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Bridging the Ocean Literacy Gap: Teacher Needs and Design Requirements for Virtual Reality-Based Sustainable Maritime Education for Coastal High Schools in Tanjungpinang, Indonesia

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ABSTRACT

Ocean literacy is an essential competence for understanding the reciprocal relationship between humans and the ocean and supporting sustainable development, particularly in coastal communities. However, including marine-related content in Biology education does not necessarily ensure the systematic integration of maritime contexts, authentic learning experiences, or multidimensional ocean literacy assessment. This study aimed to identify Biology teachers' instructional, contextual, technological, and assessment needs and to formulate evidence-based design requirements for developing Virtual Reality (VR) supported Sustainable Maritime Education (SME) in coastal high schools. We employed a convergent mixed-methods approach involving 26 Biology teachers from nine secondary schools in Tanjungpinang City, Riau Islands Province, Indonesia. We analysed quantitative data using descriptive statistics and examined open-ended questionnaire responses using a hybrid inductive-deductive thematic analysis. We integrated the two strands through a joint display to identify convergence, complementarity, and potential divergence, and to formulate empirically informed design requirements. Most teachers (84.6%) reported teaching marine and coastal ecosystem content and using educational technology, but only 15.4% frequently integrated maritime contexts into Biology learning. VR equipment was unavailable in 69.2% of the participating schools, and 84.6% of teachers indicated that a specific ocean literacy assessment instrument was needed or highly

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needed. The integrated findings yielded seven context-specific design propositions: contextual authenticity, immersive experiential learning, pedagogical integration, ocean literacy alignment, accessibility and feasibility, realistic curriculum-aligned content, and action-oriented sustainability. These findings provide preliminary design propositions for future development, validation, and testing of SME–VR's effectiveness in strengthening ocean literacy among secondary school students.

Keywords: Biology education, coastal education, ocean literacy, sustainable maritime education, virtual reality

INTRODUCTION

The ocean is a fundamental component of the Earth system, covering approximately 70% of the planet's surface and playing critical roles in climate regulation, carbon and water cycles, biodiversity conservation, food provision, livelihoods, and the ecosystem services that underpin human wellbeing (Asikin et al., 2026; Kelly et al., 2022; Watson et al., 2020). This relationship is reciprocal, as human activities also exert substantial pressure on the ocean through resource exploitation, pollution, habitat alteration, and climate change (Fielding et al., 2019; Kelly et al., 2022). Ocean sustainability is therefore both an ecological and a social issue that requires people to understand the reciprocal relationship between humans and the ocean and make responsible decisions (Fauville et al., 2021; Mendler de Suarez et al., 2014). Within the framework of sustainable development, education has a strategic role in building such capacity through Sustainable Development Goal (SDG) 4 on quality education and SDG 14 on the conservation and sustainable use of the oceans (Asikin et al., 2023; Diz et al., 2018). UNESCO-IOC also positions ocean literacy as an important means of developing a society that understands how the ocean influences people and how human activities influence the ocean, and that can translate such understanding into responsible action (Francesca et al., 2017; Pinardi, 2019). This relevance is particularly pronounced in Indonesia as an archipelagic country whose ecological, social, and economic systems are closely connected to coastal and marine environments. This condition positions education as a strategic instrument for developing ocean literacy at the secondary education level.

Ocean literacy (OL) refers to the capacity to understand the reciprocal relationship between the ocean and humans and to apply that understanding in decision-making and responsible action toward the marine environment (Asikin et al., 2023; Francesca et al., 2017; Kelly et al., 2022). The concept of OL has evolved from an initial emphasis on marine knowledge toward a more multidimensional construct encompassing knowledge, awareness, attitudes, behaviours, experience, emotional connectedness, communication, and the capacity to act (Costa et al., 2021; Koutsopoulos & Stel, 2021; Mokos et al., 2020; Zielinski et al., 2022). Thus, knowing about marine ecosystems does not necessarily mean an individual has attitudes and behaviours that support ocean sustainability (Asikin et al., 2026). In education, OL therefore needs to be developed through learning experiences

that connect scientific understanding with environmental contexts, values, attitudes, and actions. A systematic review of OL teaching in science education indicates that curriculum integration, project-, problem-, and inquiry-based learning, the use of technology, and the development of assessment instruments that address knowledge, attitudes, and behaviours are important requirements for marine education (Asikin et al., 2026). This issue matters in coastal communities because proximity to the ocean does not automatically lead to greater understanding of, or responsible behaviour toward, the marine environment (Heck et al., 2018; Kasten et al., 2021; Pazoto et al., 2022). Low levels of ocean literacy indicate that students need learning experiences that go beyond transmitting knowledge about the ocean and connect that knowledge with attitudes and behaviours toward the marine environment (Asikin et al., 2023).

At the secondary education level, Biology provides relevant opportunities to develop OL through topics such as ecosystems, biodiversity, organism–environment interactions, environmental change, and conservation (Lucrezi et al., 2018; Ward et al., 2022). However, the presence of marine-related content in the curriculum does not guarantee that maritime contexts are systematically integrated into students' learning experiences (Asikin et al., 2025; Shi & Fan, 2021). Learning may remain focused on conceptual transmission and rely on representations such as text, images, or videos without providing sufficient opportunities for students to explore marine environments contextually (Sahriana et al., 2020; Shi & Fan, 2021; Shih, 2024). This challenge is further complicated by the fact that marine ecosystems are relatively difficult to access directly. Phenomena such as coral reef structures, seagrass communities, organism interactions, habitat changes, and the impacts of human activities on coastal ecosystems cannot always be routinely observed by students (Asikin et al., 2025; Shi & Fan, 2021). Field activities can provide authentic experiences, but site accessibility, cost, time, weather conditions, safety, and school facilities may constrain their implementation. Furthermore, assessments used in learning do not always measure OL multidimensionally (Lin et al., 2020; O'Brien et al., 2023). Systematic evidence indicates that OL assessment instruments still need to be developed to measure not only knowledge but also attitudes and behaviours toward the ocean (Asikin et al., 2026). These conditions indicate a gap between the availability of marine content in Biology education and the availability of learning experiences that can develop ocean literacy in contextual and multidimensional ways.

Virtual Reality (VR) technology offers an opportunity to address some of these limitations in learning experiences (Asikin et al., 2025; Liu et al., 2020). VR enables learners to interact with three-dimensional digital environments and experience immersive representations of objects or environments that are difficult to access directly (Hite, 2022; Huang et al., 2019). In marine education, these characteristics matter because virtual environments can visualise and support exploration of underwater environments, organisms,

habitat structures, and ecological processes (Fauville et al., 2021, 2026; Frank et al., 2026). Research on underwater virtual reality shows that immersive experiences can generate high levels of presence and evoke affective responses such as awe, empathy, and flow, potentially reducing students' psychological distance from marine environments (Fauville et al., 2026). Research in science education has also shown that VR can provide interactive learning experiences, and systematic evidence identifies VR as a technology with the potential to support OL learning (Asikin et al., 2026). However, this potential does not mean that using VR automatically produces better learning outcomes. VR's pedagogical value depends on alignment among technological characteristics, learning objectives, student activities, environmental context, and assessment. Therefore, VR should be positioned as part of a learning-experience design rather than as a substitute for pedagogy or merely as a medium for displaying three-dimensional objects (Frank et al., 2026; Gomez, 2020; Hite, 2022). VR can make meaningful pedagogical contributions only when designed as part of a structured, contextualised, reflective learning experience aligned with ocean literacy objectives.

