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Sustainable Management of Vocational Education Systems Through Virtual Reality-Based Pre-Training: Evidence from Learning Readiness and Skill Transfer

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Abstract

Vocational education systems face increasing pressure to deliver high-quality skills training while ensuring resource efficiency, safety, and scalability. In machining programs, traditional hands-on training relies heavily on physical equipment, consumables, and close supervision, posing challenges for sustainable management. This study employs a quasi-experimental design with pretest–posttest measures and a comparison group to examine the effects of VR-based pre-training with 50 first-year vocational students. The findings indicate that VR-based preparation supports learners' cognitive and experiential readiness and contributes to perceived preparedness for subsequent hands-on activities. No statistically significant differences in posttest performance were observed between groups. VR-based preparatory training supports risk mitigation in learning contexts by enabling cognitive rehearsal and structured procedural familiarization before physical practice. At the system level, VR-based pre-training transforms early-stage trial-and-error learning into a guided virtual environment that incorporates predefined operational sequences, procedural cues, and embedded safety prompts. This approach helps reduce safety risks for inexperienced learners and supports the more strategic use of instructional resources. Rather than establishing generalized or causal effects, the findings provide exploratory, empirically grounded insights derived from a single institutional context, offering a structured reference framework to inform the design, scaling, and validation of future multi-site or longitudinal research in vocational education management. Furthermore, the study explicitly aligns with Sustainable Development Goals 4 (Quality Education) and 8 (Decent Work and Economic Growth). This alignment underscores the study's relevance to sustainability-focused vocational training initiatives.

Keywords: SDG 4; SDG 8; sustainable vocational education management; vocational education; VR-based pre-training; learning readiness; skill transfer

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1. Introduction

Vocational education systems play a critical role in strengthening workforce skills, enhancing employability, and promoting social sustainability in the context of a global knowledge economy and rapidly evolving technologies [1,2]. The United Nations Sustainable Development Goals (SDGs) explicitly highlight "ensuring inclusive and equitable quality education and promoting lifelong learning opportunities" (Goal 4, Quality Education) as a key task for sustainable development [3]. This objective encompasses not only the

universal provision of basic education but also the contribution of vocational and technical education to workforce adaptability and skill competitiveness.

Vocational Education and Training (VET) typically emphasizes practical skill development, often requiring extensive physical equipment, consumables, and dedicated teaching resources. While this traditional mode of instruction provides hands-on experience, it also entails systemic challenges, including high operational costs, high resource demands, and safety risks [4–6]. Educational institutions face the urgent task of enhancing resource efficiency, minimizing safety incidents, and strengthening the scalability of instructional processes, while ensuring effective learning outcomes. Effective management must balance the three pillars of sustainability—economic, social, and environmental—to prevent resource waste and misallocation and to support the long-term systemic stability of vocational education systems [7].

Recent advances in digital transformation and educational technology have created new opportunities to address these challenges. Virtual Reality (VR) technology, characterized by immersive, interactive, and repeatable simulations, has emerged as a promising instructional tool that can enhance learning safety and reduce reliance on physical resources [8,9]. Systematic reviews indicate that VR applications in higher and technical education correspond to multiple SDGs, demonstrating potential to enhance teaching quality and promote inclusive learning opportunities [10].

Empirical studies further suggest that VR can function beyond pedagogy as a management-level intervention. Prior empirical and review studies have shown that immersive VR-based training can significantly enhance learners' knowledge acquisition, self-efficacy, and learning motivation compared with traditional instructional approaches [11]. Similarly, Long et al. [12] found that VR simulations enhanced mastery of professional skills, operational proficiency, and learning satisfaction, while enabling safe, repeatable practice that supports resource efficiency and sustainable instructional management. Despite these advances, research has rarely examined how VR-induced improvements in learning outcomes translate into system-level sustainability benefits or align with measurable SDG targets [13]. Most studies focus on learning outcomes, leaving a gap in understanding VR's role in organizational efficiency, safety governance, and scalable instructional delivery [14].

Addressing this gap, the present study investigates VR-based pre-training in vocational machining education as both an instructional innovation and a strategic approach to sustainable management. Using a quasi-experimental design, this research examines VR's effects on learning readiness, knowledge transfer, and hands-on performance, while evaluating its impacts on resource allocation, risk reduction, and process efficiency through institutional management indicators. By explicitly linking educational outcomes to system-level benefits, this study provides actionable insights for policymakers and managers, demonstrating how immersive technologies can advance resilient, efficient, and sustainable vocational education systems in alignment with SDG 4 and 8. Rather than claiming direct management outcomes, this study examines how VR-based preparatory training may contribute to condition-setting insights that support institutional management considerations in vocational education systems.

Accordingly, this study aims to examine the instructional effects of VR-based preparatory training in vocational machining education by integrating experimental comparison and multivariate statistical analysis. Specifically, learning motivation, learning satisfaction, and learning performance are analyzed to clarify both within-group learning gains and between-group differences. Details on the research design, participants, instruments, and analytical procedures employed to address these research objectives are provided in the Section 3.

In the context of vocational education systems, institutional management indicators refer to system-level considerations that support managerial decision-making rather than directly measured performance metrics. Such indicators may include equipment utilization efficiency, mitigation of novice safety risks, instructional scalability, and the stability of learning outcomes across cohorts. The present study does not attempt to operationalize or quantify these indicators. Instead, it focuses on the initial assessment stage by examining how VR-based preparatory training may contribute to conditions that inform institutional management decisions.

2. Literature Review and Conceptual Foundations for Sustainable Management of Vocational Education Systems

In practice, vocational education systems face challenges that extend beyond achieving learning objectives, including efficient resource utilization, operational safety, and system scalability. From a sustainability perspective, education systems must simultaneously address economic, social, and environmental dimensions to avoid excessive resource consumption, inefficient operational processes, or structural fragility, thereby ensuring the long-term viability of educational activities.

Based on existing research, this chapter sequentially reviews the sustainability challenges confronting vocational education systems, the application of digital and immersive technologies in education system management, the contributions of VR-based training at both learning and system levels, and the limitations of the current literature. On this basis, the conceptual foundation of the present study is proposed. Through an integrated literature review and conceptual analysis, this chapter aims to systematically connect vocational education, technological applications, and sustainability-oriented management strategies, thereby providing theoretical support for subsequent empirical investigation.

2.1. Sustainability Challenges Facing Vocational Education Systems

Compared with academically oriented education systems, vocational education systems rely heavily on contextualized practice, physical equipment, and repetitive skills training in instructional delivery. This operational model inherently places greater demands on resource allocation and management efficiency. Previous studies indicate that vocational education and training often involve substantial fixed costs and continuous expenditures related to equipment acquisition, material consumption, training facility maintenance, and instructor deployment, imposing considerable financial and managerial pressure on institutions over the long term [15]. As a result, sustainability challenges in vocational education extend beyond pedagogical concerns and represent fundamental organizational and system-level management issues.

Economically, vocational education institutions must maintain instructional quality, ensure equipment renewal, and safeguard instructional safety under constrained budgetary conditions. However, traditional training models based on physical practice often undergo equipment deterioration, inefficient use of consumables, and rigid scheduling. These factors reduce resource-use efficiency and reduce the cost-efficiency of educational investment. Existing studies suggest that, when vocational education systems lack flexible resource allocation mechanisms, cross-unit integration, and scalable management frameworks, the resources required per unit of learning outcome increase progressively, thereby undermining long-term financial sustainability [16].

