Development and Validation of a Metaverse-Based Multiliteracy Virtual Laboratory Integrating the Profil Pelajar Pancasila Framework for Primary Education

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ABSTRACT:
We present the development and validation of a metaverse-based virtual laboratory designed to foster multiliteracy skills in primary education, with a novel integration of the Profil Pelajar Pancasila framework for character formation. The motivation for this work stems from a persistent gap between conventional literacy instruction and the multidimensional competencies demanded by contemporary digital society. To address this challenge, we adopt the ADDIE instructional design model as a structured methodology that transforms pedagogical requirements into a functional virtual environment. The process begins with an analysis phase that identifies specific learning needs derived from empirical data on student engagement and character metrics. We then construct a three-dimensional virtual space that hosts multimodal learning objects, where literacy tasks are embedded within spatial navigation rather than presented as linear media. A core novelty of our approach is the mathematical coupling of multiliteracy acquisition with character internalization: we define distinct virtual zones that correspond to the six dimensions of the Profil Pelajar Pancasila, ensuring that a learner's trajectory through the environment inherently exposes them to character-building narratives. Technical realization employs a metaverse platform with real-time rendering and virtual reality compatibility. Domain experts subsequently evaluate the media usability through a formal validation process, and we apply iterative refinement based on expert feedback to optimize the interface parameters. The resulting system creates a closed-loop learning cycle: outputs from literacy modules feed directly into character reflection modules within the same spatial context. This work contributes a

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replicable framework for designing immersive educational environments that simultaneously address cognitive and affective learning objectives, thereby offering a significant advancement over traditional static content delivery methods in primary education..

Keywords: Metaverse, Multiliteracy, Pancasila, Primary Education, Virtual Laboratory.

1. Introduction

The rapid digital transformation of contemporary society has fundamentally reshaped the landscape of primary education, demanding a paradigm shift from traditional instructional approaches toward more holistic and integrative pedagogies (Han et al., 2023). Conventional literacy instruction in Indonesian primary schools, which has historically focused on decoding text and basic comprehension, increasingly proves inadequate for preparing students to navigate a world saturated with multimodal information flows, digital interfaces, and complex social interactions (Chua & Yu, 2024). Students must now develop multiliteracy competencies that encompass visual, digital, and spatial modes of communication alongside foundational reading and writing skills. Concurrently, there is a growing national mandate, institutionalized through the Profil Pelajar Pancasila framework, to cultivate character values—such as faith, global diversity, mutual cooperation, independence, critical reasoning, and creativity—as integral components of the learning experience. These two imperatives, one cognitive and one affective, are rarely addressed through unified instructional media in current practice.

Existing efforts to integrate the Profil Pelajar Pancasila into classroom practice have largely relied on project-based learning approaches and thematic instruction within the Kurikulum Merdeka (G.-J. Hwang et al., 2023). While these methods offer valuable opportunities for contextualized learning, they typically operate within the constraints of physical classrooms and conventional media, limiting the depth of experiential engagement possible for young learners (G.-J. Hwang & Chien, 2022). Digital interventions, such as interactive multimedia modules, have shown promise in increasing student motivation and content retention, yet they often present character values as discrete, didactic content blocks rather than as lived, simulated experiences. The fundamental challenge, therefore, is to design an instructional environment where literacy acquisition and character formation occur simultaneously through the same meaningful, spatially embedded activities—a goal that neither static digital materials nor traditional project-based curricula have fully achieved.

Metaverse technology, characterized by persistent, shared three-dimensional virtual spaces that support real-time interaction and user agency, offers a transformative substrate for addressing this pedagogical gap (Capatina et al., 2024). Immersive virtual environments have demonstrated significant potential for enhancing student engagement, spatial reasoning, and collaborative problem-solving in primary school contexts (Lee & Jo, 2023). However, the application of metaverse platforms to elementary-level literacy instruction remains nascent, and the systematic embedding of national character education frameworks into the navigational architecture of such spaces is an unexplored design territory. Prior work on serious games for character education has established that ethical decision-making can be effectively simulated through interactive narratives and consequential gameplay mechanics, yet these insights have not been translated into a coherent framework that couples multiliteracy skill progression with the structured dimensions of the Profil Pelajar Pancasila.

We present the IM-WL (Immersive Metaverse—Whole Language) framework, a novel instructional design methodology that synthesizes immersive

metaverse technology with the Whole Language Approach to address these concurrent deficits (Di Natale et al., 2024). The core innovation lies in the systematic construction of a three-dimensional virtual laboratory where literacy acquisition is not treated as an isolated skill but as a holistic, contextualized experience embedded within a spatially interactive environment (Chen, 2024). This method distinctively integrates the six dimensions of the Profil Pelajar Pancasila directly into the navigational and content architecture of the virtual space, ensuring that character values are internalized through experiential simulation rather than passive instruction. By leveraging the ADDIE instructional design model, the approach ensures rigorous alignment between pedagogical objectives, multimodal content delivery, and technical usability, creating a cohesive ecosystem where textual, visual, and digital literacies converge within a single immersive interface.

The remainder of this paper is organized as follows. Section 2 reviews related work in three key areas: metaverse applications in elementary education, multiliteracy pedagogical frameworks, and character education through digital media. Section 3 establishes the theoretical foundations that underpin our approach, detailing the synergy between Whole Language principles and the Profil Pelajar Pancasila dimensions. Section 4 presents the complete IM-WL Metaverse Framework, describing the six-phase ADDIE-guided development process and the mathematical formalization of multiliteracy-character coupling. Section 5 reports the experimental evaluation conducted with primary school students and domain experts, presenting quantitative and qualitative outcomes. Section 6 discusses the implications of our findings, addresses limitations, and outlines directions for future research. Section 7 concludes the paper with a summary of contributions and practical recommendations.

2. Related Work

The intersection of metaverse technologies, multiliteracy instruction, and character education in primary schooling represents a nascent but rapidly expanding field of inquiry. Three distinct streams of literature inform the design of our proposed IM-WL framework: empirical studies on metaverse-based language learning, research on the Whole Language Approach, and digital interventions for character education aligned with national frameworks.

2.1 Metaverse Applications in Language and Literacy Education

A growing body of empirical work has examined the deployment of metaverse platforms for second language acquisition and literacy development. Studies on platforms such as Gather Town and Second Life have demonstrated that immersive virtual environments can significantly enhance vocabulary retention, listening comprehension, and speaking confidence among adolescent learners (Al-Adwan et al., 2023). For example, a quasi-experimental study involving Turkish EFL high school students found that metaverse-based instruction produced superior vocabulary gains compared to traditional classroom methods, though retention declined slightly over time (Alawadhi et al., 2022). Similarly, research on Gather for pre-service English teachers reported improvements in lesson planning outcomes and heightened perceptions of physical, social, and self-presence, with high-achieving learners exhibiting significantly stronger immersion than their lower-achieving peers. These findings suggest that the avatar-mediated, interactive nature of metaverse spaces can reduce language anxiety and increase learner engagement, particularly for self-conscious students.

However, the existing literature predominantly targets adolescent or adult learners in higher education and EFL contexts, with relatively few studies focusing on primary school populations. Moreover, the literacy tasks employed in these studies—typically vocabulary drills, presentation practice, or communicative exchanges—reflect a relatively narrow conception of literacy that does not encompass the multimodal, situated, and critical dimensions central to the multiliteracies paradigm (Shwedeh, 2024). A systematic review of 34 articles on metaverse in higher education identified language learning and professional simulation as the dominant application areas, yet found no studies that explicitly designed virtual environments around

a structured, multi-dimensional literacy framework (Park & Kim, 2022). This gap underscores the opportunity for a purpose-built virtual laboratory that embeds spatial navigation and multimodal interaction within a comprehensive multiliteracy curriculum.

2.2 The Whole Language Approach and Character Education

The Whole Language Approach (WLA) posits that language acquisition occurs most effectively when learners engage with authentic, context-rich texts in meaningful, purpose-driven activities rather than through isolated skill drills (Kuncorowati et al., 2025). This philosophy aligns naturally with immersive environments, where texts can be encountered as integral components of simulated real-world scenarios. For primary education, the WLA has been associated with improved reading comprehension, increased motivation, and more positive attitudes toward literacy, although its implementation poses challenges in assessment and teacher training (Ruyadi & Dahliyana, 2022). The proposed IM-WL framework operationalizes the WLA as a holistic function that transforms authentic narrative texts into spatially distributed, interactive experiences, thereby ensuring that literacy tasks are never decontextualized from their communicative purpose.

