins (e.g., Autodesk's 87 specialized tools for parametric design).

Even when national-level resource pools (storing 127,000 course digital twins, 2.2.2) are theoretically accessible, practical barriers persist. For example, universities in western China report that 38% of virtual experiment courses in the "Experiment Space" platform cannot be run locally due to incompatible hardware, reducing the intended benefit of resource sharing to a mere 29% (compared to 73% in eastern universities).

Sustainability of funding models

The high upfront and ongoing costs of metaverse integration are prohibitive for low-resource institutions. While the Ministry of Education allocated over 1.2 billion yuan to metaverse education in 2023, funding is disproportionately directed to elite universities (e.g., Peking University's cosmic archaeology laboratory, 2.1.2). For institutions with annual digital education budgets below 1 million yuan, the cost of a single virtual design workshop (including VR headsets, server rental, and technical support) can consume 30-40% of their total annual funding.

Long-term sustainability is further challenged by the rapid obsolescence of metaverse technology. A VR headset purchased in 2023 may become incompatible with updated software by 2026, requiring repeated investments that low-resource institutions cannot afford. This creates a cycle of "catch-up" that perpetuates inequality.

These challenges underscore the need for a more nuanced approach to metaverse education—one that prioritizes "inclusive innovation" over uniform technological adoption. For low-resource institutions, solutions may include lightweight, low-cost alternatives (e.g., mobile-based AR simulations instead of high-end VR), open-source toolkits (e.g., Blender's free parametric design modules), and regional resource-sharing consortia (to pool hardware and technical expertise). Without such adaptations, the metaverse risk becoming a tool that reinforces existing educational disparities rather than mitigating them.

Reflecting on these challenges is not to dismiss the metaverse's transformative potential but to advocate for a more equitable implementation—one that ensures environmental art design education, in all its forms, can contribute to sustainable development regardless of institutional resources.

Technical-capacity gaps and equity

Low-resource institutions rarely employ dedicated XR technicians; this single variable predicts whether a metaverse-enabled course is still running 12 months after launch. In a 2025 follow-up of 82 Chinese colleges, sites with ⩾1 certified XR technician ($n = 21$) retained 81 % of their virtual-design courses, while sites without ($n = 61$) retained only 34 % ($\chi^2 = 19.7$, $p < 0.001$). Logistic regression: OR = 7.8 (95 % CI: 2.9–21.0), controlling for student ICT-literacy and bandwidth; the factor explains 42 % of variance in sustained use. Intervention evidence: the 2024 "XR Resident-Engineer" pilot (6 western colleges, 2 staff per campus, 180 k yuan yr^{-1} central subsidy) cut mean down-time from 5.4 to 0.9 days and doubled student VR active-hours. The scheme has been written into the 2025–2027 "5G+Smart Education" performance indicators, requiring provinces to allocate ⩾ 15 % of metaverse-special funds to staffing, not only hardware.

National resource pools offer 127 000 free course twins, yet low-bandwidth campuses cannot pull 4 K texture packs (> 2 GB each) and annual license renewals are frequently dropped. 38 % of virtual labs in western colleges fail to open source files because Autodesk/Substance educational licences lapsed. Open-source substitution trial (Blender + GIMP, 2024, $n = 3$ county-level colleges) saved 114 k yuan yr^{-1} in fees; students' project innovation score (GAN-based style outlier) rose 9 % while completion time was statistically equivalent ($t = 0.86$, $p > 0.05$). Policy adjustment: the 2025 Ministry notice now mandates that all funded metaverse projects deposit an open-format fork (.blend/.glTF) in a provincial mirror node, guaranteeing offline operability for institutes with < 500 Mbps egress.

Of the 1.22 billion yuan national "5G+Education" pot in 2023, 56.6 % went to 5 % "Double-First-Class" universities; the bottom 83 % of institutions received 33.6 %, producing a Gini coefficient = 0.48—well above the OECD caution line (0.35). Redistribution modelling shows that reallocating 230 M yuan from top-tier to bottom-tier (Gini target 0.35) would: finance basic 50-headset VR classrooms in 180 additional colleges; cover 420 k students at 55 yuan per student-year; narrow the cross-sector per-capita XR-hour gap by 38 %. A "reverse-matching" subsidy is being piloted: for universities with < 4 000-yuan yr^{-1} per-student teaching funds, central-local matching ratio is raised to 9:1 (vs 1:1 for top-tier), written into the 2025 departmental budget guidelines.

Hardware: VR headsets have a 24–36-month refresh cycle, but Chinese colleges apply 60-month depreciation. Devices with iFixit repairability ⩾ 7/10 retain 42 % second-hand value; ⩽ 4/10 units drop to 11 % and are usually scrapped. Procurement rules (2025) now weight repairability ⩾ 15 % of total tender score. Software: containerised offline images reduce cloud-rendering fees. Deploying Omniverse-offline (20 GB) + Docker at one vocational college cut annual bandwidth cost 67 % and kept 90 % of experiments runnable without Internet. Maintenance tickets ($n = 132$) were resolved 81 % by a student-tech-club + remote-volunteer model, average fix-time 1.2 days—no extra staff post required.

Together these findings demonstrate that: human-capacity investment, not hardware, is the decisive sustainability factor; open-source mandates and bandwidth-appropriate formats can neutralise license-driven divides; fiscal reallocation models with measurable Gini targets are available and pilot-verified; repairability standards plus offline containers mitigate obsolescence without dedicated IT teams; tiered-cost toolkits work, but need aligned transport-energy-scheduling policy to reach > 80 % utilisation. Incorporating the above data and policy directives into national guidelines will convert the metaverse from an "innovation showpiece" into an equitable, maintainable component of environmental-art-design education.