From a social sustainability standpoint, vocational education systems play a critical role in workforce development, employment equity, and fostering lifelong learning. Nevertheless, training environments that depend mainly on physical facilities are often limited by space capacity, equipment availability, and safety regulations. These constraints may result

in restricted learner participation and reduced access to hands-on practice, potentially leading to unequal learning opportunities among learners from diverse backgrounds. As suggested by macroeconomic development studies [17], when training resources cannot be flexibly expanded in response to demand, education systems become less responsive to changes in industrial structures and learner diversity, which in turn may weaken social inclusiveness and adaptive capacity.

From an environmental sustainability standpoint, the energy consumption, material usage, and waste generation associated with vocational training have received growing attention. In particular, disciplines such as machining, engineering technology, and manufacturing often require repeated hands-on trials, which typically entail high energy consumption and material waste. Consequently, educational activities themselves may constitute a non-negligible source of environmental burden. Recent studies emphasize that, in the absence of alternative training approaches or systematic resource-reduction strategies, vocational education systems may unintentionally create structural challenges with sustainable development goals, thereby affecting their long-term legitimacy and policy support [18].

Overall, sustainability challenges in vocational education encompass economic, social, and environmental dimensions. These challenges highlight the management limitations of traditional hands-on training models and establish the research context for exploring the role of digital and immersive technologies in education system management.

2.2. Digital and Immersive Technologies for Education System Management

With the rapid advancement of educational technologies, digital and immersive tools have progressively become critical instruments for managing vocational education systems. These technologies not only support instructional interaction and enhance learning processes but also provide new approaches to support instructional and operational monitoring, resource management, and performance assessment within educational systems, as illustrated in studies on LMS-level learning analytics [19], which highlight the potential of digital platforms to support data-informed decision-making at the instructional and operational level. Digital platforms enable real-time data collection and analysis, allowing institutions to monitor learning progress, equipment utilization, and safety incidents, thereby supporting more accurate and efficient management decisions.

Immersive technologies, such as Virtual Reality (VR) and Augmented Reality (AR), provide demonstrable benefits for managing educational systems. Firstly, by simulating real operational scenarios, administrators and instructors can assess learners' practical skills and evaluate the quality of instructional design in a risk-free environment. Secondly, immersive technologies generate quantifiable indicators of learner engagement, including practice frequency, error rates, and task completion times. These data may inform course scheduling, resource management, and safety planning, which VR/AR studies indicate can support instructional and operational decisions at the course and departmental level [20].

Furthermore, digital and immersive technologies improve the adaptability and expandability of vocational education systems. When institutions face variations in class enrollment or distributed teaching demands, virtual platforms enable rapid adjustments at the course and instructional module level, leveraging learning analytics to mitigate reliance on physical resources [21]. This flexibility not only lowers economic and environmental costs but also strengthens the capacity of education systems to respond to sudden changes in demand or industry requirements.

In summary, digital and immersive technologies improve resource efficiency, support data-driven management decisions, and enhance process safety and scalability, providing

both theoretical and practical foundations for examining the system-level sustainability of VR-based training.

2.3. VR-Based Vocational Training: From Learning to System-Level Sustainability

The application of Virtual Reality (VR) technology in vocational training has gradually evolved from a supplementary learning tool to a mechanism with implications for individual and course-level outcomes [8]. VR offers immersive, interactive, and repeatable simulation capabilities that allow learners to practice complex or high-risk tasks in a safe environment, thereby improving learning outcomes and skill mastery. Through real-time feedback and interactive simulations, VR not only enhances knowledge comprehension and operational proficiency but also strengthens learners' self-efficacy and motivation, providing evidence-based support for individual learning outcomes. These course-level improvements may contribute to system-level sustainability considerations, including alignment with educational SDGs [10].

From a system-level management viewpoint, VR-based training can directly improve resource use and process performance. Because learners can engage in repeated practice in virtual environments without extensive dependence on physical equipment or consumable materials, VR training reduces resource consumption and operational costs. In addition, data generated through VR-based activities can serve as objective evidence for instructional assessment and course improvement, including practice frequency, error rates, and task completion times, thereby supporting precise and sustainable management at the system level [22].

Moreover, VR-based training indicates high levels of flexibility and scalability, making it suitable for diverse instructional contexts, including varying class sizes, cross-regional courses, and rapidly evolving industry demands [23]. Through modular course design and virtual operational platforms, educational institutions can adjust training content and schedules more efficiently. This reduces dependence on physical infrastructure and mitigates both economic costs and environmental impacts. Such flexibility enhances system responsiveness to emergencies and industry changes, while simultaneously strengthening the long-term sustainability of institutional management.

Overall, VR-based training contributes not only to individual learning enhancement but also to resource optimization and education system management, providing empirical support for system-level sustainability and alignment with sustainable development objectives.

2.4. Gaps in Existing Literature: Managerial, Longitudinal, and Mechanism-Based Perspectives

Although existing research has extensively examined the effects of Virtual Reality (VR) on vocational education learning outcomes, including skill acquisition, knowledge comprehension, and motivation enhancement [8], notable gaps remain in linking these findings to institutional management and sustainability assessment. First, from a managerial perspective, most studies focus on individual learners or single courses, with limited attention to overall institutional operations, resource management efficiency, or structured management strategies. As a result, the systemic benefits of VR technology remain insufficiently explored in the current literature.

Second, longitudinal evidence is limited, with only a few studies, such as immersive medical training across multiple cohorts, demonstrating long-term engagement and outcomes [24]. The majority of empirical studies rely on short-term experimental designs or single assessment points, which are insufficient for evaluating the sustained effects of VR training on learning outcomes, skill transfer, and system-level management effectiveness over time. The absence of longitudinal evidence constrains educational institutions' capac-

ity to plan long-term curricula, manage resources strategically, and implement sustainable management policies.

Third, from a mechanism-based perspective, the literature lacks clear theoretical and evidence-based explanations of how VR influences learning outcomes through immersive interaction, real-time feedback, and simulated environments, and how these effects are subsequently translated into system-level resource optimization and process improvement. Although evidence supports the effectiveness of VR in enhancing individual learning outcomes, the causal pathways linking learning mechanisms to management decision-making and system-level sustainability remain insufficiently articulated [25].

Taken together, these gaps underscore the need for research that adopts a system-level, longitudinal, and mechanism-oriented perspective. While the present study does not fully address all these gaps, it provides initial empirical evidence and methodological insights within a single institutional context, thereby partially contributing to the exploration of these issues and informing future hypothesis development and larger-scale investigations.

From a critical synthesis perspective, existing VR-related studies in vocational education predominantly emphasize short-term learning outcomes, task performance, or usability metrics, while offering limited analytical engagement with system-level or managerial implications. In particular, mechanisms through which preparatory VR training may influence instructional stability, resource allocation efficiency, or novice risk mitigation are rarely examined in a structured manner. Moreover, longitudinal evidence and institution-oriented analytical frameworks remain underdeveloped in the current literature. These gaps indicate that, while VR-based training is frequently discussed as a promising instructional innovation, its relevance to institutional decision-making conditions has not been sufficiently theorized or empirically contextualized.

