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Developing and Pilot-Testing an Evidence-Based Ocean Literacy Toolkit for Early Childhood Education

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Abstract

Despite the critical importance of ocean literacy for addressing environmental challenges, marine topics remain underrepresented in early childhood education due to curriculum constraints and teacher preparation gaps. This paper presents a two-phase sequential mixed-methods research study designed to document young children's ocean literacy and evaluate an evidence-based professional development framework. Building on prior desk research that mapped existing curricular gaps, empirical field research with 109 children (ages 4–8) across Greece, Cyprus, Poland, and Portugal documented baseline ocean knowledge and robust alternative conceptions. These findings directly informed the creation of the multi-component TeachBlue toolkit (handbook, activities guide, board game, and 360° videos). The toolkit's pedagogical effectiveness and teachers' implementation readiness were evaluated through a five-day intensive workshop with 25 educators. Mixed-methods evaluation, combining descriptive statistical quantification and inductive thematic analysis, revealed significant gains in teachers' pedagogical content knowledge, confidence, and digital skills. Participants highly valued the experiential, collaborative learning approach and the toolkit's immediate classroom applicability. By systematically linking empirical child assessment with teacher professional development, this study addresses a critical gap in early marine education while providing a rigorous, replicable framework for evidence-based curriculum design.

Keywords: ocean literacy, kindergarten, primary school, alternative conceptions, teacher professional development, mixed-methods research.

Introduction

The ocean plays an essential role in sustaining life on Earth, providing economic, social, and environmental benefits essential to human prosperity and wellbeing (Molony *et al.*, 2022; IOC-UNESCO, 2024). Understanding the ocean is essential to understanding and, thereby, protecting the planet on which we live (Cava *et al.*, 2005). Ocean literacy (OL) is defined as "an understanding of the ocean's influence on you and your influence on the ocean," encompassing the knowledge, skills, and attitudes necessary for making informed and responsible decisions regarding ocean resources and conservation (National Oceanic and Atmospheric Administration, 2024). Addressing global challenges such as climate change and biodiversity loss is inseparable from understanding the ocean, as these issues are inherently connected to marine systems, making OL a crucial component of contemporary science education (World Ocean Initiative, 2024).

Early childhood represents a critical developmental period when children are most receptive to absorbing and learning new concepts (Lind, 1999). During this stage, children also form robust informal theories and alternative conceptions about natural phenomena based on their everyday experiences, which can conflict with scientific facts (Driver *et al.*, 1994). Research by Ardoin & Bowers (2020), which reviewed 66 empirical studies on environmental education programs, indicates that

early childhood (ages 0-8) represents a critical period for developing environmental literacy, cognitive skills, and socio-emotional growth. Their findings emphasize that experiences in nature during this stage are strongly linked to the formation of lasting environmental concern and participation in pro-environmental behaviors later in life. During these formative years, schools provide an opportune setting where future active citizens can be exposed to the knowledge and skills necessary to actively participate in decision-making regarding the ocean and its resources (Boaventura *et al.*, 2021; Boubonari *et al.*, 2024). Furthermore, educational interventions tend to be most effective when they emphasize locally relevant, concrete, and actionable dimensions of sustainable development and environmental education (Kevrekidis *et al.*, 2024). Children who better understand the ocean's importance to humankind will probably influence their peers and families, and as adults, are more likely to make informed and responsible decisions regarding the ocean's role in regulating the planet's climate and the sustainable use of its resources.

In this context, school education remains a pivotal focus for promoting OL, raising awareness, and achieving global commitment to the sustainable development of marine environments (Freitas *et al.*, 2022). This is particularly relevant for coastal regions, where populations depend heavily on marine ecosystem services. For instance, approximately 67% of Australia's population lives within 50 km of the southern coastline and depends on the ecological services provided by the Great Southern Reef (Freitas *et al.*, 2022). Similarly, integrating OL into school curricula is vital for regions such as those around the Mediterranean Sea, which hosts between 4% and 19% of global marine biodiversity (United Nations Environment Programme, 2019) and supports a major share of global tourism, welcoming nearly 360 million visitors annually (IUCN, IATUR, IDDRI & eco-union, 2025). The Mediterranean is also a climate change hotspot, experiencing accelerated warming, sea-level rise, and increasing frequency of marine heatwaves, which intensify biodiversity loss and ecosystem degradation (Sarkar *et al.*, 2022). Moreover, it is one of the most polluted seas globally, particularly affected by plastic pollution, overfishing, coastal urbanization, and intense maritime traffic (United Nations Environment Programme/Mediterranean Action Plan and Plan Bleu, 2020). Given the close interconnection between marine ecosystems, local economies, cultural heritage, and human well-being in Mediterranean societies, fostering OL from an early age is essential to promote informed decision-making, sustainable behaviors, and active citizenship capable of addressing region-specific environmental challenges. These examples underscore the economic, ecological, and social imperative for developing ocean-literate populations from the earliest years of education.