Although research on OL and VR in education continues to expand, an important gap remains in learning design. Previous studies have examined OL development in science education and explored VR's potential to provide immersive marine experiences. However, few studies have systematically integrated teachers' needs, local maritime contexts, pedagogical constraints, technological readiness, and OL assessment practices into VR-based learning design (Asikin et al., 2025). Recent evidence indicates that technologies such as VR have been used to create interactive experiences in OL education, while also emphasising the need to integrate curriculum, innovative pedagogy, technology, and assessment appropriately (Asikin et al., 2026). Even underwater VR studies that explicitly connect VR with OL have largely focused on technological potential and users' psychological experiences. Further research is therefore needed to translate these potentials into learning-design requirements that are appropriate for school contexts and teachers' needs (Fauville et al., 2026; Frank et al., 2026). This gap matters for secondary schools in Indonesia's coastal regions because effective learning design must account for local environmental characteristics, Biology content, students' abilities and needs, teacher readiness, technological infrastructure, and assessment practices. Therefore, before developing VR and testing its effectiveness, an evidence-based needs analysis is required to identify the pedagogical, contextual, technological, and assessment requirements that can serve as the foundation for Sustainable Maritime Education (SME).

Although research on ocean literacy (OL) and VR in education continues to expand, a key gap remains in understanding how teachers' locally situated needs, instructional practices, technological constraints, and assessment priorities can inform the design of maritime learning. VR can represent underwater environments and processes that may be difficult to access directly, but it is not the only approach. Resources such as 360-degree

media, simulations, multimedia, virtual field trips, and direct field experiences may also address some learning needs, separately or in combination. The present study did not compare these alternatives. Instead, it examined teacher-reported needs and constraints within a research programme that proposes VR-supported SME as the development direction. Therefore, the study does not seek to establish VR as the optimal or superior solution; it seeks to identify context-specific conditions to consider when developing VR for this setting.

Based on this gap, this study aimed to identify Biology teachers' instructional, contextual, technological, and assessment needs and to integrate quantitative and qualitative evidence to inform provisional design propositions for VR-supported learning within Sustainable Maritime Education in coastal secondary schools. The analysis focused on current Biology teaching practices related to marine content, maritime contextualisation, perceived learning difficulties and experiential needs, technology and VR readiness, priority marine content, pedagogical expectations, and ocean literacy assessment practices. The study contributes context-specific evidence from 26 teachers across nine secondary schools in Tanjungpinang City. Because students did not participate in this phase, references to student learning needs represent teachers' perceptions rather than direct evidence from students. The propositions are intended to guide subsequent development and validation, not to constitute a validated design framework.

THEORETICAL BACKGROUND

Ocean Literacy as a Multidimensional Educational Construct

Ocean literacy (OL) was initially developed to enhance public understanding of the ocean and the reciprocal relationship between humans and the marine environment. Conceptually, OL refers to understanding how the ocean influences humans and how human activities influence the ocean, including the ability to understand marine-related information and use such knowledge to make responsible decisions (Cava, 2005; Francesca et al., 2017; NOAA, 2020). Over time, OL has evolved beyond the acquisition of factual knowledge about marine ecosystems and is now conceptualised as a multidimensional construct encompassing knowledge, awareness, attitudes, behaviours, experiences, emotional connectedness, communication, and the capacity to act (Asikin et al., 2026; Bastos et al., 2026; McKinley et al., 2023). This conceptual expansion suggests that individuals may know marine concepts without necessarily developing concern for, or taking actions that support, ocean sustainability. Therefore, OL education needs to give students opportunities to connect scientific understanding, environmental experiences, values, attitudes, and action (Kelly et al., 2022; McKinley et al., 2022). In the present study, knowledge, attitude, and behaviour are the three primary dimensions because they represent the relationships among cognitive understanding, affective orientation, and behavioural tendencies toward

the marine environment. Selecting these three dimensions also provides an operational basis for developing and evaluating secondary-school learning.

Place-Based and Contextual Environmental Education

Place-based education provides a theoretical foundation for explaining why local environmental contexts are important in environmental education (Almeida & Cutter-Mackenzie, 2011; Asikin et al., 2026; Otto & Pensini, 2017). This approach positions place, environment, community, and learners' lived experiences as sources of learning, ensuring that acquired knowledge remains connected to the environmental conditions students know (Fauville et al., 2021; Kao et al., 2026; McPherson et al., 2018). In marine education, a place-based approach is particularly relevant because students' relationships with the ocean are shaped not only by scientific knowledge but also by their experiences, geographical proximity, local identity, and understanding of environmental issues in their surrounding areas (Bastos et al., 2026; Freitas et al., 2026; Mothershed & Stilwell, 2025). Research on place-based marine education indicates that connections with local environments can strengthen students' understanding, perceptions, and relationships with marine environments and support the development of concern for the ocean (Bastos et al., 2026; Freitas et al., 2026; Mothershed & Stilwell, 2025). This framework has direct implications for SME development because maritime learning is insufficient when it relies solely on generic ocean representations disconnected from students' lives. Content such as mangroves, seagrass, coral reefs, marine biodiversity, and coastal pollution has greater pedagogical value when situated within environmental contexts that are relevant to students' lived experiences (Asikin et al., 2026). Therefore, this study positions place-based environmental education as a principle for ensuring that SME–VR achieves contextual authenticity, namely the capacity to represent marine ecosystems and maritime issues relevant to the coastal contexts in which students live and learn.

Experiential Learning for Marine Environmental Education

Experiential learning provides a theoretical basis for understanding how experience can develop environmental knowledge and competencies. From the perspective of Kolb & Kolb (2017), learning occurs through a cycle involving concrete experience, reflective observation, abstract conceptualisation, and active experimentation. This framework is particularly relevant to marine education because ocean-related objects and phenomena are often difficult to understand solely through verbal descriptions or two-dimensional visual representations (Asikin et al., 2023; Williams, 2024). Students need opportunities to observe phenomena, interpret information, connect observations with scientific concepts, and apply their understanding to analyse environmental problems. In marine education, direct experiences through field observations, coastal exploration, organism observation,

or conservation activities can provide concrete experiences that strengthen connections between knowledge and the environment (Ditrich & Lachmair, 2026; Frank et al., 2026; Zhang et al., 2026). However, direct experiences with marine ecosystems cannot always be conducted routinely because of geographical limitations, safety considerations, weather conditions, costs, time constraints, site accessibility, and available facilities. Technology can therefore complement direct experiences, particularly when learning objects or environments are difficult to access (Ditrich & Lachmair, 2026; Fauville et al., 2026; Hetherington et al., 2026). In this context, VR can provide technology-mediated experiences that allow students to explore environments that are difficult to observe directly (Fauville et al., 2026; Frank et al., 2026). Thus, within SME–VR, virtual experiences are not intended to replace real environmental experiences but rather to extend access to marine experiences when direct experiences are difficult to provide.