2.5. Conceptual Rationale for the Present Study

Based on the preceding literature review and analysis, the conceptual foundation of this study is constructed around three core perspectives: the system management perspective, the long-term benefits perspective, and the learning mechanism and process interaction perspective.

From an organizational management perspective, this study argues that sustainability in vocational education depends not only on enhancing individual learning outcomes but also on optimizing institutional operational processes, efficient allocation of resources, and formalization of management strategies. By leveraging digital and immersive technologies, educational institutions can continuously monitor learning progress, equipment utilization, and operational safety, and integrate these data into management decision-making processes, thereby enhancing resource efficiency and operational stability at the institutional level.

From a long-term benefits perspective, this study emphasizes the importance of assessing the sustained effects of VR-based training on learning outcomes, skill transfer, and management effectiveness. Through longitudinal observation and quantitative analysis, short-term learning gains are linked to long-term system-level benefits, providing empirical evidence to support institutional decisions related to curriculum design, resource investment, and sustainable management strategies.

From the perspective of learning mechanisms and process interactions, VR technologies enhance knowledge acquisition, skill proficiency, and self-efficacy through immersive interaction, real-time feedback, and simulated operational tasks. These individual-level learning outcomes are subsequently translated into system-level improvements in process optimization, resource conservation, and safety management, forming a self-reinforcing positive cycle. Within the proposed conceptual model, learning interaction, feedback

mechanisms, and operational simulation are positioned as core mechanisms that connect individual learning processes with system management decisions, resource allocation, and sustainability performance.

Within this framework, institutional management relevance is addressed at the conceptual level by examining how individual learning mechanisms and instructional processes may generate condition-setting insights meaningful for system-level management considerations, rather than by directly measuring or predicting management outcomes.

In summary, the conceptual foundation of this study integrates individual learning mechanisms with education system management, linking VR technology to sustainability-oriented strategies. This framework provides a theoretically grounded and operationally actionable basis for empirical research, clarifying the mechanisms through which digital technologies contribute to the long-term sustainability of vocational education systems.

3. Research Methodology and Design

Building on the analytically synthesized gaps identified in Section 2, this section does not advance empirical claims regarding institutional management outcomes. Instead, it articulates a conceptual framework that links individual-level learning mechanisms to potential system-level considerations, thereby positioning the study as an initial assessment of the applicability of enabling conditions rather than outcome validation.

To evaluate the effectiveness of Virtual Reality (VR)-based pre-training in vocational machining education, this study adopts a methodological framework that integrates empirical rigor, practical feasibility, and sustainability-oriented considerations. The chapter presents a research design combining expert-guided instructional development with a quasi-experimental approach to examine how immersive VR interventions influence learning readiness, knowledge transfer, and skill performance. The study protocol was approved by the Institutional Review Board of National Changhua University of Education (approval number: NCUEREC-111-039), and informed consent was obtained from all participants, who voluntarily signed written consent forms before participation during the data collection period from 28 September to 26 October 2022. By emphasizing transparent measurement procedures, instructional control, and ecological validity, the methodological framework not only ensures credible and replicable findings but also aligns with criteria highly valued by peer reviewers, including methodological transparency, practical relevance, and explicit linkages to sustainable educational management [26,27].

3.1. Research Design

A quasi-experimental design was employed to examine the effects of VR-based pre-training compared with conventional preparatory instruction on learning readiness, knowledge transfer, and machining skill performance. Due to practical constraints in the instructional setting, intact classroom groups were used, and participants were assigned to either an experimental or a control group. This design ensured ecological validity while allowing control over key instructional variables, including teaching hours and instructor effects. The research was implemented in two sequential phases. During the development phase, expert consensus informed the design of the VR instructional framework and the assessment instruments through a Delphi-based approach, addressing content relevance and measurement validity [28]. In the implementation phase, a pretest–posttest quasi-experimental design was conducted to evaluate the impact of VR-based pre-training on students' learning readiness, knowledge transfer, and machining skill performance. Figure 1 presents the overall research process developed in this study, showing Delphi-guided VR instructional development, participant grouping, pretest–posttest measurements, and VR-based pre-training within the quasi-experimental instructional sequence. As illustrated in Figure 1,

the control group was provided access to the VR simulations only after the completion of all posttest measurements. This post-study VR exposure was implemented solely for ethical and instructional equity purposes and was not included in the experimental design or any measured variables.

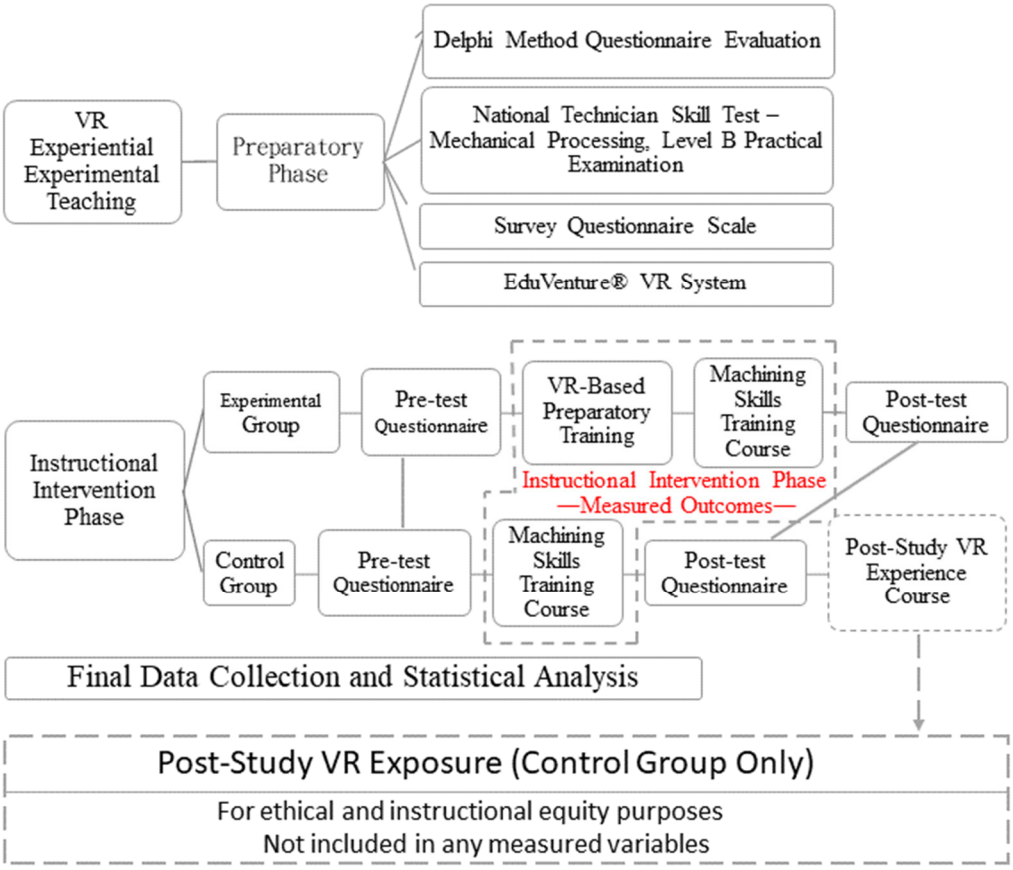

Figure 1. Overall research process developed in this study. Note: Red font indicates the instructional intervention phase and measured outcomes.