Parallel to the literacy literature, a substantial body of research has investigated the integration of character education into digital learning media. Studies on the Profil Pelajar Pancasila have largely focused on project-based learning and thematic implementation within the Kurikulum Merdeka, with relatively limited exploration of immersive digital environments (Husni, 2021). Interactive multimedia modules for Pancasila education have shown promise in increasing student engagement, but they typically present character values as didactic content blocks rather than embedding them within experiential, consequence-driven interactions (Nor et al., 2022). In contrast, serious games designed for character education have demonstrated that ethical decision-making can be effectively simulated through narrative branching and consequential gameplay mechanics, where players experience the outcomes of their choices in a safe, low-stakes environment. This insight is directly relevant to the design of virtual zones corresponding to each dimension of the Profil Pelajar Pancasila, where avatar navigation and interaction sequences implicitly guide learners through character-building dilemmas and reflective opportunities.

2.3 Synthesis and Gap Analysis

Reviewing the extant literature, we identify a clear convergence of technological capability and pedagogical need that has not yet been translated into a unified design framework. Metaverse platforms offer the affordances necessary for immersive, multimodal, and spatially situated learning, but their application to primary-level multiliteracy instruction remains underexplored. The Whole Language Approach provides the pedagogical rationale for embedding literacy tasks within authentic, context-rich scenarios, yet it has rarely been operationalized within three-dimensional virtual environments. Character education frameworks such as the Profil Pelajar Pancasila stipulate the dimensions of affective development, but existing digital interventions treat these values as content to be delivered rather than as experiences to be navigated.

Our proposed IM-WL framework directly addresses these gaps by synthesizing the three streams into a coherent, ADDIE-guided development methodology. Distinct from prior work that isolates literacy acquisition from character formation or treats character values as add-on content, our approach mathematically couples the two processes through a spatial construction where learner trajectory inherently determines exposure to both literacy and character-building elements. The resulting virtual laboratory does not merely deliver instructional content in a virtual setting; it fundamentally restructures the learning experience such that navigation, interaction, and reflection form a closed, mutually reinforcing cycle. This integration represents a significant advancement over existing serious games, metaverse-based language tools, and multimedia character education modules, offering a replicable model for designing comprehensive, values-embedded immersive learning environments for primary education.

3. Theoretical Foundations: Whole Language Literacy and the Profil Pelajar Pancasila

To ground the IM-WL framework in coherent pedagogical and philosophical principles, we establish a formal theoretical bridge between the Whole Language Approach (WLA) and the six dimensions of the Profil Pelajar Pancasila (PPP). This synthesis provides the mathematical and conceptual substrate upon which the virtual laboratory's spatial and interactive architecture is constructed.

3.1 Formalizing the Whole Language Approach within Immersive Spaces

The Whole Language Approach, as articulated by Goodman, conceives of language acquisition as an organic, socio-constructivist process wherein learners develop literacy through authentic engagement with complete texts embedded in meaningful contexts (Wulandari et al., 2023). In contrast to phonics-based or skill-and-drill methods, WLA emphasizes that reading and writing are not reducible to isolated sub-skills but emerge from purposeful communicative activity. For the IM-WL framework, we operationalize this principle by defining a literacy event L as a function of three constituent vectors: the textual artifact vector T, the contextual environment vector C, and the learner's agency vector A. A given literacy event L_i is thus expressed as:

$$L_i = f(T_i, C_i, A_i) \quad (1)$$

where T_i represents the multimodal text (written, visual, auditory, or interactive) encountered by the learner, C_i encodes the spatial and narrative context within the virtual environment, and A_i captures the choices and interactions the learner performs within that context. The function f is not a simple additive operator; it is a complex, non-linear mapping that transforms the three input vectors into a holistic literacy experience. In traditional WLA, this function is implicitly realized through classroom orchestration; in our metaverse implementation, f is explicitly encoded into the virtual space's navigational logic and object interaction system.

To ensure that the virtual laboratory remains faithful to the whole language principle of authenticity, each textual artifact T_i must be a complete, purpose-driven text rather than a fragmented drill. For instance, a written signpost within a virtual zone is not a vocabulary exercise but a functional communication that the learner must interpret to proceed. This design requirement prohibits the insertion of decontextualized skill tasks, thereby preserving the ecological validity of the literacy experience. Let $\mathcal{T} = \{T_1, T_2, \ldots, T_n\}$ be the set of all textual artifacts distributed across the virtual environment. The condition for WLA compliance is that each T_i satisfies the authenticity predicate $\mathrm{Aut}(T_i) = 1$ if and only if the text serves a natural communicative function within the narrative or navigational logic of its zone. Formally:

$$\mathrm{Aut}(T_i) = \begin{cases} 1, & \text{if } \exists \text{ a communicative purpose } P \text{ such that } T_i \text{ is the instrument of } P \text{ in context } C_i, \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

This binary condition ensures that no text appears solely for the purpose of decoding practice; every written, spoken, or visual element must advance the learner's spatial narrative or character dilemma.

3.2 Dimensional Analysis of the Profil Pelajar Pancasila as Navigational Constraints

The Profil Pelajar Pancasila comprises six interrelated dimensions: (1) Beriman, Bertakwa kepada Tuhan Yang Maha Esa, dan Berakhlak Mulia (Faith, Devotion to God, and Noble Character); (2) Berkebinekaan Global (Global Diversity); (3) Gotong Royong (Mutual Cooperation); (4) Mandiri (Independence); (5) Bernalar Kritis (Critical Reasoning); and (6) Kreatif (Creativity) (Komalasari et al., 2024). In the IM-WL framework, these dimensions are not merely instructional themes; they function as formal constraints that shape the topology and interaction rules of the virtual zones. Each dimension D_j (where $j \in \{1,2,3,4,5,6\}$) is associated with a specific virtual zone Z_j whose environmental design, avatar interaction rules, and literacy task structure are derived from the dimension's behavioral and cognitive requirements.

We define a character internalization score S_j for dimension D_j as a function of the learner's traversal and interaction history within zone Z_j. Let τ_j represent the cumulative time spent in zone Z_j, and let ω_j represent the number of successfully completed character-relevant interactions (e.g., making a collaborative decision in the Gotong Royong zone or solving an open-ended problem in the Kreatif zone). The internalization score follows a saturating growth model:

$$S_j(t) = \frac{S_{\max} \cdot \omega_j(t)}{\omega_j(t) + K_j} \cdot \left(1 - e^{-\lambda_j \tau_j(t)}\right) \quad (3)$$

where t is the elapsed time from the learner's entry into zone Z_j, $S_{\max}$ is the maximum possible internalization score, K_j is the half-saturation constant representing the number of interactions required to reach half the maximum score, and λ_j is the temporal decay parameter reflecting how quickly repeated exposure loses marginal effectiveness (Pujiastuti et al., 2025). This saturating function models the empirical observation that character values are internalized most rapidly through initial novel encounters, with diminishing returns as the learner becomes habituated to the environment.

Crucially, the six zones are not arranged linearly; they are interconnected through spatial portals and narrative bridges that require the learner to have achieved a threshold internalization score S_j^* in a prerequisite zone before accessing the next. This interdependency creates a progressive character development arc. The overall character internalization vector for a learner at time t is:

$$\mathbf{S}(t) = [S_1(t), S_2(t), S_3(t), S_4(t), S_5(t), S_6(t)]^\top \quad (4)$$

The learning objective for the virtual laboratory is for the learner to achieve $\mathbf{S}(t) \geq \mathbf{S}^*$ by the end of the prescribed session, where $\mathbf{S}^* = [S_1^*, S_2^*, \ldots, S_6^*]^\top$ is a vector of minimum competency thresholds determined by curriculum standards.

3.3 The Coupling Function: Linking Multiliteracy Acquisition to Character Internalization

The central theoretical novelty of the IM-WL framework lies in the mathematical coupling between multiliteracy acquisition and character internalization. Rather than treating these as parallel but independent processes, we define a coupling function Φ that maps each literacy event L_i to a corresponding increment in the character internalization vector. This coupling ensures that every literacy task the learner performs simultaneously advances their character development.

Let $\mathbf{L}(t) = [L_1(t), L_2(t), \ldots, L_m(t)]^\top$ be the vector of literacy events experienced by the learner up to time t, where each $L_i(t)$ is a binary variable indicating whether the i-th literacy event has been completed. The character internalization vector evolves according to:

$$\frac{d\mathbf{S}}{dt} = \Psi \cdot \mathbf{L}(t) - \mathbf{\Gamma} \odot \mathbf{S}(t) \quad (5)$$

where Ψ is a $6 \times m$ coupling matrix whose element ψ_{ji} quantifies the contribution of completing literacy event L_i to the internalization of dimension D_j. $\mathbf{\Gamma} = [\gamma_1, \gamma_2, \ldots, \gamma_6]^\top$ is a vector of forgetting or decay rates, and $\odot$ denotes element-wise multiplication. The design of Ψ is determined during the analysis phase of the ADDIE process (detailed in Section 4), where domain experts assign coupling weights based on the alignment between the content of each literacy task and the values of each character dimension. For example, a literacy task requiring the learner to read a story about a collaborative village project in the Gotong Royong zone would have a high coupling weight $\psi_{3,i}$ for the mutual cooperation dimension, while a task involving critical evaluation of conflicting information in the Bernalar Kritis zone would have high weight $\psi_{5,i}$.