Immersive Learning and the Pedagogical Affordances of VR

Virtual Reality has characteristics that distinguish it from conventional learning media, as it allows users to interact with three-dimensional digital environments and experience a sense of presence within them (Elme et al., 2022; Makransky et al., 2020; Petersen et al., 2020). In education, these characteristics offer several pedagogical affordances, including representing environments that are difficult to access, facilitating exploration from multiple perspectives, and providing more interactive learning experiences (Di Natale et al., 2020; Han, 2020; Jensen & Konradsen, 2018). Bower & Jong (2020) showed that immersive VR can support various learning activities, particularly when virtual environments are designed around learning objectives and appropriate activities. Hamilton et al. (2021) Likewise, reported generally positive evidence regarding the effects of immersive VR on several learning outcomes. However, its effectiveness is not automatic and depends on the characteristics of the intervention and the research design. More specifically, the Cognitive Affective Model of Immersive Learning (CAMIL) provides a framework for explaining the mechanisms underlying learning in immersive VR (Makransky & Petersen, 2021). Makransky & Petersen (2021) proposed that immersive VR characteristics can influence presence and agency, which in turn relate to cognitive and affective processes during learning. Thus, immersion should not be regarded as a learning outcome, but as a condition that may facilitate cognitive and affective experiences (Cheng & Tsai, 2020; Gomez, 2020; Makransky & Petersen, 2021). Marine contexts provide a particularly relevant setting for these affordances because underwater environments, habitat structures, organism interactions, and ecosystem changes are not always directly observable by students (Kelly et al., 2022; Markowitz et al., 2018). Therefore, VR has potential as a marine learning environment; however, educators must translate that potential into practice through effective pedagogical design.

Pedagogical Integration: From VR Experience to Meaningful Learning

VR in education cannot be separated from instructional design, which guides students in interpreting and reflecting on their virtual experiences (Asikin et al., 2025; Han, 2020; Makransky & Petersen, 2021). Immersive experiences without clear learning objectives, investigative questions, analytical activities, or reflection may remain primarily visual experiences and fail to produce deep conceptual understanding (Liu et al., 2020; Moro et al., 2017; Yahaya, 2007). Therefore, VR should be positioned as part of a learning sequence that connects experience with cognitive processes, social interaction, and action (Adams et al., 2021; Armougum et al., 2019; Paulsen et al., 2024). In the SME–VR context, pedagogical integration can follow a sequence of problem orientation, VR exploration, investigation, analysis, discussion and reflection, decision-making, and sustainability-oriented action. During the exploration stage, students experience marine environments through VR; during the investigation stage, they identify relevant phenomena or problems; during the analysis stage, they connect their observations with Biology concepts; and during reflection and decision-making, they consider the ecological and social consequences of alternative actions. The final stage can connect virtual experiences with real-world activities such as environmental campaigns, waste management, mangrove conservation, or coastal ecosystem protection (Asikin et al., 2025; McKinley et al., 2023). Thus, the central principle of SME–VR is not simply to use VR to teach about the ocean, but to use VR as part of a learning experience designed to understand, reflect on, and respond to marine issues. This positioning frames VR as a pedagogical affordance that must be aligned with learning objectives. It explains why teachers' needs extend beyond a VR application itself to include instructional modules, investigative activities, discussion, reflection, and ocean-literacy assessment.

Sustainable Maritime Education as an Integrative Framework

Building on these theoretical foundations, this study positions Sustainable Maritime Education (SME) as an integrative educational framework that connects maritime contexts, learning experiences, immersive technology, ocean literacy, and sustainability-oriented learning. SME is not treated as a standalone theory but as a conceptual framework that integrates several complementary educational perspectives. Ocean literacy defines the competencies to be developed (Asikin et al., 2025); place-based environmental education determines the learning context (Almeida & Cutter-Mackenzie, 2011; Otto & Pensini, 2017); experiential learning explains the importance of experience as a source of knowledge construction (Kolb & Kolb, 2017; Roland, 2017); while immersive learning and CAMIL explain how VR can provide experiences that are difficult to obtain directly (Makransky & Petersen, 2021). These components then support the goals of environmental education:

developing learners' capacity to understand environmental issues, develop responsible attitudes, and take actions that support sustainability. This integrative framework matters because sustainability-oriented education requires more than transmitting environmental knowledge. It requires learning experiences that connect knowledge with context, experience, reflection, values, decision-making, and action. Within this framework, SME–VR integrates what students need to learn through ocean literacy, where learning takes place in local maritime contexts, learning experiences are constructed through experiential and immersive learning, and learning is directed toward sustainability-oriented action. Accordingly, SME–VR provides the conceptual basis for translating the needs-analysis findings into concrete learning-design requirements, including contextual authenticity, immersive experiential learning, pedagogical integration, ocean-literacy alignment, accessibility and feasibility, realistic curriculum-aligned content, and action-oriented sustainability.

METHODOLOGY

Research Design

This study used a convergent mixed methods design to investigate Biology teachers' needs, perceptions, current instructional practices, and contextual constraints related to integrating Virtual Reality (VR) into Sustainable Maritime Education (SME) to develop ocean literacy in coastal senior high schools. Quantitative and qualitative data were collected during the same needs-analysis phase from the same 26 participants using a single questionnaire. Closed-ended items provided quantitative data, while open-ended responses provided qualitative material. The strands were analysed separately, then integrated through a joint display. This design allowed the open-ended responses to contextualise and expand patterns in the closed-ended data; however, because both strands shared the same instrument and participants, they do not constitute independent sources of corroboration. The resulting integrated interpretations are therefore treated as context-specific meta-inferences rather than as independent validation of a design framework. This approach aligns with established mixed-methods principles, which call for explicit integration rather than presenting quantitative and qualitative findings as two unrelated strands (Fetters & Tajima, 2022; Han, 2020).

Research Context

The study was conducted in Tanjungpinang City, Riau Islands Province, Indonesia, a coastal and maritime region where marine and coastal environments are an important part of the local geographical and socio-environmental context. The study focused on secondary school Biology education because Biology curricula offer opportunities to address marine

ecosystems, biodiversity, environmental change, and human–environment interactions. The study treated the coastal setting as an educational context rather than only as a sampling location. The study examined how maritime contexts were incorporated into Biology learning and which technology-supported learning approaches could provide meaningful access to marine environments. The findings are therefore interpreted primarily within the participating Tanjungpinang context, while the resulting design requirements may provide propositions for examination in other coastal settings.