Despite the recognized importance and opportunity to integrate OL in schools, limited global evidence spanning the last 20 years indicates that OL has rarely been prioritized in formal educational curricula (e.g., Freitas *et al.*, 2022; Mogias *et al.*, 2021), and while science curricula offer opportunities for ocean education, these opportunities are frequently underutilized, with examples focusing instead on the terrestrial environment (Strang *et al.*, 2007). An overloaded curriculum, teachers' lack of ocean knowledge (e.g., Mogias *et al.*, 2015), and the limited availability of educational resources represent the main barriers for the inclusion of ocean topics in schools (e.g., Asikin *et al.*, 2025; Freitas *et al.*, 2022). The overcrowded curriculum has been noted as the most common obstacle by marine educators, as teachers struggle to include new topics such as OL by sacrificing other content (Pazoto *et al.*, 2024; Freitas *et al.*, 2025).

Additionally, teachers often lack confidence in their own ocean science knowledge and in delivering ocean-related content, often due to the absence of explicit curriculum requirements and targeted training (e.g., Ardoin & Bowers, 2020; Freitas *et al.*, 2022; Bastos *et al.*, 2025; Freitas *et al.*, 2025). Pre-service and in-service teachers are typically not trained in OL during their education careers, creating a significant gap in their preparedness to teach marine science concepts effectively (e.g., Boubonari *et al.*, 2013; Mogias *et al.*, 2015). Furthermore, when marine science is addressed in curricula, there is often insufficient availability of high-quality, curriculum-aligned educational resources that teachers can readily implement in their classrooms. This need is particularly acute in early childhood education, where national and local educational standards often place limited emphasis on OL, resulting in young children having minimal exposure to foundational concepts of ocean ecology, conservation, and sustainability (Freitas *et al.*, 2025). Persistent barriers include generally low levels of OL among educators, inadequate policies and strategies for embedding ocean content within education systems, and the lack of suitable teaching resources to support classroom implementation (Bastos *et al.*, 2025).

In response to these challenges, the Erasmus+ TeachBlue project was developed with the overarching aim of bridging the gap between the recognized importance of OL and its limited presence in formal early childhood education systems. The project addressed three interrelated research questions:

As part of the broader TeachBlue project, a systematic desk research review across the four partner countries mapped existing curricular gaps and available resources for OL education (Król *et al.*, unpublished data); this review established the theoretical and contextual foundation for the empirical work reported in the present paper.

What is the current state of young children's (aged 4-8) OL knowledge across diverse European educational contexts?

What evidence-based, multi-component educational resources can effectively support the integration of OL into early childhood classrooms?

How effective is a structured professional development program in building teachers' OL knowledge, pedagogical confidence, and readiness to implement educational resources concerning OL?

These questions correspond to the different phases of the study: field research with children, toolkit develop-

ment, and teacher training evaluation.

This paper presents the comprehensive research process undertaken to address these questions: it describes the field research with 109 children across four European countries that documented current OL knowledge and misconceptions, presents the resulting multi-component educational toolkit and its pedagogical foundations, and examines the professional development program implemented to empower teachers with the knowledge, confidence, and practical tools necessary to effectively integrate OL into their classrooms. Beyond addressing a critical gap in early childhood OL education, the study demonstrates a replicable methodological framework, combining systematic literature review, empirical field research with children, multi-modal resource development, and iterative pilot testing, that could inform evidence-based curriculum development across diverse educational domains where age-appropriate materials are lacking.

Materials and Methods

Building on the prior desk research summarized in Król *et al.* (unpublished data), this study employed a two-phase sequential mixed-methods research design to develop and evaluate the TeachBlue OL toolkit for early childhood education (aged 4-8). In the first phase, empirical field research with young children across four countries (Greece, Cyprus, Poland, and Portugal) documented current OL knowledge and misconceptions, directly informing toolkit content. In the second phase, the resulting toolkit was pilot-tested through a professional development workshop with teachers, whose evaluations were assessed quantitatively and qualitatively.