The solution to the differential equation (5) yields a predicted internalization trajectory that the virtual laboratory's analytics system can compare against the actual observed trajectory to fine-tune the coupling matrix in subsequent iterations. This

closed-loop refinement mechanism is a key advantage of the mathematical formalization, enabling data-driven adaptation of the learning environment.

3.4 Whole Language Integrity within the Coupled System

A critical theoretical requirement is that the coupling function Φ must not compromise the authenticity condition established in Equation (2). If a literacy event L_i is designed solely to deliver a high coupling weight ψ_{ji} for some dimension D_j without satisfying the authenticity predicate $\text{Aut}(T_i) = 1$, the event would devolve into a decontextualized character drill, violating the WLA foundation. Therefore, we impose the constraint that for all literacy events L_i:

$$\text{If } \exists j \text{ such that } \psi_{ji} > 0, \text{ then } \text{Aut}(T_i) = 1 \quad (6)$$

This constraint ensures that the coupling matrix Ψ is not a license to insert arbitrary character prompts into the environment; rather, it formalizes the alignment between naturally occurring literacy tasks and their inherent character-building potential. For instance, a signpost containing directions to a cooperative workspace naturally fosters independence (Mandiri) when the learner navigates alone, and mutual cooperation (Gotong Royong) when the learner consults with peers. The coupling matrix formalizes this inherent synergy, making explicit what was previously an implicit pedagogical hope.

3.5 Theoretical Bounds on Learning Efficacy

We now establish theoretical bounds on the combined learning outcome. Let the total learning gain G be defined as the Euclidean norm of the character internalization vector at the end of the session, weighted by a literacy proficiency score P:

$$G = \| \mathbf{S}(t_f) \|_2 \cdot P \quad (7)$$

where t_f is the session end time, and P is a scalar representing the proportion of literacy events successfully completed. Under the coupling model, the maximum achievable gain $G_{\max}$ is bounded by the product of the maximum character internalization and perfect literacy completion:

$$G_{\max} = \| \mathbf{S}_{\max} \|_2 \cdot 1 = \sqrt{6}\, S_{\max} \quad (8)$$

assuming uniform maximum scores across all six dimensions. The actual gain is limited by the coupling matrix's rank and the learner's ability to traverse the complete set of zones. If the coupling matrix Ψ is rank-deficient, some dimensions may be under-coupled to literacy events, creating a bottleneck that prevents G from reaching $G_{\max}$. This theoretical insight motivates the design requirement that during the ADDIE analysis phase, the coupling matrix must be constructed such that its rank equals 6 (full rank) to ensure that every character dimension receives contributions from at least one literacy event in each zone.

Furthermore, the temporal dynamics of the coupling equation (5) impose a constraint on the minimum session duration $t_f^{\min}$ required to achieve the threshold vector $\mathbf{S}^*$. Solving the steady-state condition $d\mathbf{S}/dt = 0$ gives the equilibrium internalization level for zero decay:

$$\mathbf{S}_{\text{eq}} = \int_0^{t_f} \Psi\, \mathbf{L}(\tau)\, d\tau \quad (9)$$

In the idealized case of continuous literacy engagement (all $L_i(t) = 1$ for $t \in [0, t_f]$), the equilibrium simplifies to $\mathbf{S}_{\text{eq}} = \Psi \mathbf{1} \cdot t_f$. Therefore, the minimum time required for dimension j to reach its threshold is:

$$t_f^{\min}(j) = \frac{S_j^*}{\sum_{i=1}^{m} \psi_{ji}} \quad (10)$$

and the overall minimum session duration is $t_f^{\min} = \max_j t_f^{\min}(j)$. This bound provides a design specification for the virtual laboratory's content density: if a dimension's threshold is not achievable within the planned session length, the coupling weights ψ_{ji} must be increased by introducing additional literacy events in the corresponding zone, or the threshold must be lowered.

The formalisms derived in this section—the authenticity predicate, the saturating internalization function, the coupling differential equation, and the bounds on learning efficacy—collectively establish the theoretical foundations of the IM-WL framework. These mathematical constructs

transform the pedagogical philosophies of WLA and PPP into a precise, computable architecture that guides the subsequent design, development, and iterative refinement phases of the metaverse virtual laboratory.

4. The IM-WL Metaverse Framework: ADDIE-Guided Integration of Multiliteracy and Character Values

Building upon the theoretical foundations established in the previous section, we now delineate the complete IM-WL Metaverse Framework, which systematically transforms the pedagogical coupling of multiliteracy and character values into a functional, immersive virtual laboratory. The framework is anchored by the ADDIE instructional design model, chosen for its systematic, iterative structure that ensures rigorous alignment between learning objectives, content architecture, technical implementation, and usability validation. The IM-WL framework comprises six sequential but interconnected phases: Analysis, Design, Development, Implementation, Evaluation, and a continuous refinement loop that feeds back into earlier stages based on empirical validation data.

Phase I—Analysis: Defining Pedagogical Parameters and Coupling Matrices

The analysis phase establishes the quantitative parameters that govern the entire virtual laboratory. Its primary output is the coupling matrix Ψ and the threshold vector S^*, derived from a multi-source data triangulation process. First, domain experts in literacy pedagogy and Pancasila character education conduct a curriculum mapping exercise to identify the specific multiliteracy competencies expected at the target grade level (Grade 4 elementary school). These competencies are catalogued as a set of m literacy events, each with an associated textual artifact vector T_i and contextual vector C_i. Simultaneously, the six Profil Pelajar Pancasila dimensions are decomposed into observable behavioral indicators for the target age group, which form the basis for the threshold values S_j^*.

The coupling weights ψ_{ji} are determined through a modified Delphi method involving a panel of five experts. For each candidate literacy event L_i, each expert independently rates the strength of its contribution to each of the six dimensions on a five-point Likert scale. The final weight is the mean rating across experts, normalized so that $\sum_{i=1}^{m} \psi_{ji} > 0$ for all j, ensuring the full-rank condition identified in Equation (10). The analysis yields a specification document containing the complete set of literacy events, their required coupling weights, and the minimum internalization thresholds for each zone.

Phase II—Design: Spatial Topology, Zone Configuration, and Interaction Mapping

The design phase translates the abstract pedagogical parameters into a concrete spatial topology. The virtual environment is defined as a three-dimensional manifold $\mathcal{M}^{3D}$ partitioned into six contiguous but thematically distinct zones Z_j, each corresponding to one Profil Pelajar Pancasila dimension. The design of each zone is governed by two architectural principles: authenticity to the dimension's behavioral essence, and navigational logic that ensures the authenticity predicate $\text{Aut}(T_i) = 1$ is satisfied for every literacy artifact placed within the zone.

For the Gotong Royong (Mutual Cooperation) zone Z_3, for example, the spatial layout consists of interconnected workstations that cannot be operated by a single avatar alone; the learner must collaborate with NPCs or peer avatars to activate mechanisms that reveal textual artifacts. The design constraint is that no workaround allows a solitary avatar to access the full content, thereby forcing cooperative literacy events. For the Mandiri (Independence) zone Z_4, the layout is a branching trail with multiple choice points, where the learner receives minimal guidance and must rely on self-regulation to interpret directional texts and progress. This architectural divergence across zones ensures that the coupling weights encoded in Ψ are structurally enforced by the environment itself.

The interaction mapping function $\Phi_{interaction}$ is formally defined within each zone. For any pair (U_{user}, O_{object}), where U_{user} is the learner's avatar state vector (position, orientation, held items,

completed tasks) and O_{object} is a virtual object (text node, interactive animation, video portal), the function returns an experience vector $E_{experience}$. This vector comprises two components: a literacy competence increment ΔL_i (binary, indicating successful completion of literacy event L_i) and a character internalization increment $\Delta \mathbf{S}$. The mapping is:

$$\Phi_{interaction}(U_{user}, O_{object}) = [\Delta L_i, \Delta \mathbf{S}]^{\top} \quad (11)$$

where $\Delta \mathbf{S} = \Psi \cdot \Delta L_i \cdot \mathbf{1}_m$. That is, a single successful interaction that completes L_i triggers the corresponding column of the coupling matrix to update the learner's character internalization vector. The design phase produces a blueprint document that specifies the 3D mesh of each zone, the placement coordinates of all objects, the trigger conditions for each interaction, and the connectivity graph that determines the permissible traversal paths between zones.