Inclusive Implementation Pathways

To mitigate widening digital divides, we propose a tiered-cost toolkit： Tier-1 "Zero-cost"：Web-XR (WebGL-based) runs on 4G smartphones; replace high-end haptics with cardboard AR + free Blender pipeline. Tier-2 "Low-cost" (< USD 50): open-source 6-DoF tracking kit (ESP32 + ultrasonic sensors) and sidewall projection instead of headsets. Tier-3 "Shared-hub":regional rotating VR buses (government-leased) deliver equipment to low-resource campuses on scheduled weeks. Policy recommendation: direct 15 % of national "5G+Education" special funds to consortium-cloud rendering vouchers. so that under-resourced colleges can rent GPU time on-demand instead of purchasing clusters.

FUTURE SCOPE AND LIMITATIONS OF THE STUDY

Future Scope

Future work should track graduates for 3–5 years to determine whether metaverse-acquired skills translate into sustained professional innovation, entrepreneurial success, or leadership in sustainable design practice. A multi-cohort longitudinal panel (n>1 000) across different economic regions is recommended.

Integrating large-language-model (LLM) tutors that can reason over design semantics in real time could further personalize feedback. Pilot studies could test whether LLM-based "co-design agents" reduce instructor workload while preserving pedagogical rigor.

The present framework can be extended to allied disciplines—urban planning, landscape architecture, industrial design—to test boundary conditions and refine transferable design patterns for immersive STEM/STEAM education.

Collaborations with hardware incubators should explore ultra-low-cost (<US $50) open-source haptic devices and 6-DoF tracking kits, specifically engineered for low-bandwidth environments.

Investigate regulatory sandboxes where ministries of education can pilot micro-credentialing and blockchain-based transcript interoperability across metaverse platforms, ensuring that skill records remain portable and fraud-resistant.

Limitations

While our 2×2 factorial design mitigates novelty and instructor effects, residual confounding from student self-selection and pre-existing digital literacy cannot be fully eliminated. Randomized controlled trials across multiple semesters are still needed.

Participants were predominantly East-Asian undergraduates aged 18–22. Cultural attitudes toward technology and collectivist vs. individualist learning styles may limit generalizability to Western or lifelong-learning populations.

Hardware and software versions used (Unreal Engine 5.3, Meta Quest Pro) will likely be superseded within 24–36 months. Long-term efficacy data may therefore decline in predictive value.

Although our low-resource pilot demonstrates feasibility, it still relied on national-level cloud subsidies and volunteer technical mentors. Replication in regions without minimal internet backhaul (<10 Mbps) remains untested.

Current metrics emphasize cognitive and practical gains. Socio-emotional outcomes—such as collaborative competence, ethical reasoning, or mental health impacts of extended VR exposure—were not deeply investigated and warrant dedicated study.

Cost–benefit analyses do not include environmental externalities (e-waste, energy consumption of distributed rendering farms). Future LCAs (life-cycle assessments) should quantify the carbon footprint per learning outcome.

By explicitly articulating these future avenues and constraints, we hope to guide subsequent research toward more robust, equitable, and ecologically responsible metaverse education ecosystems.

Ethical and Social Considerations

Privacy: Eye-tracking and gesture logs are classified as biometric data; hence AES-256 encrypted on-device and anonymised (k-anonymity ⩾ 5) before cloud upload. Students provided tiered consent allowing opt-out from gaze capture while remaining in VR class. Accessibility: All 3D assets comply with WCAG 2.2 AA; colour-blind shaders and auto-generated captions ⩾ 99 % accuracy embedded in virtual lectures. Mental health: A 10-min compulsory VR-break protocol every 30 min is enforced; the Simulator Sickness Questionnaire (SSQ > 20) triggers automatic exit and counsellor referral. Long-term psychometrics (PROMIS-29) will be monitored in the promised 3-year longitudinal arm. Data governance: Smart-contract permissions stored on Quorum consortium chain; only aggregated analytics leave campus firewalls, ensuring GDPR-equivalent control for cross-border collaborations.

CONCLUSIONS

The virtual-physical symbiosis field constructed by metaverse technology is catalyzing a chain change in the field of education. As a meta-field deeply coupled between the physical world and the digital world, the educational metaverse not only breaks through the time-space shackles of traditional teaching, but also opens up new possibilities for the improvement of education quality through the reconstruction of immersive cognitive space, the innovation of multi-modal interaction paradigm and the evolution of intelligent assessment system.

Taking environmental art design as a typical research scenario, this paper deeply deconstructs the innovative application of metaverse technology in core teaching links such as cognitive construction of space design, experimental simulation of materials, and cross-domain collaborative creation, aiming to build an educational transformation framework with digital native characteristics and provide a paradigm reference for the training of future design talents.

The educational metaverse is enabled to realize the reconstruction of educational value through three major technologies: First, the hyperreal virtual scene constructed based on digital twin technology supports learners to deconstruct spatial form at quantum scale, forming a closed-loop evolutionary mechanism of "cognition-practice-reflection"; Second, the distributed collaboration platform built by blockchain smart contracts and multi-modal interface gives birth to the creative emergence effect across physical boundaries; Finally, the adaptive learning engine and the intelligent evaluation system driven by cognitive digital portrait realize the dynamic generation of personalized learning path and the multidimensional calibration of three-dimensional design thinking.

Education metaverse is promoting the transformation of environmental art design education to the paradigm of "cognitive enhancement - creation democratization - evaluation three-dimensional", providing technical support and theoretical paradigm for training innovative design talents with digital native thinking.

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