3.2. Participants

This study employed a convenience sampling method, prioritizing accessibility and resource efficiency [29], to recruit fifty first-year students enrolled in a mechanical machining course at a national university in Taiwan. Participants were assigned to either the experimental group or the control group according to their existing class allocations, resulting in 25 students per group. The instructional sequence and group assignment procedures are summarized in Table 1. Demographic information, including age, gender, and prior experience in machining, was collected to provide a descriptive profile of the participants.

Table 1. Participant groups and instructional sequence.

Group	*n*	Instructional Sequence
Experimental	25	VR-based pre-training then Hands-on machining
Control	25	Hands-on machining then VR exposure at course end

Baseline equivalence between groups was confirmed via pretest measures of prior knowledge, learning motivation, and expectations using independent-samples *t*-tests, supporting the internal validity of the study [30]. The overall research design adopted a quasi-experimental framework, controlling for potential confounding variables, including

instructional hours and teaching style [31]. Ethical approval for the study was obtained from the university's institutional review board, and all participants provided informed consent before participation.

3.3. Intervention Procedures

The experimental group participated in a VR-based preparatory intervention before engaging in hands-on machining tasks, while the control group received conventional preparatory instruction before completing the same hands-on activities; the control group was subsequently exposed to VR simulations at the end of the course. This post-course VR exposure occurred only after all posttest data had been collected and was not included in the instructional intervention or outcome assessment. Both groups performed identical hands-on tasks with equivalent instructional hours and supervision, thereby controlling for potential confounding variables.

The VR intervention was delivered using a low-cost display (Google Cardboard), selected to ensure accessibility and scalability within vocational education settings (Figure 2). The VR-based preparatory training was guided by established pedagogical principles to optimize learning outcomes in vocational machining education. Specifically, the instructional design integrates guided practice, experiential learning, and scaffolding to support learners' cognitive, psychomotor, and affective development. Guided practice was implemented by providing step-by-step virtual demonstrations of machining tasks, allowing learners to observe and internalize correct procedures before engaging in hands-on practice. Experiential learning principles were incorporated through immersive, scenario-based simulations that enable learners to actively engage with realistic machining operations in a risk-free virtual environment. Scaffolding mechanisms, including contextual hints, immediate feedback, and progressively complex task sequences, were embedded to help learners gradually gain autonomy while maintaining performance support. These pedagogical choices directly informed the structure and content of the VR modules, the sequencing of tasks, and the feedback mechanisms, ensuring alignment with instructional objectives and enhancing learners' readiness and ability to transfer skills.



Figure 2. Google Cardboard Head-Mounted Display used for VR learning [32].

Using this setup, the experimental group engaged in VR-based simulations of machining operations and safety procedures, allowing learners to rehearse procedural sequences and safety considerations in a virtual environment before physical practice (Figure 3).



Figure 3. Participants are engaging in VR-based machining simulations.

During the intervention, participants' engagement, operational performance, and adherence to safety procedures were monitored. By leveraging VR simulations, students gained a contextualized understanding of machining processes before entering the workshop, supporting learning readiness and reducing resource-intensive trial-and-error during early-stage physical practice.

Following the VR-based preparatory phase, participants proceeded to identical hands-on machining tasks under standardized instructional conditions. Figures 4 and 5 visually document the transition from virtual rehearsal to physical practice and the types of machining tasks completed during the intervention period.



Figure 4. Participants engaging in hands-on machining tasks following the VR-based preparatory training phase.



Figure 5. Representative machining products completed during the hands-on practice phase.

3.4. Research Instruments

To ensure methodological rigor and alignment with sustainability-oriented educational research, this study employed three complementary research instruments: 1. an expert-guided Delphi questionnaire, 2. a VR-based learning system, and 3. a structured quantitative survey scale. In this study, learning performance was operationalized as perceived task execution readiness and procedural understanding immediately following instruction, rather than objective skill mastery. The questionnaire items were therefore designed to capture learners' self-assessed ability to perform task-related procedures under instructional conditions, which is consistent with prior vocational education research employing self-reported performance indicators in preparatory or simulated learning contexts. Together, these instruments enabled triangulated data collection across instructional design validation, immersive learning intervention, and learning outcome assessment, enhancing construct validity and supporting robust statistical analysis [33].

Established theories of multimedia learning and learner motivation guided the selection and integration of these instruments. In particular, Mayer's Cognitive Theory of Multimedia Learning provided a theoretical foundation for designing immersive instructional content and promoting learner engagement. This framework is particularly relevant in sustainability-oriented vocational education, where efficiency, learner readiness, and reduced material waste are critical considerations.

1. Delphi Expert Questionnaire

A Delphi-based expert consultation process was conducted to establish instructional consensus and validate the VR instructional framework and learning competency indicators. Drawing on a systematic literature review and preliminary instructional experiments, an

initial set of VR teaching modules and assessment dimensions was developed following established Delphi methodological principles [34]. To ensure interdisciplinary validity, nine experts from precision machinery, community health and disease cognition, metaverse technology, and educational technology participated in a multi-round Delphi process.

Four sequential rounds of questionnaires were administered: an expert review questionnaire followed by three formal Delphi surveys. These rounds iteratively refined expert judgments regarding the appropriateness of VR instructional content, the rationality of machining operation procedures, and the validity of learning outcome indicators. Inter-rater reliability and consensus consistency were assessed using Kendall's coefficient of concordance as a standard statistical measure in Delphi studies [35]. Recent studies have demonstrated the effectiveness of the Delphi method in achieving expert consensus on blended and technology-enhanced learning strategies [36].

Based on expert consensus, the VR instructional modules and assessment indicators were aligned with the practical requirements of the Technician Skill Certification Level B–Mechanical Processing Practical Test issued by the Workforce Development Agency, Ministry of Labor, Taiwan, ensuring both ecological validity and practical relevance.

2. VR-Based Learning System

The VR-based instructional intervention employed in this study was designed to support sustainable vocational training by reducing early-stage material consumption, equipment wear, and safety risks commonly associated with machining education. Scene-Based Immersive Virtual Reality (SV-IVR) was selected as the instructional modality because it is more cost-effective and scalable than fully interactive 3D VR systems, while still enabling learners to engage with immersive learning scenarios through accessible hardware.

Immersive VR has been shown to influence psychological processes such as presence and agency, which in turn affect cognitive and affective factors, including learning motivation and engagement. These factors are particularly relevant in context-specific vocational applications, where learners' readiness and procedural understanding directly affect training efficiency and safety outcomes [37].

This study employed the EduVenture® VR (EVVR) platform (version 2.3.0), developed by the Centre for Learning Sciences and Technologies at the Chinese University of Hong Kong. The EVVR system integrates a cloud-based content management system, an online instructional editor, and an SV-IVR learning interface, allowing instructors to embed audio narration, instructional prompts, and formative assessment questions within panoramic learning scenes.