Participants and Sampling

The participants were 26 Biology teachers from nine secondary schools in Tanjungpinang City. The researchers purposively recruited participants because they had direct experience teaching Biology at the senior high school level and could provide informed perspectives on marine-related Biology content, instructional practices, technology use, and perceived student learning needs. The participant group included 25 female teachers (96.2%) and one male teacher (3.8%). Eighteen teachers (69.2%) had more than 10 years of teaching experience, six (23.1%) had 5–10 years, and two (7.7%) had less than five years. Participation was voluntary. Before completing the questionnaire, participants were informed about the study purpose, voluntary participation, intended data use, and confidentiality. We anonymised schools and teachers in reporting and identified qualitative quotations using participant codes R1–R26.

Data Sources and Instruments Development

We collected data using a structured needs-analysis questionnaire developed specifically for this study, which gathered both quantitative and qualitative evidence to inform the development of SME–VR. The questionnaire was developed from the research objectives, relevant literature on ocean literacy, contextual and experiential learning, immersive learning, and VR-supported science education, as well as the biology curriculum and the coastal educational context of Tanjungpinang. The instrument was organised into six domains: (1) existing Biology learning practices; (2) maritime contextualization; (3) marine learning needs and difficult-to-teach content; (4) technology and VR readiness; (5) priority content and learning requirements for VR; and (6) ocean literacy assessment practices. The questionnaire included categorical and multiple-response items, rating-scale items, and open-ended questions. Closed-ended items identified the distribution and priority of teachers' responses, while open-ended items sought contextual explanations of perceived learning difficulties, implementation constraints, expectations for VR-supported learning, and ocean literacy assessment needs.

Before administration, the research team discussed the questionnaire, and three experts with relevant expertise in Biology education, educational technology/VR-

supported learning, and marine or environmental education reviewed it. The experts reviewed the items' relevance and clarity, their alignment with the study objectives and intended domains, and their suitability for Biology teachers in the coastal educational context. We revised the instrument based on the expert review before administration. We did not conduct a separate pilot test with an independent sample. This limitation is acknowledged explicitly. We designed the questionnaire as a multidomain needs-analysis instrument rather than a unidimensional psychometric scale. Because its items represented heterogeneous categorical, multiple-response, rating-scale, and open-ended formats and were not intended to measure a single latent construct, the questionnaire did not have a single internal consistency coefficient, such as Cronbach's alpha. The three-expert review, therefore, served as evidence of content relevance and clarity rather than a substitute for psychometric reliability.

Data Collection Procedure

Data collection was conducted during the initial needs-analysis phase of the SME–VR research program. Participants completed the questionnaire individually and were encouraged to provide detailed responses to the open-ended questions. The same participant group contributed both quantitative and qualitative data, allowing direct integration between the two strands. Quantitative items identified the distribution and relative priority of teachers' responses, while open-ended items explained why they reported needs, challenges, or preferences. For example, the quantitative pattern of difficulty in teaching marine ecosystems was interpreted alongside qualitative explanations of limited access to underwater environments, constraints on field observation, and difficulty visualising complex ecological interactions. This structure enabled the qualitative data to provide contextual depth rather than merely supplementary quotations. This approach matters in mixed-methods research because integration should generate understanding beyond what either quantitative or qualitative analysis can provide independently (Boda & Brown, 2020; Fetters & Tajima, 2022; Han, 2020).

Quantitative Data Analysis

We analysed quantitative data using descriptive statistics. Frequencies (n) and percentages (%) were calculated for categorical and multiple-response items. The analysis focused on current instructional practices, maritime contextualisation, technology and VR readiness, priority marine content, and ocean literacy assessment practices and needs.

Because the sample was purposive, geographically restricted, and relatively small, the study did not use inferential tests to make population-level generalisations. We interpreted the quantitative results as context-specific evidence from the participating coastal schools.

Qualitative Data Analysis

We analysed the open-ended questionnaire responses using hybrid inductive-deductive thematic analysis. The deductive component drew on sensitising concepts from the theoretical framework, particularly contextual learning, experiential learning, pedagogical integration, technology readiness, ocean literacy, and sustainability-oriented learning. These concepts guided attention to theoretically relevant issues but were not treated as predetermined final themes. This hybrid approach is consistent with methodological work showing that theory-informed and data-driven coding can be combined within mixed-methods research (Fereday & Muir-Cochrane, 2006; Proudfoot, 2023). The inductive component allowed additional codes to emerge directly from teachers' responses. The analysis involved repeated familiarisation with the responses, identifying meaningful segments, generating initial codes, comparing and refining codes, grouping related codes into broader categories, developing and reviewing themes, and defining final themes. The initial coding framework included 16 codes covering issues such as limited authentic maritime experience, the need for realistic and immersive visualisation, contextual and active pedagogy, technology and infrastructure constraints, gaps in ocean literacy assessment, and sustainability-oriented action. The team then organised these codes into six broader themes.

To strengthen the research team's analytic credibility, the team reviewed the initial coding framework and thematic structure. The team discussed and resolved coding differences through consensus, and refined code definitions as needed. We maintained an audit trail through the codebook, respondent-level coding records, thematic structure, and joint display. We report no inter-coder reliability coefficient because the study did not use independent parallel coding to calculate one. Because the qualitative data came from open-ended questionnaire responses rather than individual interviews or focus groups, the qualitative strand was intended to provide contextual explanations of quantitative patterns rather than claim the depth associated with extended qualitative interviewing. Representative quotations were translated into English while preserving their intended meaning and were identified using anonymous participant codes R1–R26.

Mixed-Methods Integration & Development of Design Requirements

The quantitative and qualitative findings were integrated through a joint display. Joint displays can function as analytic tools for examining relationships between quantitative and qualitative evidence and for developing integrated interpretations (Haynes-Brown & Fetters, 2021; Reeping & Edwards, 2022). The joint display in this study contained four components: quantitative findings, qualitative explanations, integrated inferences, and design implications. Four criteria determined whether an integrated finding could be translated into a design requirement. First, the finding had to demonstrate clear empirical

relevance to teachers' reported needs, challenges, priorities, or instructional practices. Second, it had to be supported or meaningfully expanded by the qualitative evidence rather than relying on an isolated response. Third, it had to have a direct and operational implication for SME–VR design. Fourth, the implication had to be consistent with the educational purposes of Biology learning, ocean literacy, and sustainability-oriented maritime education. We treated convergence as confirmation when both strands supported the same interpretation. When qualitative evidence added context to a quantitative pattern, we treated the relationship as complementary or expansive. We examined potentially divergent evidence before formulating an integrated inference. This procedure moved beyond parallel reporting toward meta-inferences grounded in both strands. The final seven SME–VR design requirements were therefore not treated as predetermined outcomes. The team developed them iteratively by linking theoretical sensitising concepts, empirical findings, thematic interpretations, and integrated meta-inferences. The requirements are consequently interpreted as empirically informed design requirements for subsequent development and validation, not as validated intervention principles.