Field Research

Participants and Setting

Field research was carried out with 109 young children in total, aged 4 to 8 years (kindergarten through second grade) in the four partner countries between October and December 2024. This age group aligns with the first age group of the OL Scope and Sequence (National Marine Educators Association, 2010). Participant distribution was as follows: Greece (n = 40), Poland (n = 44), Portugal (n = 13), and Cyprus (n = 12). The sample comprised single-grade classroom groups in each participating school, representing one to two classes per country. Both age groups (kindergarten and Grades 1–2) were represented in the sample from each participating country. Schools in Greece, Cyprus, and Portugal were located in coastal areas, while those in Poland were inland. Prior to data collection, formal institutional approval was secured from the respective school administrations, and active written informed consent was obtained from the children's parents or legal guardians, ensuring anonymity, voluntary participation, and compliance with ethical standards for research involving minors. The research was conducted in classroom environments to ensure authenticity and comfort for the children, creating a familiar setting conducive to natural interaction and honest expression of their ideas and perceptions (Flewitt, 2005). Data collection took place during a three-hour session in each classroom, allowing sufficient time for engagement, discussion, and the expression of children's ideas. To ensure the activity was both engaging and informative, two facilitators were involved in each session: the children's regular classroom teacher, who possessed professional pedagogical expertise, and an academic researcher from the project team. The first facilitator (the classroom teacher) interacted directly with the children, encouraging them to explore materials and share their observations and thoughts. The second facilitator (the academic researcher) documented the children's responses in real-time, ensuring that all insights, observations, and verbal expressions were captured accurately for subsequent analysis.

Research Design and Approach

The field research employed creative, child-centered methods to gather qualitative data through interactive, multisensory, and playful activities that maximized young learners' engagement and participation (Sun *et al.*, 2023). A pirate-themed activity introduced OL concepts through play-based learning, which harnesses children's natural curiosity, experimentation, problem-solving, and sustained engagement (Zosh *et al.*, 2022) (Fig. 1). Integrating storytelling with guided play promotes children's agency in science learning by positioning them as protagonists in their investigations (Cremin *et al.*, 2016). A pirate character, represented by a puppet or costumed teacher, led the activity, using a treasure chest to spark curiosity and motivation. Inside, children explored educational materials including: a globe and world map for basic geography and marine environments; photographs depicting marine life and oceanic features; tactile items such as sand and seashells that provided sensory interaction, making the learning experience more immersive and memorable (Fig. 2).

The framework was structured around the seven fundamental principles of OL (National Oceanic and Atmospheric Administration, 2024) and the OL Scope and Sequence for grades K-2 (National Marine Educators Association, 2010), with questions and activities systematically adapted to early childhood cognitive and linguistic capabilities. To optimize classroom implementation and maintain the focus of young learners, the seven principles were clustered into five main thematic blocks within the interview protocol. Specifically, concepts from Principle 4 were integrated into items evaluating global ocean coverage and the severe consequences of ocean degradation, while Principle 7 was embedded directly within the items investigating human dependency on marine ecosystem services. A unified protocol standardized questions and



Fig. 1: The pirate-themed activity for the field research. Photo credit: DUTH, TeachBlue project.



Fig. 2: Introducing the material to the children. Photo credit: (A–C) DUTH; (D–F) Stando LTD, TeachBlue project.

tactile materials across all partner countries, enabling systematic data collection while maintaining flexibility for culturally and linguistically appropriate implementation in each national context (see Supplementary File 1).

Data Collection Methods

The field research integrated multiple qualitative data collection methods to capture the breadth and depth of children's OL (Sun *et al.*, 2023):

Visual Stimuli and Discussion: Children were shown photographs depicting ocean scenes, as well as objects or environmental issues, to spark discussions and elicit their perceptions and prior knowledge.

Storytelling and Narrative Elicitation: Storytelling prompts were used to encourage children to narrate their understanding of marine images and concepts, allowing them to express their ideas in a natural, developmentally appropriate format.

Semi-structured Interviews: Following the photographic and storytelling activities, semi-structured in-

terviews were conducted using the children's outputs as conversation starters. Open-ended questions encouraged children to share their thoughts on ocean environments, deepening the understanding of their perceptions, knowledge gaps, and misconceptions.