The EVVR system was implemented as a VR-based pre-training intervention before hands-on machining practice. Learners accessed the instructional content through mobile devices and completed guided learning tasks and embedded quizzes within immersive environments. The VR modules were designed with structured procedural guidance, in which operational steps were presented in a predefined sequence accompanied by contextual cues and embedded safety alerts. These design features guided novice learners through correct machining procedures while preventing unsafe actions that commonly occur during unguided early-stage physical practice. In addition, the system incorporates real-time feedback, simulated operational cues, and multisensory stimuli to support the development of procedural memory and enhance learners' readiness for subsequent physical machining tasks. Given its applicability in technical and vocational education contexts, as indicated by the present exploratory findings, EVVR may serve as a sustainable instructional platform for evaluating VR-enhanced machining education.

The VR modules were explicitly designed following pedagogical principles to optimize learning outcomes. Guided practice was implemented via step-by-step virtual demonstrations, experiential learning was supported through immersive scenario-based simulations,

and scaffolding mechanisms—including contextual hints, feedback, and progressively complex tasks—helped learners gradually gain autonomy while maintaining performance support. These design decisions directly informed the sequencing, content, and feedback features of the EVVR modules, ensuring alignment with instructional objectives and enhancing both learning readiness and skill transfer potential.

3. Questionnaire Survey

The structured questionnaire survey was developed based on the Delphi consensus results and aligned with both the EVVR instructional content and national vocational certification standards. The instrument measured three primary constructs: learners' prior machining knowledge, familiarity and experience with VR technology, and learning motivation and expectations regarding VR-assisted machining education.

Item development was based on Bloom's Taxonomy. This framework identifies cognitive, psychomotor, and affective learning domains, as conceptualized in revised educational frameworks [38]. The questionnaire was administered as both a pretest and a posttest at the beginning and conclusion of the machining course.

Due to institutional constraints, a quasi-experimental design with convenience sampling was employed. Participants were assigned to experimental and control groups based on intact class units. Learning outcomes were assessed using a structured five-point Likert scale questionnaire (1 = Strongly Disagree; 5 = Strongly Agree), focusing on learners' perceived cognitive engagement, experiential readiness, and subjective learning outcomes. These self-reported measures capture learners' perceptions and do not directly measure hands-on skill performance or observational records of task proficiency. This limitation is acknowledged in the study and taken into account when interpreting the findings. Quantitative data were analyzed using IBM SPSS Statistics 25. Analyses included descriptive statistics, independent-samples *t*-tests, paired-samples *t*-tests, and ANCOVA to examine group differences and the impact of the VR-based intervention on perceived learning outcomes.

All constructs were assessed both before and after the VR-based instructional intervention using the same validated instruments, enabling a comparison of learning gains.

3.5. Data Analysis

Quantitative analyses were conducted using IBM SPSS Statistics 25 to examine the effects of instructional modalities on students' learning motivation, learning satisfaction, and perceived learning outcomes, within the context of sustainable educational management. Prior to inferential analyses, all variables were assessed for normality, homogeneity of variance, and internal consistency reliability using Cronbach's α to ensure data quality and measurement validity [31]. These procedures support the robustness of the statistical findings and their relevance for resource-efficient instructional decision-making.

Descriptive statistics were used to summarize participant demographic characteristics, including gender, academic discipline, and prior skill background, as well as baseline measures of learning motivation, learning satisfaction, and perceived learning outcomes. These descriptive results are reported in Table 2 and provide essential contextual information for understanding learner heterogeneity, supporting equitable instructional planning, and informing sustainable allocation of educational resources [36].

The hypothesized relationships among instructional modality, learning motivation, learning satisfaction, and perceived learning outcomes are summarized in Table 2 and illustrated in Figure 6. For all three constructs, data were collected both prior to and following the VR-based intervention, ensuring that observed differences reflect changes associated with the instructional program.

Table 2. Research hypotheses and related sustainability considerations.

Hypothesis	Statement of Variable Relationship	Analytical Purpose and Sustainability Implication
H1	Different instructional modalities (experimental vs. control group) have a significant positive effect on students' learning motivation.	This study aims to examine whether VR-based instruction enhances students' motivation and supports sustainable instruction by potentially reducing the need for in-person supervision.
H2	Different instructional modalities have a significant positive effect on students' learning satisfaction.	To evaluate overall satisfaction; informs sustainable curriculum planning by assessing efficient engagement strategies.
H3	Different instructional modalities have a significant positive effect on students' learning outcomes.	This study aims to determine whether VR enhances learning efficiency, which is relevant for sustainable resource allocation in hands-on vocational training.
H4	Students' learning motivation has a significant positive effect on their learning satisfaction.	Explore intrinsic motivation; reduce redundant instruction and conserve resources.
H5	Students' learning motivation has a significant positive effect on their learning outcomes.	To assess the predictive value of motivation; sustainable learning design can target motivational factors to improve outcomes with fewer resources.
H6	Students' satisfaction with their learning has a significant positive effect on their learning outcomes.	Analyzing satisfaction as a driver of performance informs efficient instructional methods that maximize learning with minimal resource input.

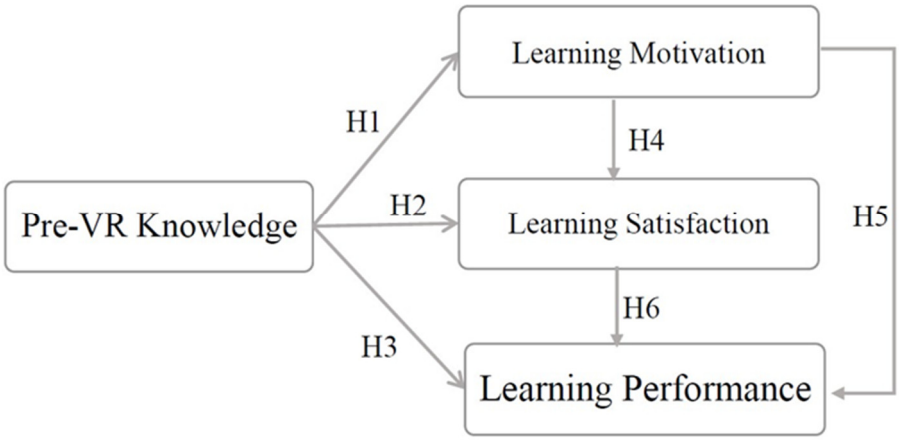

Figure 6. Conceptual framework illustrating the examined relationships among instructional modality, learning motivation, learning satisfaction, and perceived learning outcomes.

To ensure baseline equivalence between groups, independent-samples t-tests were conducted on pretest scores for all key constructs. No statistically significant differences were identified ($p > 0.05$), indicating that the experimental group (VR-based pre-training) and the control group (conventional face-to-face instruction) were comparable prior to the intervention. Establishing baseline equivalence is essential for attributing observed posttest differences to the instructional treatment rather than pre-existing group disparities [27].

Analysis of covariance (ANCOVA) was employed as the primary inferential method to compare posttest outcomes between instructional conditions while controlling for pretest scores. This approach enhances statistical sensitivity and reduces potential confounding effects, enabling a more accurate estimation of instructional impact.

For ANCOVA analyses, instructional modality (VR-based pre-training versus standard face-to-face instruction) was the independent variable, and learning motivation, learning satisfaction, and perceived learning outcomes were the dependent variables, with pretest scores included as covariates.

Effect sizes were reported using partial η^2 to assess practical significance and to evaluate the scalability and sustainability potential of VR-based pre-training, particularly in terms of reducing physical material consumption, equipment wear, and instructional supervision demands [39].