Trustworthiness and Quality Assurance

For the quantitative strand, the team checked data for completeness, response consistency, and coding accuracy before analysis. For the qualitative strand, the team reviewed themes against the original responses to ensure traceability between interpretations and participants' accounts. The research team reviewed the coding framework and thematic definitions and retained an audit trail through respondent-level coding, the codebook, thematic structure, and joint display. For mixed-methods integration, the quantitative and qualitative strands were first analysed separately, then integrated through a joint display. The integration explicitly considered convergence, complementarity, and potential divergence before formulating design implications. These procedures made the analytical pathway from raw responses to design requirements transparent.

Ethical Considerations

Participation in the study was voluntary. Before completing the questionnaire, participants were informed about the study's purpose and procedures, the voluntary nature of participation, the confidentiality of their responses, and the use of their data for research purposes. Formal ethics approval was not required for this study under the applicable institutional procedures because it involved a non-interventional educational needs analysis based on voluntary teacher participation and did not involve clinical procedures, interventions, or the collection of personally identifying or sensitive information. Informed consent was obtained from all participants before their participation. Participants could decline participation without consequence. No personally identifying information was

reported, and anonymous participant codes (R1–R26) were used for quotations. The study data were handled confidentially and used solely for research purposes.

RESULT AND DISCUSSIONS

Characteristics of the Participants

A total of 26 Biology teachers participated in the needs analysis. The participants represented nine secondary schools in Tanjungpinang City, Riau Islands Province, Indonesia. As presented in Table 1, Most participants were female (25, 96.2%), while one participant was male (3.8%). In terms of teaching experience, 18 teachers (69.2%) had more than 10 years, 6 (23.1%) had 5 to10 years, and 2 (7.7%) had less than 5 years. The sample was predominantly composed of experienced Biology teachers. Given the purposive sample and local setting, these characteristics should be considered when interpreting the findings.

Existing Biology Learning Practices and Maritime Contextualisation

The quantitative findings indicate that teachers had already adopted student-centred learning approaches. As shown in Table 2, Problem-Based Learning (PBL) was the most frequently reported model (17, 65.4%), followed by Project-Based Learning (PBL) and Discovery Learning (each 3, 11.5%). However, teachers had not yet consistently integrated maritime contexts into Biology instruction. Although 22 teachers (84.6%) reported teaching marine and coastal ecosystem content, only four teachers (15.4%) reported frequently integrating maritime contexts into their instruction. Most teachers (18, 69.2%) reported

Table 1
Participant Characteristics (N = 26)

Characteristic	Category	n	%
Gender	Female	25	96,2
	Male	1	3,8
Teaching experience	<5 years	2	7,7
	5–10 years	6	23,1
	>10 years	18	69,2
School	School 1	8	30,8
	School 2	5	19,2
	School 3	4	15,4
	School 4	3	11,5
	School 5	2	7,7
	School 6	1	3,8
	School 7	1	3,8
	School 8	1	3,8
	School 9	1	3,8

Table 2
Existing Biology Learning Practices and Maritime Contextualisation

Indicator	Category	n	%
Instructional model	Problem-Based Learning (PBL)	17	65.4
	Project-Based Learning (PBL)	3	11.5
	Discovery Learning	3	11.5
	Other approaches	3	11.5
Teaching marine/coastal ecosystem content	Yes	22	84.6
	No	4	15.4
Frequent integration of maritime context	Yes	4	15.4
	No/limited	22	84.6

integrating maritime contexts only occasionally, while four (15.4%) reported doing so rarely. The qualitative findings explain this pattern: teachers described difficulty connecting textbook-based materials with local marine environments and bringing authentic maritime experiences into the classroom. One participant stated, "It is difficult to bring authentic experiences into the classroom." (R2)

These findings distinguish between teaching marine content and systematically contextualising Biology learning within maritime environments. The quantitative pattern shows the extent of this gap, while the qualitative responses indicate that limited authentic access is one reason for it.

Priority Learning Content and Experiential Learning Needs

The findings indicate that marine ecosystem topics were among the biology topics considered relatively difficult to teach. As shown in Table 3, Teachers identified marine ecosystems as the most difficult Biology content to teach, reported by 18 teachers (69.2%), followed by marine biodiversity (15, 57.7%), marine food chains (7, 26.9%), and marine pollution (5, 19.2%). These responses were multiple-response items, so percentages do not sum to 100%. The open-ended responses provided contextual explanations for these difficulties. Teachers repeatedly referred to limited opportunities for direct observation, restricted access to marine environments, and difficulty visualising complex ecological processes. One teacher stated, "The main limitation is the difficulty of seeing the marine ecosystem directly" (R13). Participants repeatedly identified underwater exploration as difficult to conduct in real-world settings. Other challenging activities included observing interactions among marine organisms, identifying marine biodiversity, examining food webs, and monitoring environmental changes. These qualitative findings complement the quantitative pattern by indicating that difficulty is associated not only with conceptual complexity but also with limited opportunities for authentic observation and experiential engagement.

Table 3
Priority Learning Content Considered Difficult to Teach

Priority Learning Content Considered Difficult to Teach	n	%
Marine ecosystems	18	69.2
Marine biodiversity	15	57.7
Marine food chains	7	26.9
Marine pollution	5	19.2

Priority Content for VR Development

Teachers identified several marine topics as priorities for development into VR-based learning content. As presented in Table 4, seagrass was the most frequently selected topic, identified by 17 teachers (65.4%). Mangroves and marine biota were each selected by 16 teachers (61.5%), followed by coral reefs, selected by 15 teachers (57.7%). The findings indicate that teachers prioritised marine topics that are both ecologically important and relevant to the coastal environment surrounding students. Teachers also emphasised that VR content should be realistic, natural, locally relevant, and aligned with the biology curriculum.

Teachers specifically requested realistic visualisations rather than predominantly animated representations. One participant stated:

> The visual presented through the VR device should be real video footage of the actual condition being studied.
>
> (R16)

Another participant emphasised:

> The development should use real videos rather than animation, so students can actually see and experience the system being studied.
>
> (R19)

Teachers also indicated that VR should not be developed as a stand-alone virtual tour. Instead, the VR experience should be integrated into student worksheets, teaching modules, investigations, discussions, reflections, and assessments.

Table 4
Priority Marine Content for VR Development

Rank	Marine content	n	%
1	Seagrass	17	65,4
2	Mangrove	16	61,5
2	Marine biota	16	61,5
4	Coral reef	15	57,7
5	Marine pollution	13	50,0

Technology Readiness and Implementation Constraints

The quantitative findings revealed a discrepancy between teachers' general experience with educational technology and the availability of VR infrastructure in schools. As shown in Table 5, 22 teachers (84.6%) reported having previously used technology in their teaching. However, 18 teachers (69.2%) reported that VR devices were not available at their schools. This finding indicates that general digital experience does not automatically translate into institutional readiness for VR-based learning.