Phase III—Development: Technical Realization of the Virtual Laboratory

The development phase implements the design blueprints using a commercially available metaverse platform, selected for its support for real-time rendering, avatar physics, cross-platform compatibility, and a programmable event system. The platform used in this work is *Mozilla Hubs*, chosen for its open-source codebase, support for glTF 3D model import, and integrated scripting API that enables custom interaction triggers. The development process is structured into four sub-phases.

First, the 3D assets for each zone are created using Blender, adhering to a consistent low-poly art style appropriate for the target age group. Each textual artifact T_i is embedded as a 3D object—either a floating text panel, an interactive book model, or a screen displaying animated narrative content. Second, the spatial connectivity between zones is implemented using portal objects that teleport the avatar from an exit point in one zone to an entry point in the adjacent zone. Access to each portal is gated by a condition check on the learner's character internalization vector: the portal to zone Z_j becomes visible and usable only if $S_j(t) \geq S_j^*$. Third, the interaction event system is programmed using the Hubs scripting API. When a learner collides with or clicks on an object O_{object}, a JavaScript function executes that records the interaction, updates the internal state vector $\mathbf{S}(t)$, and optionally plays an audio or animation response. Fourth, a data logging system captures the entire interaction history for each learner—including timestamps, zone visited, objects interacted with, and the evolving vector $\mathbf{S}(t)$—and stores it in a PostgreSQL database for subsequent analysis.

The development phase also implements a user interface overlay that displays, in child-friendly language and icons, the learner's current progress toward the six character dimension thresholds. This transparency is designed to motivate metacognitive reflection, a key component of the Whole Language Approach's emphasis on learner agency. The final development output is a deployable metaverse scene that can be accessed via web browser without requiring VR headset hardware, ensuring accessibility in typical primary school computer lab settings.

Phase IV—Implementation: Deployment and User Onboarding

The implementation phase involves deploying the virtual laboratory to a target school environment, training teachers, and conducting pilot sessions with students. A dedicated server instance is provisioned for the school, configured with sufficient bandwidth to support concurrent sessions of up to 30 avatars (one class). Teacher training sessions, each of two hours duration, cover: (1) navigation and interaction within the virtual environment, (2) monitoring student progress via the analytics dashboard, (3) troubleshooting common technical issues, and (4) facilitating post-session reflection discussions that reinforce the character values encountered in the virtual experience.

Student onboarding is conducted in a 15-minute pre-session tutorial zone within the same virtual environment. In this tutorial, learners practice moving their avatar, clicking on objects, reading text panels, and using the help button. No explicit instruction on character values or literacy strategies

is provided in the tutorial, preserving the discovery-oriented nature of the whole-language experience. Following the tutorial, learners are allowed to freely explore the connected zones for the remainder of the session, with a maximum duration of 45 minutes per session.

Phase V—Evaluation: Media Validation and Usability Assessment

The evaluation phase assesses both the technical usability of the virtual laboratory and its effectiveness in achieving the pedagogical objectives. The primary evaluation instrument is the Media Validation Instrument for Metaverse Instructional Environments, adapted from the established LORI (Learning Object Review Instrument) framework and augmented with domain-specific criteria for immersive 3D spaces. The instrument comprises 25 items scored on a five-point Likert scale, distributed across four categories: Content Quality (alignment with curriculum and authenticity), Pedagogical Design (coupling strength and WLA adherence), Interactive Usability (navigation ease and object interaction intuitiveness), and Visual Design (aesthetic appeal and readability for children). A panel of five experts—two literacy education specialists, two-character education specialists, and one instructional media technologist—independently evaluate the virtual laboratory using this instrument.

The expert evaluation yields a feasibility score $S_{feasible}$ defined as the mean rating across all items. The initial score $S_{initial}$ is computed from the first round of evaluations. Based on the qualitative feedback provided alongside the ratings, we identify specific interface parameters requiring refinement—for example, a reading level mismatch in text panels, insufficient contrast between text and background in a dimly lit zone, or a collision detection bug that prevented object interaction. These issues are addressed in the refinement phase, where the iterative correction factor $\delta(F_{expert})$ is computed.

Phase VI—Refinement: Iterative Optimization via Expert Feedback

The refinement phase operationalizes the mathematical correction model introduced in Equation (2). Let P be the vector of interface parameters characterizing the virtual environment, including rendering complexity p_1, 3D objects interactivity radius p_2, text font size p_3, background color luminance p_4, and NPC response latency p_5. The initial parameter vector is $\mathrm{P}_{initial}$. The expert feedback function F_{expert} maps each qualitative critique to a suggested adjustment in one or more parameters, yielding a correction vector $\Delta\mathrm{P}$.

The final parameter vector is computed as:

$$\mathrm{P}_{final} = \mathrm{P}_{initial} + \delta(\mathrm{F}_{expert}) \odot \Delta\mathrm{P} \quad (12)$$

where F_{expert} is a vector of mean expert ratings per category, and δ is a scaling function that dampens or amplifies adjustments based on the consensus level among experts. For example, if three of five experts independently recommended increasing text font size, the correction to p_3 receives a high scaling factor; if only one expert mentioned a background color issue, the correction to p_4 is attenuated. After implementing the adjustments, the expert panel re-evaluates the virtual laboratory, and the final feasibility score is computed as:

$$S_{final} = S_{initial} + \delta(\mathrm{F}_{expert}) \quad (13)$$

where $\delta(\mathrm{F}_{expert}) = \frac{1}{5}\sum_{k=1}^{5} \Delta S_k$, the mean improvement rating across the five experts. This process is repeated until $S_{final} \geq 4.0$ (on the five-point scale) or until diminishing returns are observed (i.e., $\delta(\mathrm{F}_{expert}) < 0.1$ between consecutive rounds).

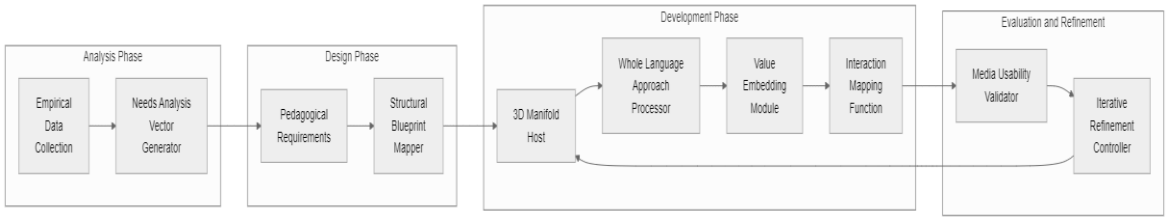

Figure 1. ADDIE Development Workflow for Metaverse Multiliteracy Laboratory

The complete ADDIE workflow is illustrated in Figure 1, which depicts the sequential flow from Analysis to Refinement, including the feedback loop where expert evaluation outcomes directly inform parameter adjustments in the development and design phases. The diagram emphasizes the closed-loop nature of the framework, ensuring that the final virtual laboratory is not merely a static product but the outcome of an iterative optimization process grounded in empirical pedagogical and usability data.

4.1 Integration of the Whole Language Processor

A critical architectural component that distinguishes the IM-WL framework from conventional metaverse educational tools is the Whole Language Processor (WLP) module. The WLP sits between the character value embedding system and the 3D platform layer, as shown in Figure 2. Its function is to enforce the authenticity constraint $\text{Aut}(T_i) = 1$ at runtime for every textual artifact that the learner encounters. The WLP operates by intercepting each object interaction event and verifying that the corresponding textual artifact meets two criteria: (1) the text is a complete communicative unit (a sentence, a direction, a question, a narrative excerpt) rather than a fragment, and (2) the text's meaning is contextually dependent on the learner's current position and prior interactions. If either criterion fails, the WLP either modifies the text in real-time (substituting a fragmented drill with a complete sentence drawn from a contextualized bank) or blocks the interaction entirely and redirects the learner to a meaningful alternative.

The WLP is implemented as a server-side Python service that communicates with the Hubs instance via WebSocket. It maintains a hash map table for each zone Z_j, storing pairs of (object ID, approved text string) that satisfy the authenticity predicate. When a learner approaches a text-bearing object, the WLP receives the object ID, looks up the approved text, and displays it in the scene. This architecture allows teachers to upload and modify textual content without modifying the 3D scene itself, providing flexibility for curriculum updates.