Within-group learning gains were further examined using paired-samples *t*-tests, comparing pretest and posttest scores for each group. Cohen's d was calculated to quantify effect sizes, allowing the interpretation of learning improvements in relation to both educational effectiveness and resource efficiency. These analyses help clarify the extent to which VR-based pre-training supports learning enhancement while minimizing reliance on consumables and intensive instructional inputs, contributing to sustainable vocational education practices [33].

The overall analytical structure of the study, including group assignment, pretest–posttest measurement design, and the integration of VR-based pre-training within the quasi-experimental framework, is summarized in Figure 7. This ANCOVA analytical framework represents the empirical strategy adopted in the study and shows the integration of descriptive and inferential statistical methods used to evaluate the effects of the instructional intervention within a sustainability-oriented educational context.

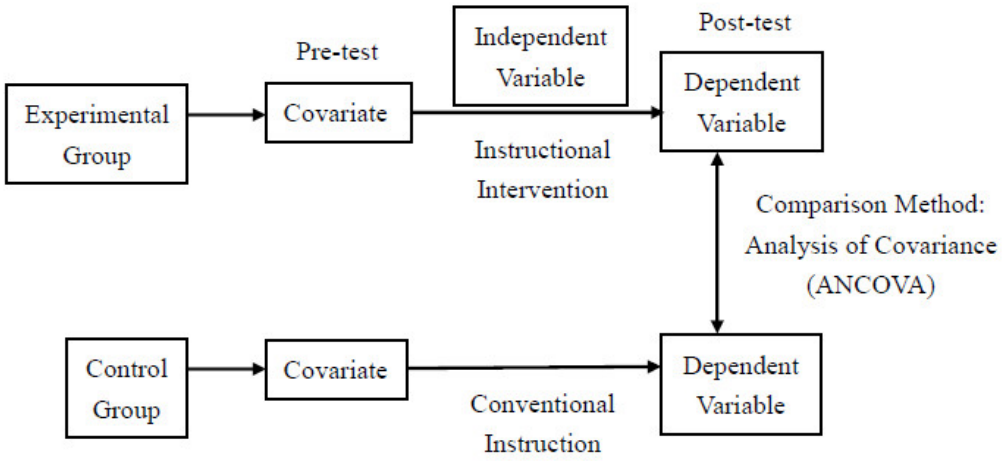

Figure 7. ANCOVA Analytical Framework.

3.6. Chapter Summary

This chapter presents a comprehensive methodological framework that integrates expert-guided instructional design, VR-based pre-training, and a quasi-experimental research design tailored for vocational machining education. The systematic development of VR instructional modules and the validation of assessment indicators align with current scholarly discourse on immersive virtual reality learning environments and their pedagogical evaluation, as synthesized in recent systematic reviews published in *Sustainability* [40].

The quasi-experimental approach adopted in this study achieves a pragmatic balance between methodological rigor and feasibility in applied educational research contexts. Such designs are widely adopted in sustainability-oriented education studies, particularly when immersive technologies are examined under controlled yet non-randomized instructional conditions to generate actionable evidence on learning effectiveness and contextual factors influencing technology implementation.

A key limitation of the study is that learning performance was assessed through self-reported questionnaires rather than objective performance tests or observational assessments. As a result, the findings pertain to learners' perceived readiness and cognitive outcomes rather than direct skill acquisition. Future research should incorporate performance-based assessments and observational data to complement self-reported measures.

4. Results and Discussion

This chapter presents the empirical findings of the study and offers an integrated discussion of the instructional effects of VR-based preparatory training in vocational machining education. Quantitative analyses were conducted to examine both within-group learning gains and between-group differences using descriptive statistics, paired-samples *t*-tests, and analysis of covariance (ANCOVA), with pretest scores treated as covariates to control for baseline variation.

The results section focuses on objectively reporting statistical outcomes related to learning motivation, learning satisfaction, and learning performance, ensuring transparency and methodological rigor. Building on these findings, the discussion section interprets the observed effects in relation to prior research and theoretical expectations, while situating the results within the broader context of sustainable vocational education systems.

Consistent with the scope of *Sustainability*, the discussion extends beyond instructional effectiveness to address implications for sustainable education management, including instructional efficiency, resource utilization, safety considerations, and the scalability of VR-enhanced training models. By linking empirical learning outcomes with system-level management perspectives, this chapter highlights how VR-based pre-training can contribute to more sustainable and resilient vocational education practices.

4.1. Overview of Learning Outcomes

As presented in Table 3, descriptive statistics indicate that the experimental and control groups were comparable in pretest scores across all measured dimensions, supporting baseline equivalence before the instructional intervention.

Table 3. Descriptive statistics of pretest and posttest scores (Mean, SD).

Group	Dimension	Pretest Mean (SD)	Posttest Mean (SD)
Experimental	Prior Knowledge	3.26 (0.95)	3.86 (0.83)
Experimental	VR Experience Cognition	3.07 (0.94)	3.91 (0.79)
Experimental	Learning Motivation	3.94 (0.87)	4.15 (0.69)
Control	Prior Knowledge	3.21 (0.90)	3.48 (0.81)
Control	VR Experience Cognition	2.98 (0.91)	3.26 (0.88)
Control	Learning Motivation	3.92 (0.87)	3.98 (0.84)

Establishing baseline equivalence is a critical prerequisite for evaluating the effectiveness of VR-based instructional interventions and for ensuring the internal validity of findings related to sustainable educational practices.

4.2. Analysis of Between-Group Posttest Differences: ANCOVA Results

To examine whether VR-based preparatory training resulted in differential post-instruction learning outcomes, analysis of covariance (ANCOVA) was conducted to compare adjusted posttest scores between the experimental (VR-based pre-training) and control (standard face-to-face instruction) groups while controlling for pretest performance as a covariate. This analytical approach is widely applied in quasi-experimental educational research to adjust for baseline variation and improve the precision of instructional effect estimates. Partial eta squared (η^2) was used to estimate the proportion of variance

explained by the instructional condition after accounting for covariates. Following conventional benchmarks, values of approximately 0.01, 0.06, and 0.14 are interpreted as small, medium, and large effects, respectively, based on established guidelines [41], with further recommendations for transparent effect size reporting provided in the literature [42].

After controlling for pretest scores, the experimental group exhibited higher adjusted posttest means than the control group across all three learning dimensions; however, none of these differences were statistically significant. For prior knowledge, the ANCOVA yielded F = 0.80, $p = 0.375$, with a partial η^2 of 0.016, indicating a small effect. In the VR experience cognition dimension, the effect size was slightly larger (F = 1.41, $p = 0.241$, partial $\eta^2 = 0.029$). Learning motivation and expectations showed a similar pattern, with F = 0.89, $p = 0.351$, and a partial η^2 of 0.018.

Although the observed differences were not statistically significant, the consistent pattern of higher adjusted means and small effect sizes suggests a modest instructional trend favoring VR-based preparatory training. From a sustainable education management perspective, such incremental effects may warrant consideration when VR interventions are implemented over extended instructional periods or across larger cohorts. Detailed ANCOVA results are presented in Table 4.

Table 4. ANCOVA results for posttest scores controlling for pretest performance.