Teachers identified several constraints that could affect implementation, including device availability, cost, infrastructure, instructional time, and teacher readiness. The qualitative findings reinforced these concerns. Teachers emphasised that VR implementation should consider device availability and supporting infrastructure, affordability, teacher competence, and classroom time. One teacher identified "permission, time, cost, and safety" as constraints on marine field activities (R5). These findings suggest that SME–VR should be designed as an accessible, feasible learning solution rather than assuming schools have dedicated VR infrastructure.

Ocean Literacy Assessment Practices

Teachers' practices for assessing students' ocean literacy showed a substantial gap. Of the 26 participating teachers, 17 (65.4%) reported previously assessing ocean literacy without a structured instrument. Eight teachers (30.8%) had never assessed students' ocean literacy, whereas only one teacher (3.8%) reported using a structured instrument specifically designed for ocean literacy. Regarding integration into Biology assessment, 13 teachers (50.0%) reported fairly integrating ocean literacy, 10 teachers (38.5%) reported limited integration, and 3 teachers (11.5%) reported no integration. Table 6 presents the teachers' practices and needs related to ocean literacy assessment.

The need for a specific ocean literacy assessment instrument was particularly evident. Eight teachers (30.8%) considered such an instrument highly needed, while 14 (53.8%) considered it needed. Thus, 22 teachers (84.6%) expressed a need for a specific instrument

Table 5
Technology Readiness and VR Implementation

Indicator	Category	n	%
Previous use of educational technology	Yes	22	84.6
	No	4	15.4
Availability of VR devices	Not available	18	69.2
	Limited availability	5	19.2
	Available	2	7.7
	Highly available	1	3.8

Table 6
Ocean Literacy Assessment Practices and Needs

Indicator	Category	n	%
Previous ocean literacy assessment	Structured assessment	1	3.8
	Previously assessed, but unstructured	17	65.4
	Never assessed	8	30.8
Integration into Biology assessment	Fairly integrated	13	50.0
	Less integrated	10	38.5
	Not integrated	3	11.5
Need for a specific instrument	Highly needed	8	30.8
	Needed	14	53.8
	Less needed	3	11.5
	Not needed	1	3.8

to assess students' ocean literacy. The teachers' responses also indicate that ocean literacy should be assessed beyond factual knowledge. Knowledge of marine and coastal ecosystems was identified by 21 teachers (80.8%) as an important assessment component, followed by marine environmental behaviour (19 teachers, 73.1%), attitudes toward the marine environment (16 teachers, 61.5%), critical thinking about marine issues (16 teachers, 61.5%), and marine-related problem-solving ability (16 teachers, 61.5%). These findings indicate that teachers perceive ocean literacy as a multidimensional competence that extends beyond students' cognitive understanding of marine ecosystems. The qualitative responses further explain this assessment gap. One teacher stated, "Ocean literacy is not only about knowledge, but also attitudes, concern, and behaviour toward marine and coastal ecosystems. This makes it difficult to measure using written tests" (R2). Another teacher identified the absence of "standardised and structured instruments" as a major constraint (R7). These responses reinforce the quantitative findings that existing assessment practices remain predominantly unstructured and that teachers require an assessment instrument capable of capturing multiple dimensions of ocean literacy.

Qualitative Themes and Subthemes

The thematic analysis generated six major themes describing teachers' experiences, perceived challenges, and expectations regarding the development of SME–VR. The themes emerged from recurring patterns in the open-ended responses and were then linked to the quantitative findings. Table 7 presents the qualitative themes, subthemes, and representative evidence derived from the teachers' responses.

The qualitative themes demonstrate that teachers' needs were interconnected. Limited access to authentic marine environments created a need for realistic, immersive visualisation. However, teachers expected these experiences to be embedded in active,

Table 7
Qualitative Themes, Subthemes, and Representative Evidence

Theme	Key subthemes	Representative evidence
Limited authentic maritime experience	Difficulty bringing authentic marine experiences into classrooms; limited access to real marine environments	"It is difficult to bring authentic experiences into the classroom." (R2)
Need for realistic and immersive visualisation	Underwater exploration; realistic marine environments; visualisation of complex ecological processes	"The visual presented through the VR device should be real video footage of the actual condition being studied." (R16)
Need for contextual and active pedagogy	PBL/PjBL; inquiry; investigation; student worksheets; discussion and reflection	Teachers requested integrating VR with worksheets, modules, assessments, and investigative activities.
Technology and implementation constraints	Device availability; cost; infrastructure; time; teacher readiness	Teachers emphasised the availability of devices, cost, infrastructure, and teacher readiness as implementation considerations.
Ocean literacy assessment gap	Lack of specific instruments; difficulty assessing attitudes and behaviour; cognitive-dominant assessment	"It is difficult to measure [ocean literacy] using written tests." (R2)
Sustainability-oriented action	Beach clean-ups; mangrove planting; waste management; conservation campaigns	Teachers proposed beach clean-ups, mangrove planting, waste management, and environmental campaigns.

contextual learning activities. At the same time, technological constraints influenced implementation feasibility, while the assessment gap indicated the need for explicit alignment between SME–VR and multidimensional ocean literacy.

Integration of Quantitative and Qualitative Findings

The study integrated the quantitative and qualitative findings through a joint display. Quantitative results established the magnitude and priority of needs, whereas qualitative findings explained or expanded the contextual reasons underlying those patterns. The joint display served as an analytic step rather than only a presentation device. The integrated evidence showed convergence across the two strands for the main design issues. Qualitative evidence generally elaborated on the quantitative patterns by explaining why teachers experienced difficulties or prioritised certain areas. No major contradiction requires discarding a quantitative or qualitative interpretation. Table 8 presents a joint display that integrates the quantitative and qualitative findings and their implications for SME–VR design.