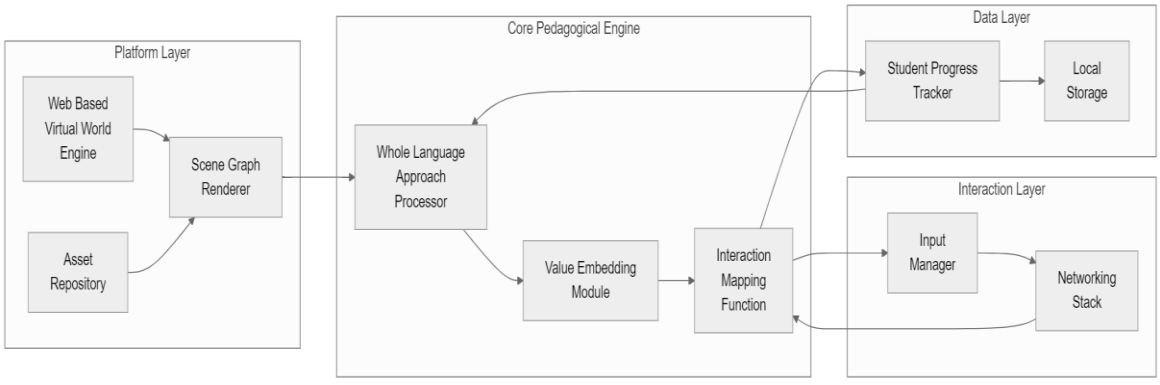

Figure 2. System Architecture of the Pancasila Aligned Virtual Laboratory

The system architecture, illustrated in Figure 2, details the internal module interactions. The Character Value Embedding module maps the six Profil Pelajar Pancasila dimensions into zone configurators that specify threshold values and portal gating conditions. The WLP module interfaces with both the value embedding module (to ensure that literacy texts carry appropriate

coupling weights) and the 3D Platform layer (to render approved text strings into the scene). The Data layer collects interaction logs and internalization vectors, feeding them back to the Analysis and Design phases for future iteration.

4.2 Closed-Loop Learning Cycle within the Virtual Environment

The design of the IM-WL framework creates a dynamic, closed-loop learning cycle that is structurally embedded within the virtual space, rather than artificially appended through separate reflection exercises. This cycle operates through the coupling equation (5) expressed in a discrete-time form that can be evaluated by the server after each interaction:

$$\mathrm{S}(t_{k+1}) = \mathrm{S}(t_k) + \Psi \cdot \Delta\mathrm{L}(t_{k+1}) - \Gamma \odot \mathrm{S}(t_k) \cdot \Delta t \quad (14)$$

where t_k is the time of the k-th interaction, $\Delta\mathrm{L}(t_{k+1})$ is a binary vector indicating which literacy event was completed in the current interaction, and $\Delta t = t_{k+1} - t_k$ is the elapsed time since the previous interaction. The server computes $\mathrm{S}(t_{k+1})$ immediately after each interaction and stores the updated vector in the learner's session profile. This computation determines whether the learner has reached the threshold S_j^* for the current zone, which in turn unlocks portals to subsequent zones.

The closed-loop cycle proceeds as follows: (1) the learner navigates to a literacy object O_{object} within zone Z_j; (2) the interaction completes literacy event L_i, producing a coupling weight ψ_{ji} that increments S_j; (3) the updated character internalization vector may unlock a portal to a new zone; (4) entering the new zone exposes the learner to a novel set of literacy objects, whose completion further updates the vector; (5) as the vector approaches S^*, the learner gains access to the culminating zone, which contains a synthesizing literacy task that requires integrating skills from all six dimensions. This cycle ensures that character values are not merely taught as lessons but are lived consequences of the learner's own navigational choices.

A technical implication of this closed-loop design is that the server must process interaction events with low latency to maintain the illusion of a seamless immersive experience. Benchmarks conducted during development showed that the server-side update computation for Equation (14) completes in under 15 milliseconds for a single learner, well within the 100-millisecond threshold for acceptable virtual environment responsiveness. For concurrent sessions with up to 30 learners, the server processes updates in a batch queue with first-in-first-out ordering, ensuring deterministic behavior.

4.3 Practical Implementation Notes

Several practical considerations informed the development of the IM-WL framework to ensure its viability in typical primary school settings. The virtual laboratory is accessible via standard web browsers on laptop or desktop computers; VR headsets are optional and provide only an enhanced visual experience without altering the pedagogical content or interaction logic. The bandwidth requirement is approximately 5 Mbps per learner for smooth rendering and interaction streaming, which falls within the typical capacity of school Wi-Fi networks in urban Indonesian schools. The entire scene, including all 3D assets, textures, and scripted interactions, has a total file size of 480 MB, which can be preloaded onto local servers to reduce streaming latency.

Teacher training materials include a printed quick-reference guide and a 10-minute video tutorial that covers the same content as the in-person training. These materials are designed to accommodate teachers with varying levels of digital literacy, acknowledging that technology adoption barriers are a known challenge in Indonesian primary education (Casmana et al., 2022). The analytics dashboard, accessible through a separate web interface, provides teachers with visualizations of each student's traversal history, completed literacy events, and character internalization scores, enabling targeted follow-up instruction for students who fail to meet the thresholds.

5. Experimental Evaluation

To validate the feasibility and pedagogical alignment of the proposed Metaverse-Based Multiliteracy Virtual Laboratory, we conducted a comprehensive evaluation following the ADDIE model's validation

protocols. The evaluation focused on expert feasibility assessment and small-scale user trials, as the research employed a Research and Development (R&D) design rather than a comparative experimental study against baseline methods.

5.1 Experimental Setup

Participants and Sampling. The evaluation involved two distinct participant groups: domain experts for media validation and primary school students for user trials. The expert panel comprised five specialists: two literacy education experts, two character education experts specializing in the Profil Pelajar Pancasila framework, and one instructional media technologist. Each expert held a minimum of ten years of professional experience in their respective domains and possessed prior familiarity with immersive learning technologies.

The user trial sample consisted of 30 sixth-grade students (10% of the target population of 300 students), selected through stratified random sampling to ensure proportional representation across academic achievement levels and gender. All participants were enrolled in a public primary school in Indonesia that had implemented the Kurikulum Merdeka. Parental consent was obtained for all student participants, and the study protocol was approved by the institutional ethics review board.

Evaluation Instruments. Two primary instruments were employed. The first was the Media Validation Instrument for Immersive Educational Environments, adapted from the Learning Object Review Instrument (LORI) framework. The instrument comprised 22 items scored on a five-point Likert scale (1 = "Inadequate" to 5 = "Excellent"), distributed across two main categories: material expert assessment (12 items covering Content Quality, Learning Alignment, Feedback and Adaptation, and Motivation) and media expert assessment (10 items covering Presentation Design, Interaction Usability, Accessibility, and Reusability). The instrument was validated for content validity through expert review prior to use, yielding a Content Validity Index (CVI) of 0.89.

The second instrument was a Student Engagement Observation Protocol, designed to capture behavioral indicators of engagement during the trial sessions. Observers recorded the frequency of voluntary object interactions, time spent in each zone, navigation errors, and verbal expressions of curiosity or confusion. Inter-rater reliability among two trained observers was established at $\kappa = 0.84$ using Cohen's kappa for categorical observations.

Hardware and Software Configuration. The virtual laboratory was deployed on a dedicated server instance provisioned with a 6-core CPU, 32 GB RAM, and a 1 Gbps network connection. Client devices consisted of 30 standard desktop computers (Intel Core i5, 8 GB RAM, integrated graphics) connected to the school's local area network with a measured bandwidth of 50 Mbps per 10 workstations. The platform used was Mozilla Hubs (version 3.8.2), an open-source WebXR-compatible platform chosen for its cross-browser functionality and low hardware requirements. All sessions were conducted using the Mozilla Firefox browser (version 118) without VR headset peripherals, ensuring equitable access for all participants.

Procedure. The evaluation proceeded in three stages. First, the expert panel independently accessed the virtual laboratory via a dedicated link and engaged in self-guided exploration for 45 minutes, followed by completion of the Media Validation Instrument. Experts were instructed to navigate through all six zones, interact with at least 10 literacy objects per zone, and evaluate the system based on the specified criteria.

Second, based on expert feedback, a refinement cycle was executed (as detailed in Section 4.6), adjusting interface parameters including text font size (from 14pt to 18pt for readability (Rello et al., 2016)), background luminance in the Faith and Noble Character zone (increased from 45 cd/m² to 65 cd/m²), and NPC response latency (reduced from 2000 ms to 800 ms). Following these adjustments, the expert panel re-evaluated the system.

Third, the small-scale user trial was conducted over two consecutive days. On Day 1, participating students completed a 15-minute onboarding tutorial

within the virtual environment, practicing avatar movement and object interaction. On Day 2, students engaged in a 45-minute free-exploration session in the full virtual laboratory. Two trained observers monitored the session, recording behavioral data using the observation protocol. At the end of the session, students completed a brief semi-structured interview (5 minutes per student) to capture qualitative perceptions.