Dimension	F	*p*-Value	Partial η^2
Prior Knowledge	0.80	0.375	0.016
VR Experience Cognition	1.41	0.241	0.029
Learning Motivation and Expectations	0.89	0.351	0.018

4.3. Pretest and Posttest Performance Within Groups

While between-group analyses provide insight into comparative effectiveness, examining within-group changes offers a more sensitive assessment of short-term instructional impact. Within-group analysis captures learners' progress over time, which is particularly informative in small-sample quasi-experimental designs where instructional effects may manifest more clearly as intra-group change than as between-group contrasts.

Accordingly, this section examines pretest and posttest performance separately for the experimental and control groups to determine whether meaningful learning gains occurred within each instructional condition. Descriptive statistics and paired-samples *t*-tests were used to quantify within-group changes and provide insight into learning gains attributable to the instructional modality.

4.4. Paired-Samples t-Test Analysis of Pretest and Posttest Differences

To further examine the magnitude and direction of learning changes attributable to instructional intervention, paired-samples *t*-tests were conducted to compare pretest and posttest scores within each group. Unlike ANCOVA, which focuses on between-group differences, this analysis emphasizes intra-group learning progress, providing a more sensitive indicator of short-term instructional effectiveness. All paired-samples *t*-tests were conducted with degrees of freedom set at 24 ($n = 25$ per group). In addition to statistical significance, effect sizes (Cohen's d) were calculated to assess the practical importance of observed learning gains, consistent with best practices in educational research reporting.

4.4.1. Statistical Formulation and Effect Size Estimation

To ensure statistical transparency and enhance interpretability, both significance testing and effect size estimation were employed. While *t*-tests determined whether pretest–posttest differences reached statistical significance, effect size indicators quantified the

magnitude of instructional impact, which is particularly relevant for sustainability-oriented research that evaluates the practical significance of results and their scalability.

For within-group comparisons, Cohen's d was calculated to estimate the standardized mean difference between pretest and posttest scores, as shown in Equation (1):

$$d = \frac{M_{post} - M_{pre}}{SD_{pooled}} \quad (1)$$

where M_{post} and M_{pre} represent posttest and pretest means, respectively. The pooled standard deviation was computed using Equation (2):

$$SD_{pooled} = \sqrt{\frac{SD_{pre}^2 - SD_{post}^2}{2}} \quad (2)$$

Eta squared (η^2) was calculated to indicate the proportion of variance in learning outcomes attributable to the instructional intervention. For *t*-test analyses, η^2 was derived using Equation (3):

$$\eta^2 = \frac{t^2}{t^2 + df} \quad (3)$$

where t denotes the observed t-value, and df represents the degrees of freedom. Eta squared provides an intuitive measure of effect magnitude, facilitating comparisons across studies and evaluating the sustainability and transferability of instructional innovations in vocational education.

Effect size interpretation followed established conventions, with larger values indicating stronger instructional impact. Reporting both statistical significance and effect size supports a robust assessment of the effectiveness of VR-based pre-training and its implications for sustainable education management.

4.4.2. Experimental Group Results

To examine adjusted posttest differences between groups while controlling for pretest performance, ANCOVA was conducted. The results are summarized in Table 5.

Table 5. ANCOVA results for posttest performance (controlling for pretest scores).

Dimension	F	*p*	Partial η^2
Prior Knowledge	0.80	0.375	0.016
VR Experience Cognition	1.41	0.241	0.029
Learning Motivation	0.89	0.351	0.018

4.4.3. Control Group Results

The control group exhibited only marginal improvements across all three dimensions, and these changes were not statistically meaningful. Prior Knowledge increased from pretest M = 3.21 (SD = 0.90) to posttest M = 3.48 (SD = 0.81), t(24) = −1.37, p = 0.178, Cohen's d = 0.26. VR Experience Cognition rose from M = 2.98 (SD = 0.91) to M = 3.26 (SD = 0.88), t(24) = −1.64, p = 0.109, Cohen's d = 0.29. Learning Motivation and Expectations increased minimally from M = 3.92 (SD = 0.87) to M = 3.98 (SD = 0.84), t(24) = −0.46, p = 0.651, Cohen's d = 0.07. Paired-samples *t*-test results are presented in Table 6.

Table 6. Paired-samples *t*-test results for pretest and posttest scores within groups (n = 25 per group).

Group	Dimension	Pretest M (SD)	Posttest M (SD)	t (df = 24)	p-Value	Cohen's d
Experimental	Prior Knowledge	3.26 (0.95)	3.86 (0.83)	−3.64	0.001	0.66
Experimental	VR Experience Cognition	3.07 (0.94)	3.91 (0.79)	−5.18	< 0.001	0.93
Experimental	Learning Motivation and Expectations	3.94 (0.87)	4.15 (0.69)	−1.39	0.172	0.27
Control	Prior Knowledge	3.21 (0.90)	3.48 (0.81)	−1.37	0.178	0.26
Control	VR Experience Cognition	2.98 (0.91)	3.26 (0.88)	−1.64	0.109	0.29
Control	Learning Motivation and Expectations	3.92 (0.87)	3.98 (0.84)	−0.46	0.651	0.07

M = mean; *SD* = standard deviation. Cohen's d values of 0.20, 0.50, and 0.80 indicate small, medium, and large effects, respectively, based on Jacob Cohen [41].

4.5. Integrated Discussion and Sustainability Implications

Integrating the results of the ANCOVA and paired-samples *t*-test analyses, this study indicates that VR-based preparatory training produced clear, educationally meaningful improvements in learners' prior knowledge and experiential cognition, whereas traditional instruction produced only limited short-term gains. While the ANCOVA results did not reveal statistically significant between-group differences in posttest performance, the findings suggest that VR-based preparatory training may contribute to learners' readiness and confidence before hands-on practice, rather than directly enhancing measurable performance outcomes. Although between-group differences did not reach statistical significance, the consistent pattern of higher adjusted means and larger within-group effect sizes in the experimental group underscores the practical value of VR-based instruction. These observed patterns reflect differences in learning readiness and procedural familiarity rather than direct evidence of skill mastery or performance superiority.

From a sustainable education management perspective, these findings suggest that VR-based preparatory modules can enhance instructional efficiency, reduce reliance on material-intensive training resources, and improve learner readiness before entering physical workshop environments. From a sustainable education management perspective, these findings suggest potential implications for curriculum planning rather than constituting direct empirical evidence. Such outcomes align with broader sustainability objectives, including resource optimization, safety enhancement, and scalable vocational training systems that support Sustainable Development Goal 4 (Quality Education) [43] Given the relatively limited sample size (n = 50) and the single-institution context of this study, the findings should be interpreted as exploratory rather than confirmatory. While the statistical analyses provide indicative evidence regarding the potential benefits of VR-based preparatory training, the results are not intended to support broad population-level generalization. Instead, this study serves as a proof-of-concept that informs future large-scale or multi-site investigations.

From a methodological perspective, this study is deliberately positioned as an exploratory investigation conducted within a controlled educational setting. The empirical analyses are intended to clarify potential learning mechanisms and instructional implications of VR-based preparatory training, rather than to establish definitive or universally generalizable effects. In this sense, the findings are best understood as offering empirically grounded insights that may inform future research design and hypothesis refinement, particularly in the context of larger-scale or multi-site studies.