Table 8
Joint Display of Integrated Quantitative and Qualitative Findings

Integrated issue	Quantitative finding	Qualitative explanation	Integrated inference	Design implication
Maritime contextualization gap	84.6% teach marine/coastal ecosystem content, but only 15.4% frequently integrate maritime contexts	Teachers reported limited authentic examples and difficulty connecting textbook content with local marine environments	Marine content is present, but systematic maritime contextualization remains limited	Contextual maritime learning
Experiential learning constraint	69.2% identify marine ecosystems as difficult content	Underwater exploration, direct observation, complex interactions, and long-term changes are difficult to conduct	Learning difficulty is partly related to limited experiential access	Immersive experiential learning
Priority content	Seagrass 65.4%; mangrove/marine biota 61.5%; coral reef 57.7%	Teachers requested realistic, natural, local, and curriculum-aligned content	VR content should be selected according to contextual relevance and learning difficulty	Localised realistic VR content
Technology readiness gap	84.6% have used technology, but 69.2% report no VR availability	Cost, devices, infrastructure, time, and teacher readiness constrain implementation	Digital familiarity does not automatically imply VR readiness	Accessible and feasible VR design
Pedagogical integration	PBL is used by 65.4%	Teachers requested inquiry, projects, student worksheets, discussion, and reflection around VR	VR should function within a pedagogical sequence rather than as a stand-alone medium	Pedagogically integrated VR
Assessment gap	84.6% need a specific ocean literacy instrument	Teachers reported difficulty assessing attitudes, behaviour, and environmental concern	Ocean literacy assessment needs to become multidimensional and structured	Knowledge–attitude–behaviour assessment

SME–VR Design Requirements

The integrated findings were subsequently translated into seven design requirements for VR-supported Sustainable Maritime Education (SME-VR), as presented in Table 9.

Table 9
Design Requirements for VR-Based Sustainable Maritime Education

Requirement	Evidence from the findings	Proposed design specification
DR1. Contextual authenticity	Maritime content is taught, but has not been consistently contextualised	Use local coastal and marine environments and authentic maritime issues
DR2. Immersive experiential learning	Direct observation and underwater exploration are difficult	Provide immersive exploration and simulation of difficult-to-access environments
DR3. Pedagogical integration	Teachers support PBL, PjBL, inquiry, student worksheets, discussion, and reflection	Integrate VR into a structured learning sequence
DR4. Ocean literacy alignment	Knowledge, behaviour, attitudes, critical thinking, and problem-solving are prioritised	Explicitly align learning activities and assessment with ocean literacy dimensions
DR5. Accessibility and feasibility	VR availability, cost, infrastructure, time, and readiness are constraints	Develop a practical, accessible, and teacher-friendly implementation model
DR6. Realistic and curriculum-aligned content	Teachers request realistic, natural, and curriculum-relevant visualisations	Use authentic visual content aligned with Biology learning objectives
DR7. Action-oriented sustainability	Teachers emphasise conservation and environmental action	Connect VR experiences with reflection, problem-solving, and real-world conservation actions

The seven propositions translate the reported needs and constraints into possible specifications for subsequent development. DR1 addresses the gap in systematic maritime contextualization; DR2 responds to limitations in students' access to direct marine experiences; DR3 addresses teachers' expectations for pedagogical integration; DR4 responds to the need for multidimensional ocean literacy assessment; DR5 addresses technological and institutional constraints; DR6 addresses teachers' demand for realistic and curriculum-aligned content; and DR7 connects learning experiences with sustainability-oriented action. Overall, the findings indicate that teachers' needs extend beyond providing VR technology itself. These links are design interpretations informed by both theory and local evidence, not proof that the proposed specifications are effective or feasible. The study did not test an SME–VR intervention or compare VR with alternative approaches.

DISCUSSION

From Teaching Marine Content to Contextualised Maritime Learning

The findings distinguish between teaching marine-related content and implementing contextualised maritime learning. Although 84.6% of participating teachers reported teaching marine and coastal ecosystems, only 15.4% reported frequently integrating

maritime contexts. Because the participants were 26 teachers from nine secondary schools in Tanjungpinang, this result should be interpreted as a local instructional pattern rather than a representation of all coastal schools in Indonesia. The open-ended responses provide contextual explanations for this pattern, but their depth is limited compared with interviews or focus groups. The finding supports the need to examine contextualised maritime learning in this setting; it does not, on its own, establish which technology would best address that need. Nevertheless, this finding aligns with research indicating that ocean literacy education requires stronger alignment among curriculum, pedagogy, technology, and assessment (Asikin et al., 2026; Bastos et al., 2026). The qualitative evidence helps explain this contextualization gap. Teachers described difficulty bringing authentic marine experiences into classrooms and connecting textbook materials with local marine environments. In practical design terms, teachers can address contextual authenticity by using locally relevant marine settings and issues, such as seagrass beds, mangrove areas, coral reefs, marine biota, and coastal pollution, and by connecting these settings to Biology learning objectives. This interpretation aligns with place-based approaches to marine education, which emphasise relationships among learners, local environments, and environmental issues (Asikin et al., 2025).

VR Addresses the Experiential Access Gap, but Its Educational Value Depends on Pedagogical Design

Teachers' reports that marine ecosystems and biodiversity are difficult to teach align with the need for better access to observation and visualisation of underwater environments, organism interactions, and ecological processes. VR is one possible way to provide mediated access to environments that may be difficult to observe directly. However, this needs analysis did not compare VR with 360-degree media, simulations, multimedia, virtual field trips, or direct field experiences. It therefore cannot establish VR as the most appropriate or effective response. VR is discussed here as the proposed technological direction of the broader SME research programme; its feasibility, usability, and educational value in participating school contexts remain to be tested. Any future implementation should complement, rather than automatically replace, direct experiences where these are practical and safe. Immersive VR is relevant to this challenge because it can provide access to environments that are difficult to experience directly and allow students to explore complex phenomena from perspectives unavailable through conventional media (Hamilton et al., 2021; Petersen et al., 2020; Radianti et al., 2020). Systematic evidence indicates that immersive VR can positively affect learning outcomes, although these effects are not uniform and depend substantially on intervention characteristics and assessment design (Adams et al., 2021; Hamilton et al., 2021; Paulsen et al., 2024). Recent marine education research has also demonstrated the potential of underwater VR to reduce psychological distance from marine environments and evoke affective responses such as awe and empathy

(Fauville et al., 2021, 2026). Therefore, VR's contribution to SME should not be understood merely as providing attractive visualisation. VR needs to function as an experiential learning environment that enables observation, exploration, inquiry, and reflection on marine phenomena that are difficult for students to access within their physical environments.

SME–VR Requires Pedagogical Integration Rather Than Technology Substitution

The findings indicate that teachers did not view VR as an adequate technology when used independently; instead, they saw it as part of an overall learning design. Teachers expected VR experiences to be followed and reinforced through student worksheets, instructional modules, investigation activities, discussion, reflection, and assessment. This indicates that VR's pedagogical value depends on how immersive experiences connect to learning objectives and students' cognitive activities (Han, 2020; Makransky & Petersen, 2021; Petersen et al., 2020). This finding aligns with research showing that the effectiveness of VR-based learning depends not only on immersion but also on learning structure, task characteristics, learner interaction, and assessment strategies (Hamilton et al., 2021; Makransky & Petersen, 2021; Radianti et al., 2020). Therefore, immersive experiences need to be positioned within learning stages that allow students to observe phenomena, identify problems, interpret information, and construct understanding based on their experiences (Fauville et al., 2026; Lamb et al., 2019; Sunardi et al., 2022). In the context of SMEs, this pedagogical integration becomes increasingly important because learning objectives extend beyond understanding marine concepts to developing ocean literacy, encompassing knowledge, attitudes, and behaviour. VR experiences involving marine ecosystems should therefore be followed by activities that encourage students to connect virtual phenomena with the conditions of their surrounding coastal environments, analyse maritime problems, discuss alternative solutions, and reflect on their implications for marine environmental sustainability (Asikin et al., 2025; Warahmah et al., 2022). Research in marine education has also shown that VR visualisation and perspective-taking can help students understand complex marine phenomena that are difficult to observe directly (Fauville et al., 2021, 2026; Hetherington et al., 2026; Petersen et al., 2020).