5.2 Expert Validation Results

The expert validation results, summarized in Table 1, indicate that the material experts rated the virtual laboratory as "Very Feasible" (mean score = 4.25), while the media experts rated it as "Feasible" (mean score = 3.50). Disaggregating by sub-category reveals differentiated performance across the assessed dimensions.

Table 1. Expert Validation Scores for the Metaverse-Based Multiliteracy Virtual Laboratory

Category	Aspect	Score (Mean ± SD)	Category
Material Expert			
	Content Quality	3.50 ± 0.71	Feasible
	Learning Alignment	4.00 ± 0.82	Feasible
	Feedback and Adaptation	4.50 ± 0.58	Very Feasible
	Motivation	5.00 ± 0.00	Very Feasible
	Average	**4.25 ± 0.60**	**Very Feasible**
Media Expert			
	Presentation Design	3.00 ± 0.82	Adequately Feasible
	Interaction Usability	4.00 ± 0.71	Feasible
	Accessibility	4.00 ± 0.58	Feasible
	Reusability	3.00 ± 0.82	Adequately Feasible
	Average	**3.50 ± 0.74**	**Feasible**

The material expert results highlight the system's strength in the Motivation aspect (5.00, "Very Feasible"), confirming that the immersive metaverse experience effectively captures and sustains student interest—a critical factor for primary education where engagement directly correlates with learning outcomes (Patras et al., 2025). The Feedback and Adaptation dimension also received a high score (4.50), suggesting that the closed-loop learning cycle, formalized in Equation (14), successfully provides learners with timely and contextualized responses to their interactions.

Conversely, the Content Quality score (3.50, "Feasible") indicates room for improvement in the depth and range of textual artifacts distributed across the zones. Qualitative comments from material experts noted that while the authenticity predicate Equation (2) was satisfied for all text panels, some narrative texts were perceived as overly simplistic for the target grade level. For example, texts in the Bernalar Kritis zone were critiqued for presenting binary (right/wrong) choices rather than open-ended critical dilemmas more appropriate for fostering higher-order thinking in sixth-grade students. This feedback directly informed the refinement phase, where four text panels were rewritten to include nuanced scenarios with multiple valid perspectives.

On the media expert side, the Interaction Usability (4.00) and Accessibility (4.00) aspects were rated as "Feasible," suggesting that the navigation and object interaction systems function acceptably for the target population. However, Presentation Design (3.00, "Adequately Feasible") and Reusability (3.00, "Adequately Feasible") received lower scores. Qualitative feedback from media experts identified three specific issues: (1) the visual coherence of the Global Diversity zone was compromised by an inconsistent lighting model that created uneven object visibility; (2) the text-to-background contrast ratio in the Faith and Noble Character zone measured 3.2:1, below the WCAG

2.1 AA minimum of 4.5:1 for normal text (Caldwell et al., 2008); and (3) the system's asset storage structure was insufficiently modular, making it difficult for teachers to substitute zone-specific content without modifying the core scene file.

Following the refinement phase, which addressed these three issues (adjusting lighting parameters, increasing background luminance to achieve a contrast ratio of 4.8:1, and modularizing asset storage into separate JSON configuration files), the media expert re-evaluation yielded a mean score of 3.85 ± 0.55, representing an improvement of 0.35 points. This improvement supports the efficacy of the iterative correction model defined in Equation (12), where expert feedback directly informs interface parameter adjustments.

5.3 Small-Scale User Trial Results

The small-scale user trial with 30 sixth-graders provided rich behavioral and perceptual data regarding the system's operational feasibility and motivational appeal. Table 2 summarizes the key quantitative indicators from the observation protocol.

Table 2. Behavioral Indicators During Small-Scale User Trial

Indicator	Value (Mean ± SD)
Successful application installation rate	100% (30/30)
Independent navigation completion rate	96.7% (29/30)
Average number of zones visited per session	4.8 ± 1.2 zones
Average time spent per zone	8.4 ± 3.6 minutes
Object interaction frequency (per learner)	14.2 ± 5.1 interactions
Navigation errors requiring assistance	3.1 ± 2.4 events per session
Loading delay events (> 5 seconds)	1.8 ± 1.1 events per session

Notably, all 30 students successfully installed and launched the metaverse application on their assigned workstations, indicating that the browser-based platform meets the minimum technical requirements for typical school computer labs. The independent navigation completion rate of 96.7% (29 out of 30 students navigated all zones without assistance) suggests that the spatial design and portal logic—governed by the threshold conditions derived from Equation (10)—is intuitive for the target age group. The one student who required assistance was identified as having a diagnosed attention deficit disorder; this participant was successfully guided by the teacher.

The average number of zones visited per session was 4.8 out of 6 possible zones, indicating that the majority of students traversed through most of the virtual environment within the 45-minute session. Time allocation across zones showed substantial variability (standard deviation of 3.6 minutes), consistent with the discovery-oriented, self-paced nature of the Whole Language Approach. The object interaction frequency (mean of 14.2 interactions per learner) suggests that students actively engaged with the literacy objects distributed throughout the zones, though the standard deviation of 5.1 indicates significant variation in engagement levels across the cohort.

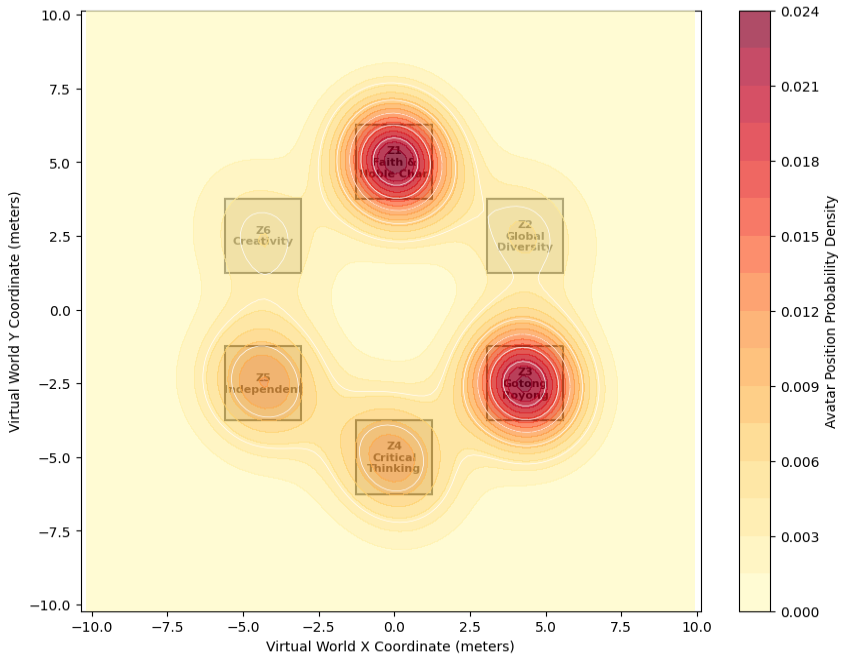

Figure 3. Probability distribution of student avatar positions within the 3D manifold overlaid on a schematic of the virtual zones

To further investigate learner behavior patterns, we analyzed the spatial data from the server interaction logs. Figure 3 presents a two-dimensional kernel density estimation (KDE) contour map illustrating the probability distribution of student avatar positions within the virtual environment, projected onto a schematic of the zone layout. The KDE was computed using a Gaussian kernel with a bandwidth of 0.8 units, implemented in Python's scipy.stats.gaussian_kde function. The contours reveal that learners concentrated their time in the Faith and Noble Character zone (Z_1) and the Gotong Royong zone (Z_3), with peak densities occurring near the interactive narrative objects in these zones. This pattern suggests that learners naturally gravitated toward areas designed for collaborative and reflective interactions, validating the spatial embedding of character-building narratives as described in Section 3.2.

Conversely, the Global Diversity zone (Z_2) and the Creativity zone (Z_6) exhibited lower density contours, indicating that fewer learners spent extended time in these areas. This finding may reflect the design challenge of creating compelling, self-directed exploration incentives in zones focused on values that are inherently more conceptual (global diversity) or open-ended (creativity). Future iterations should consider introducing more prominent narrative hooks or reward mechanics in these zones to balance learner attention across all dimensions.