5. Conclusions and Implications for Sustainable Vocational Education Management

This chapter synthesizes the empirical findings of VR-based preparatory training in vocational machining education, with a focus on sustainable management and system-level governance. Rather than presenting VR solely as an instructional innovation, the evidence positions VR pre-training as a strategic tool for optimizing resource use, mitigating

operational risks, enhancing scalability, and promoting long-term sustainability within vocational education systems. By explicitly connecting individual learning outcomes to institutional decision-making and governance, this chapter highlights actionable insights that align with reviewer expectations for methodological rigor, practical relevance, and contributions to sustainable education management.

5.1. Summary of Key Findings from a Management-Oriented Perspective

From a sustainable management standpoint, VR-based pre-training enhances learning readiness, operational efficiency, and instructional reliability in competency-oriented machining courses. Improvements in prior knowledge, VR experience cognition, and learning motivation collectively indicate how immersive preparatory modules may support resource-efficient instruction, reduce reliance on trial-and-error learning, and optimize workshop time, suggesting the potential strategic value of VR for institutional decision-making.

These outcomes indicate that VR-based pre-training not only improves individual learning performance but also contributes to institutional efficiency, reduced material waste, and optimized resource utilization, reinforcing its value as a sustainable management strategy in vocational education systems.

From an institutional management perspective, the findings of this study should be interpreted as exploratory and condition-setting insights rather than as direct empirical evidence for management outcomes or policy decisions. These findings provide interpretive guidance for curriculum planning while remaining exploratory rather than constituting direct empirical evidence.

5.2. Instructional Management, Learning Psychology, and Methodological Reliability

Integrating instructional management, learner cognition, and analytical rigor illustrates how VR-based preparatory training can be systematically governed within vocational education systems. Front-loaded VR instruction redistributes cognitive and procedural learning from high-cost, high-risk workshops to low-risk virtual environments, enabling institutions to optimize instructional capacity, maximize resource utilization, and support psychologically sustainable learning conditions. Methodological rigor through ANCOVA, paired *t*-tests, and effect size measures further strengthens these management implications by providing a credible empirical foundation for educational governance.

From a learning psychology perspective, the results align with Mayer's Cognitive Theory of Multimedia Learning and Self-Determination Theory. Multimodal sensory engagement supports cognitive construction [33], while enhanced perceptions of competence and autonomy contribute to psychologically sustainable learning conditions. Although short-term motivational effects were limited, the observed trends suggest that immersive VR environments can foster sustained engagement when embedded within a coherent instructional system.

To further contextualize these management-oriented findings, the present methodological framework integrates validated measurement instruments and standardized analytical procedures, underpinned by established theoretical models of educational technology adoption and sustained usage intention. This approach enhances the interpretability of empirical outcomes and situates the study within ongoing debates regarding the adoption of immersive VR technologies in higher education contexts [44].

At the system level, VR-based pre-training is conceptualized as a preparatory instructional modality that complements rather than replaces hands-on practice, thereby supporting sustainable educational objectives such as operational efficiency, equitable access, and resource optimization. The framework highlights VR's potential to reduce material waste,

mitigate safety risks, and streamline instructional sequencing before resource-intensive workshop engagement [45].

Emphasizing transparent instructional design, implementation fidelity, and replicable analytical procedures, this framework establishes a robust foundation for linking individual learning outcomes to management-relevant indicators, including learner readiness and institutional resource utilization. Collectively, these considerations provide a reproducible empirical basis for exploring the role of VR in advancing sustainable vocational education systems, bridging methodological rigor with system-level sustainability implications.

5.3. Operational Sustainability: Resource Efficiency and Risk Mitigation

Building on the system-level sustainability considerations introduced above, VR pre-training supports operational sustainability by reducing unnecessary machine occupancy, minimizing material waste, and lowering supervision demands. These efficiencies enhance equipment lifespan, reduce consumable expenditure, and improve learning output per machine-hour. In addition, VR provides a controlled, low-risk environment for procedural practice, mitigating safety risks and institutional liability, which collectively reinforce a safer and more resilient instructional system.

These efficiencies translate into improved learning output per machine-hour, extended equipment lifespan, and reduced consumable expenditure. From an institutional management perspective, such outcomes are particularly valuable for TVET providers facing budget constraints, aging infrastructure, or increasing enrollment demands.

Additionally, VR-based pre-training serves as a risk mitigation mechanism, enabling novice learners to practice procedures in a controlled, low-risk virtual environment before exposure to hazardous machinery. This transitional learning space reduces the likelihood of accidents during early-stage training, lowers institutional liability, and supports a safer and more resilient instructional environment.

5.4. Scalability and System-Level Sustainability

Beyond individual classrooms, VR-based preparatory modules offer scalable and replicable solutions for vocational education systems. Standardized VR instruction ensures consistent learning readiness across institutions, cohorts, and geographic contexts while allowing contextual adaptation. This scalability supports system-wide equity, optimizes resource allocation, and positions VR not merely as a technological novelty but as a strategic investment in sustainable educational infrastructure.

For large-scale TVET systems and resource-limited schools, VR-based pre-training offers a mechanism to mitigate disparities in instructional quality resulting from uneven access to equipment and expert instructors. By supporting standardized learning readiness while allowing contextual adaptation, VR pre-training contributes to system-wide resilience, equity, and long-term sustainability, positioning immersive technology as an educational infrastructure investment rather than a short-term innovation.

5.5. Alignment with Sustainable Development Goals (SDGs)

The findings suggest potential contributions to multiple Sustainable Development Goals:

- SDG 4 (Quality Education): Enhances learning readiness, inclusivity, and safety.
- SDG 8 (Decent Work and Economic Growth): Supports the development of employable skills and workplace preparedness through immersive vocational training.

By embedding sustainability principles into instructional design and institutional management, VR-based pre-training supports the translation of global sustainability objectives into actionable educational practices.

5.6. Research Limitations

While offering valuable insights for sustainable vocational education management, this study has limitations. The sample size was limited and drawn from a single technical institution, potentially constraining generalizability. Short-term outcomes were emphasized, leaving long-term retention, skill consolidation, and sustained motivational effects unexplored. Additionally, the predominantly quantitative approach limited examination of learners' emotional regulation, adaptive strategies, and social interactions within VR environments.

These limitations reflect the study's intentional focus on depth and contextual specificity rather than breadth, allowing for a detailed examination of system-level implications within a realistic educational setting.

5.7. Integrated Conclusions and Directions for Future Research

Building on the exploratory nature of the present study, future research may extend this framework through multi-site and longitudinal designs to validate observed patterns and examine scalability across diverse vocational education systems.

Within the specific institutional context examined, VR-based preparatory training is positioned as a promising instructional and managerial approach for sustainable vocational education systems. The findings indicate associations between VR-based pre-training and improvements in learning readiness, resource utilization efficiency, operational risk mitigation, and the feasibility of scalable instructional models, thereby suggesting alignment between pedagogical innovation and institutional sustainability objectives.

Future research may adopt multi-site experimental or quasi-experimental designs to validate the observed patterns across diverse vocational education contexts. Investigating VR design variables—such as interaction density, contextual realism, and task sequencing—can further enhance the effectiveness and sustainability of VR-based preparatory training.

In this regard, the present study should be understood as providing a structured empirical foundation that supports the systematic design, scaling, and validation of VR-based preparatory training models in future vocational education research.

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