Local Authenticity and Accessibility as Key Design Conditions

Teachers' prioritisation of seagrass, mangroves, marine biota, coral reefs, and marine pollution indicates that VR content needs to be locally meaningful while remaining relevant to the curriculum. This requirement aligns with developments in ocean-XR research showing that immersive technologies can support marine education through presence, interactivity, embodiment, and the representation of ocean literacy principles (Fauville et al., 2026; Hetherington et al., 2026; Mothershed & Stilwell, 2025; Petersen et al., 2020). However, contextual authenticity must align with implementation feasibility. The findings reveal a substantial gap between general digital experience and institutional

readiness for VR. Most teachers had experience using educational technologies, whereas most schools lacked dedicated VR devices. This suggests that general digital readiness does not automatically translate into readiness to implement VR. Systematic reviews likewise emphasise that immersive VR research needs to consider intervention characteristics, technological conditions, usability, and appropriate assessment, rather than if immersion alone guarantees improved learning outcomes (Hamilton et al., 2021; Luo, 2024; Matovu et al., 2022; Suh & Prophet, 2018). Therefore, SME–VR design needs to consider local authenticity alongside accessibility, device availability, cost, infrastructure, instructional time, and teacher readiness.

Ocean Literacy Assessment Needs to Move from Knowledge toward Multidimensional Competence

One of the most important findings concerns the limited use of structured ocean literacy assessment. Most teachers who reported assessing ocean literacy did so without a specific instrument, while only a small proportion used a structured assessment. This finding is consistent with the literature, indicating that ocean literacy education requires stronger alignment among learning objectives, instructional strategies, and assessment approaches (Asikin et al., 2026; McPherson et al., 2018). Teachers in this study prioritised dimensions beyond knowledge of marine ecosystems, including attitudes, environmental behaviour, critical thinking, and problem-solving. This multidimensional understanding aligns with contemporary conceptualisations of ocean literacy, which encompass knowledge, attitudes, awareness, behaviour, activism, emotional connection, and experience (Fielding et al., 2019; Hetherington et al., 2026; Kelly et al., 2022; Lin et al., 2020). Furthermore, knowledge acquisition should not automatically lead to sustainable behaviour. Stoll-Kleemann (2019) demonstrated that the relationship between environmental knowledge and behavioural change is relatively weak, indicating that ocean literacy education requires approaches that support behavioural transformation. Therefore, SME–VR needs to integrate assessment from the early stages of the design process, particularly by measuring knowledge, attitudes, and behaviour, rather than treating assessment as an additional activity implemented after the VR experience.

Toward an Empirically Grounded SME–VR Design Framework

Taken together, the findings indicate that the central design challenge is not simply the absence of marine content or educational technology. It aligns marine learning objectives, authentic learning experiences, technological feasibility, pedagogical structure, and ocean literacy assessment. The seven design requirements provide an empirical design framework for the next stage of SME–VR development: contextual authenticity; immersive experiential learning; pedagogical integration; ocean literacy alignment; accessibility and feasibility;

realistic curriculum-aligned content; and action-oriented sustainability. This interpretation extends previous research on ocean literacy education, emphasising the need to integrate curriculum, innovative pedagogy, technology, and assessment (Asikin et al., 2026) while responding to the VR literature demonstrating that immersion alone is insufficient without appropriate instructional design (Hamilton et al., 2021; Radianti et al., 2020; Stoll-Kleemann, 2019). Importantly, this study does not claim that VR has already improved students' ocean literacy because the research remains at the needs-analysis stage. Instead, the study identifies empirically derived design requirements that provide a foundation for subsequent development and effectiveness testing. The seven resulting requirements, contextual authenticity, immersive experiential learning, pedagogical integration, ocean literacy alignment, accessibility and feasibility, realistic curriculum-aligned content, and action-oriented sustainability, constitute this needs-analysis study's principal design contribution. The framework positions VR not as the goal of innovation but as a supporting technology that enables students to progress from immersive experience to understanding, reflection, decision-making, and sustainable action.

LIMITATIONS

Several limitations should be considered when interpreting the findings. First, the sample comprised 26 purposively selected Biology teachers from nine secondary schools in Tanjungpinang City, so the findings are context-specific and should not be generalised to all coastal schools. The participant group was predominantly female and experienced, which may shape reported needs. Second, the study relied on teacher self-report and did not collect data directly from students. Third, both quantitative and qualitative strands came from the same questionnaire and participants; open-ended responses offered contextual explanations but lacked the depth of interviews or focus groups. Fourth, three experts reviewed the questionnaire, but the authors did not pilot it with an independent sample before administration. Because it was designed as a heterogeneous needs-analysis instrument rather than a unidimensional scale, the authors did not estimate overall internal-consistency reliability. Fifth, the study did not compare VR with alternative technologies or direct field experiences, nor did it test implementation feasibility. Finally, the authors have not yet validated the seven design requirements through implementation. Subsequent development, expert validation, pilot implementation, and effectiveness research are needed to test their practical feasibility, usability, learning effects, and potential contribution to students' ocean literacy.

CONCLUSION

This study identified a gap between teaching marine-related Biology content and the systematic use of contextualised maritime learning in the participating coastal schools

in Tanjungpinang. Most teachers reported teaching marine and coastal ecosystems and using educational technology, but frequent maritime contextualization, institutional VR readiness, and structured ocean literacy assessment remained limited. Teachers' responses also indicated that teaching marine ecosystems and biodiversity was difficult, partly because students had limited access to direct observation of underwater environments and complex ecological processes. Integrating closed-ended and open-ended responses informed seven provisional design propositions for SME–VR: (1) contextual authenticity, (2) immersive experiential learning, (3) pedagogical integration, (4) ocean literacy alignment, (5) accessibility and feasibility, (6) realistic and curriculum-aligned content, and (7) action-oriented sustainability. These requirements were derived from the participating teachers' reported needs and explanations and should be interpreted as design propositions for subsequent development and validation. The study does not provide evidence that VR has improved students' ocean literacy because students did not participate, and no intervention was implemented. Its contribution is to provide a context-specific empirical foundation for the development and testing of SME–VR in coastal secondary education. Future research should validate the design with experts and teachers, pilot its usability and feasibility, and then examine its effects on students' ocean literacy using multidimensional measures of knowledge, attitudes, and behaviour.

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