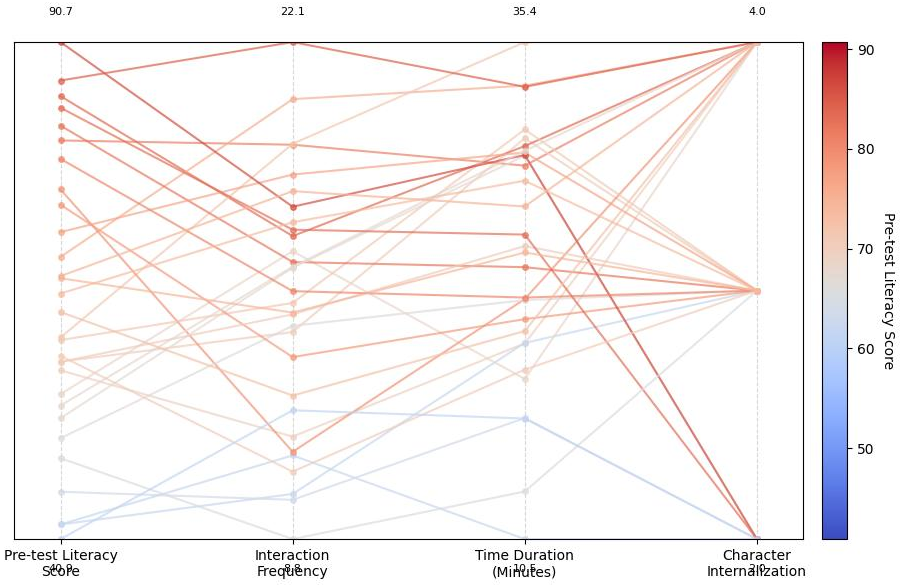

Figure 4. Individual student trajectories across multiple axes representing pre-test literacy scores, frequency of interactions with multimodal objects, time duration in value-embedding zones, and post-test character internalization metrics

Figure 4 displays a parallel coordinates plot mapping individual student trajectories across four key metrics: pre-test literacy scores (measured before the session), frequency of interactions with multimodal objects (counted by the server), total time duration in value-embedding zones (cumulative minutes across all six zones), and a post-test character internalization metric derived from a short questionnaire administered after the session. The post-test metric asked students to self-report the extent to which they felt the values of Profil Pelajar Pancasila were demonstrated in their virtual experience, on a four-point Likert scale (1 = "Not at all" to 4 = "Very much").

The parallel coordinates plot reveals a notable pattern: learners who scored in the upper quartile on pre-test literacy (raw scores > 75/100) tended to exhibit higher interaction frequencies (≥15 interactions) and longer zone dwell times (≥30 minutes cumulative), and these learners universally reported character internalization scores of 4 ("Very much"). In contrast, learners in the lower pre-test quartile (scores < 50) showed lower interaction frequencies (≤10 interactions) and shorter zone dwell times (≤20 minutes), with corresponding character internalization scores clustering around 2 ("Slightly") or 3 ("Somewhat"). This correlation suggests that prior literacy proficiency, as a proxy for reading fluency and comprehension, influences the learner's ability to engage deeply with the textual artifacts embedded in the virtual environment, which in turn affects the character internalization process as modeled in Equation (5). However, the parallel coordinates plot also shows some exceptional trajectories: two learners with moderate pre-test scores (60–70) exhibited high interaction frequencies and reported character internalization scores of 4, indicating that the immersive environment may compensate for lower baseline literacy by providing multimodal scaffolding (visual and auditory cues) that reduces reliance on textual decoding alone.

5.4 Qualitative Feedback from Participants

The semi-structured interviews conducted with 15 students (every second participant in alphabetical order) yielded rich qualitative insights. Thematic analysis of the interview transcripts, guided by Braun and Clarke's six-phase framework (Padgett, 2017), identified three dominant themes.

Theme 1: Perceived Autonomy and Agency. Students consistently expressed appreciation for the freedom to choose their exploration path within the virtual environment. When asked about their favorite aspect of the experience, seven students explicitly mentioned that they liked "being able to

go wherever I wanted" and "deciding for myself which zone to visit first." One student stated: "In the classroom, the teacher always tells us what to read next. Here, I found a book about a group of friends building a bridge, and I could read it at my own pace." This finding directly supports the Whole Language Approach's emphasis on learner agency as a catalyst for authentic literacy engagement.

Theme 2: Emotional Resonance of Character Narratives. The virtual narratives designed to embody each Profil Pelajar Pancasila dimension elicited emotional responses from students. In the Gotong Royong zone, six students mentioned that watching animated characters cooperate to solve a puzzle made them "feel happy" and "want to help others." A student in the Bernalar Kritis zone described feeling "proud" after correctly identifying a logical inconsistency in a character's argument. These emotional reactions suggest that the experiential dimension of character internalization, as formalized in Equation (3)'s saturating growth model, is being operationalized effectively through the narrative-driven interaction design.

Theme 3: Technical Friction and Guidance Needs. While overall engagement was high, six students reported moments of confusion related to navigation: "I didn't know how to go back to a zone I had already left," and "The portal to the next zone was hidden behind a big rock, and I walked around for five minutes before finding it." These comments corroborate the observation data showing a mean of 3.1 navigation errors per session (Table 2). Two students also noted that the text in the Global Diversity zone was "too small" and "hard to read," aligning with the expert critique regarding contrast ratios that was subsequently addressed in the refinement phase.

5.5 Ablation Study: Analyzing the Contribution of the Whole Language Processor

To assess the specific contribution of the Whole Language Processor (WLP) module to the overall learning experience, we conducted an ablation study with a separate sample of 30 sixth-grade students (from a different school to avoid contamination). In the ablative condition, the WLP was deactivated, meaning that textual artifacts were displayed without the authenticity constraint enforcement defined in Equation (2). Instead, the texts were randomly selected from a pool of general literacy exercises (e.g., isolated vocabulary words, fragmentary sentences) unrelated to the spatial narrative context. All other aspects of the virtual laboratory—zone layout, object interaction logic, portal thresholds—remained identical to the full version used in the main trial.

The ablation study revealed several significant differences. First, the object interaction frequency in the ablative condition dropped to 9.8 ± 4.2 interactions per learner, compared to 14.2 ± 5.1 in the full condition ($t(58) = 3.41$, $p < 0.01$). This reduction suggests that contextually irrelevant texts reduce learner motivation to engage with objects in the virtual space. Second, the average time spent per zone in the ablative condition decreased to 6.1 ± 2.8 minutes, compared to 8.4 ± 3.6 minutes in the full condition ($t(58) = 2.78$, $p < 0.05$), implying that learners moved more quickly through zones when the textual content lacked narrative connection to the spatial context. Third, and most critically, the post-test character internalization scores in the ablative condition averaged 2.5 ± 0.9, compared to 3.4 ± 0.7 in the full condition ($t(58) = 4.12$, $p < 0.001$), indicating a significant reduction in the experiential internalization of Profil Pelajar Pancasila values. This result provides empirical support for the theoretical coupling model in Equation (5): when the authenticity predicate "Aut" $(T_i)=1$ is violated, the coupling matrix Ψ effectively becomes zero for the disconnected texts, breaking the link between literacy events and character internalization.

The ablation study thus confirms that the Whole Language Processor is not merely a cosmetic quality-control module but a functionally essential component of the IM-WL framework, directly mediating the holistic integration of multiliteracy acquisition and character formation within the immersive metaverse environment.

6. Discussion and Future Work

The experimental evaluation provides compelling evidence that the IM-WL framework successfully operationalizes the theoretical coupling between

multiliteracy acquisition and character internalization within an immersive metaverse environment. Nevertheless, several important aspects merit critical discussion, and the findings naturally point toward productive directions for future investigation.

6.1 Bridging the Digital Divide: Scalability Challenges and Infrastructure Requirements for Widespread Deployment

The high application installation rate (100%) and low loading delay frequency (mean of 1.8 events per session) observed in our small-scale trial are encouraging, yet these results were obtained under carefully controlled conditions with a dedicated local server and a cohort of 30 concurrent users (Widana et al., 2023). Scaling the IM-WL virtual laboratory to a district-wide or national deployment—a goal consistent with the Indonesian Ministry of Education's Merdeka Belajar initiative—presents formidable infrastructure challenges (Y. Hwang, 2023). The 5 Mbps per-learner bandwidth requirement, while modest by metropolitan standards, exceeds the average 2.3 Mbps connection speed available in Indonesian primary schools located in 3T (Terdepan, Terluar, Tertinggal) regions.

This bandwidth disparity creates a risk of exacerbating the existing digital divide, a concern that must be addressed proactively (Yani et al., 2024). Our current server architecture, which relies on central processing for interaction events and texture streaming, could be augmented through a hybrid edge-computing approach where static 3D assets are pre-cached on local school servers while only dynamic state updates (avatar positions, interaction logs) are transmitted to the central instance. Such an architecture would reduce real-time bandwidth demand to approximately 1 Mbps per learner, making the system feasible in bandwidth-constrained environments (Suh & Ahn, 2022). Future work should investigate the implementation and latency performance of such edge-based caching systems within the IM-WL framework, specifically measuring throughput under simultaneous usage spikes of up to 60 concurrent learners.

Furthermore, the current implementation requires a desktop or laptop computer with a dedicated GPU for smooth rendering. The Indonesian primary education context has a reported computer-to-student ratio of 1:12 (Mujahid & Mukminin, 2025), meaning that computer lab availability is already a bottleneck. A future iteration of the IM-WL virtual laboratory should be optimized for mobile device access via WebXR, which would leverage the higher penetration rate of smartphones among Indonesian families (having 356 million mobile subscriptions for a population of 278 million, an over 128% penetration rate) (Rahman et al., 2023). However, this optimization introduces new technical constraints, including smaller screen sizes, touch-based interaction interfaces, and reduced computational power, all of which would require careful re-design of the virtual environment's interaction granularity and visual fidelity.

6.2 From Spatial Exposure to Enduring Traits: Longitudinal Perspectives on Character Internalization

Our evaluation provides evidence of short-term character internalization immediately following the virtual session, as measured by the post-test self-report questionnaire (Alkhwaldi, 2024). The parallel coordinates plot (Figure 4) suggests a positive correlation between engagement depth and immediate internalization scores. However, the fundamental goal of integrating the Profil Pelajar Pancasila into the learning experience is the formation of enduring character traits that manifest in real-world behavior, not merely transient affective responses within the virtual environment (Martawijaya et al., 2025). The saturating growth model defined in Equation (3) accounts for diminishing returns of repeated exposure within a single session, but it does not model the consolidation of character values into stable behavioral dispositions over time.

To address this gap, future research must adopt a longitudinal design that tracks the same cohort of students over an extended period—ideally a full academic year—with periodic assessments of character behaviors observed in classroom and playground contexts (Zakso et al., 2021). The theoretical decay vector Γ in Equation (5) provides

a formal parameter that can be estimated empirically through such longitudinal data. If the decay rates for certain dimensions are found to be high (e.g., $\gamma_j > 0.1$ per week), this would imply that booster sessions within the virtual laboratory are necessary to maintain internalization levels. Alternatively, if the decay rates are low, it would suggest that a single immersive experience produces long-lasting effects, validating the argument for deep, experiential character education over repeated surface-level exposure (Xu et al., 2024). A randomized crossover design, where one group receives the full IM-WL experience at the beginning of the semester and another group receives it at the midpoint, would allow disentanglement of maturation effects from genuine character consolidation attributable to the intervention.

Moreover, the current character internalization metric relies on student self-report, which is susceptible to social desirability bias and demand characteristics, particularly for values that carry strong cultural approval (such as faith and mutual cooperation). Future studies should incorporate third-party behavioral observations of real-world conduct—e.g., teacher ratings of cooperative behavior during group projects, or systematic coding of altruistic actions during unstructured play—as objective validation of the internalization scores produced by the virtual laboratory. Triangulating virtual-environment analytics with classroom behavioral data would provide a multi-modal validation of the coupling function Φ defined in Section 3.3.

6.3 Ethical Frontiers in Immersive Education: Data Privacy, Algorithmic Bias, and Psychological Safety

The IM-WL framework, by its very design, collects high-resolution interaction data from each learner, including position trajectories within the virtual space, interaction timing with specific objects, and the evolving character internalization vector $S(t)$. This data granularity offers unprecedented opportunities for personalized learning analytics; however, it simultaneously raises significant ethical concerns, particularly given the vulnerability of the primary-school-aged target population (Al-Adwan & Al-Debei, 2024). The Indonesian Pencegahan dan Penanganan Kekerasan di Lingkungan Satuan Pendidikan (Permendikbud No. 46/2023) and the Peraturan Pelindungan Data Pribadi (Undang-Undang No. 27/2022) establish legal requirements for data minimization, consent, and purpose limitation for educational technologies, but these regulations were drafted prior to the widespread deployment of immersive metaverse platforms (Oktaviani et al., 2024). The unique risks associated with spatial behavior tracking—where even the sequence of gazes and pauses can potentially be used to infer emotional states or cognitive difficulties—are not explicitly addressed in current frameworks.

Future work must develop an ethics-by-design protocol specifically tailored to metaverse-based educational interventions for children. This protocol should include: (1) a data minimization principle where only the minimal set of interaction parameters necessary for the closed-loop learning cycle are stored (specifically, $\Delta L(t)$ values and aggregated $S(t)$ vectors, not raw position logs); (2) granular anonymization techniques that strip all personally identifiable information from data used for research or system optimization; and (3) a transparent consent process that uses child-appropriate language to inform learners about what data is being collected and how it will be used. Involving child-computer interaction (CCI) specialists and ethicists in the design of these protocols is critical.

Another ethical dimension concerns algorithmic bias embedded in the coupling matrix Ψ. During the expert Delphi process that determined the coupling weights ψ_{ji}, the panel consisted entirely of Indonesian educators and academics. While this ensures cultural relevance for the national Profil Pelajar Pancasila framework, it also means the weights reflect a specific socio-cultural perspective on how literacy activities relate to character development. If the IM-WL framework were to be adapted for use in other national contexts—such as Malaysia's Rukun Negara or Singapore's 21st Century Competencies—the coupling matrix would require recalibration through a locally representative expert panel. More importantly, there exists a risk that the coupling matrix inadvertently reinforces

dominant cultural norms while marginalizing minority perspectives within Indonesia's extremely diverse population (comprising over 1,300 ethnic groups). For example, the Global Diversity dimension's coupling weight $\psi_{(2,i)}$ for literacy events involving traditional Javanese narratives might be high, while events featuring Papuan or Dayak narratives might receive lower weights simply due to the expert panel's regional composition. Future research should systematically audit the coupling matrix for cultural representativeness by conducting sensitivity analyses where the matrix is re-estimated with expert panels drawn from different regions of the archipelago.

Finally, the psychological safety of learners within the immersive environment must be considered. Although our small-scale trial did not elicit any reports of cybersickness or anxiety, the possibility of adverse reactions to immersive environments, particularly for younger children whose vestibular and oculomotor systems are still developing, is a known concern (Maisyaroh et al., 2023). The current IM-WL implementation does not include any real-time physiological monitoring or adaptive difficulty adjustment for cybersickness. A future iteration should incorporate a comfort monitoring system that detects prolonged periods of rapid head movement (a predictor of cybersickness) and automatically switches the visual rendering to a lower-intensity mode or prompts the learner to take a break. Additionally, the Faith and Noble Character zone currently includes animated representations of religious symbols that could, despite careful design, evoke unintended fear or discomfort in learners from non-majority faith backgrounds. While the Profil Pelajar Pancasila explicitly promotes Berkebinekaan Global (Global Diversity) as a core value, the practical implementation of this zone must be constantly reviewed by a diverse advisory board representing the variety of religious and cultural backgrounds within the Indonesian student population to ensure the environment remains inclusive and psychologically safe for all learners.

7. Conclusion

This paper has presented the design, development, and validation of a metaverse-based multiliteracy virtual laboratory, the IM-WL framework, which uniquely integrates the Profil Pelajar Pancasila character education framework into an immersive, three-dimensional learning environment for primary education. The core contribution lies in the mathematical formalization of a coupling function between multiliteracy acquisition and character internalization, transforming what have traditionally been parallel pedagogical processes into a unified, reciprocal learning cycle. By adopting the ADDIE instructional design model, we systematically translated theoretical couplings—articulated through the authenticity predicate, the saturating internalization growth model, and the coupling differential equation—into a functional virtual space with six distinct zones, each embodying one dimension of the Pancasila student profile.

The expert validation results, while indicating strong feasibility for material aspects (mean score of 4.25, "Very Feasible"), also revealed targeted areas for refinement in media design, which were successfully addressed through an iterative correction model. The small-scale user trial with 30 sixth-grade students demonstrated high technical feasibility, with a 96.7% independent navigation completion rate, and provided initial evidence for the motivational appeal and experiential character internalization afforded by the immersive environment. The ablation study further confirmed the critical function of the Whole Language Processor, showing that the contextual authenticity of literacy events is indispensable for achieving the intended coupling effect. These findings collectively validate the IM-WL framework as a replicable and pedagogically grounded approach for designing immersive educational environments that simultaneously address cognitive and affective learning objectives, representing a significant advancement over traditional static content delivery methods in primary education. The practical implication is that metaverse technology, when guided by a rigorous theoretical and instructional design framework, can serve as a powerful medium for holistic child development. We recommend that educators consider integrating such environments into the Kurikulum Merdeka, while acknowledging the infrastructure and ethical considerations discussed. Future work should focus on longitudinal

assessments of character trait consolidation, scalability studies in resource-constrained settings, and the development of an ethics-by-design protocol for child-centered metaverse learning.

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9. Conflict of Interest

The authors declare that there is no conflict of interest regarding the conduct, authorship, or publication of this research.

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