Drawing Activities: Children were asked to visually represent their understanding through drawings (e.g., depicting the ocean floor, marine organisms), providing non-verbal data that complemented their verbal responses and offered additional insights into their mental models of marine environments.

Hands-on Exploration: Real materials such as sand of varying grain sizes, pebbles, and seashells were presented to children to facilitate tactile learning and concrete understanding of coastal and marine concepts.

Data Recording and Analysis

For each principle-based activity, facilitators followed a systematic protocol: questions were first posed without hints or visual aids to capture children's spontaneous knowledge, responses were documented verbatim, children were invited to create drawings representing their ideas, and finally, photographic materials were introduced to assess recognition and extend discussion.

Data were collected at the individual child level. Each child's verbal responses were recorded separately by the second facilitator, and each child produced their own drawing independently. This individual-level data collection enabled analysis of both cross-country patterns and age-related developmental differences within the sample.

All verbal responses, drawings, and observational notes were collected and organized by country, age group, and OL principle. The analysis of the collected data involved multiple complementary approaches to ensure a comprehensive understanding of children's OL.

To ensure analytical consistency, a structured coding framework was developed prior to analysis based on the seven OL principles and their associated fundamental concepts (National Oceanic and Atmospheric Administration, 2024; National Marine Educators Association, 2010). Two researchers per country translated children's verbal responses into English and independently coded approximately 20% of the verbal responses and drawings from each country; discrepancies were resolved through discussion until full consensus was reached (Hill *et al.*, 1997), following which the remaining data were coded by one researcher per country. Regular cross-country meetings were held to monitor and maintain consistency in the application of the coding framework across all four national datasets. Not all questions in the field research protocol are reported in Table 1; given the volume of data collected, the analysis focuses on the key indicator question(s) per principle that could be most consistently coded and compared across countries and age groups.

Analysis of Verbal Responses: Children's verbal responses were transcribed and analyzed thematically (Braun & Clarke, 2006) to identify common knowledge patterns, misconceptions, gaps in understanding, and areas of particular interest or confusion among early childhood learners across the four partner countries. Responses were first coded deductively according to the seven OL principles, and then inductively to capture emergent themes not anticipated by the framework (Fereday & Muir-Cochrane, 2006). The frequency of specific knowledge categories and misconceptions was documented to allow cross-country and cross-age-group comparisons.

Analysis of Children's Drawings: The methodology for analyzing children's drawings involved several key steps aimed at understanding their perceptions, knowledge, and concerns related to ocean environments. First, a systematic content analysis of the drawings was conducted (Barraza, 1999), focusing on the elements included in the images. Particular attention was given to identifying patterns, such as the types of marine animals depicted, objects associated with water pollution, ships, people, coastal features, and other marine-related elements. The analysis documented which elements were predominant and which appeared to be absent, providing insights into the children's awareness, priorities, and focus areas (Cherney *et al.*, 2006). Frequencies of each element category were tallied per country and age group to enable comparison.

In addition to content analysis, the drawings were interpreted to uncover potential symbolism behind the elements chosen by the children (Malchiodi, 1998). For instance, the inclusion of diverse marine species could indicate an awareness of biodiversity, while depictions of factories or litter in the water might reflect concerns about pollution (Barraza, 1999; Alerby, 2000). The presence or absence of human figures, the use of color, and the spatial organization of elements were also examined for their symbolic significance (Kress & Van Leeuwen, 2021). This interpretive analysis helped to contextualize the visual elements and connect them to broader themes in OL.

Where possible, follow-up discussions with the children were conducted to deepen the understanding of their drawings. Short interviews were used to ask why they chose specific elements, what they considered most important in their pictures, and their overall thoughts about the sea and the ocean. These conversations provided valuable qualitative data, offering a more nuanced understanding of the children's ideas, priorities, emotional connections to marine environments, and underlying misconceptions that might not have been apparent from the drawings alone.

Toolkit Development

The educational toolkit was developed iteratively following the completion of the desk and field research phases, ensuring that all materials directly responded to documented needs and knowledge gaps. The development process comprised three stages: (1) evidence synthesis, in which the key findings from both the prior desk research (Król *et al.*, unpublished data) and the field research were consolidated into a set of design principles and content

Table 1. Summary of key field research findings by Ocean Literacy principle, country, and age group. Percentages represent the proportion of children providing the indicated response. 'Kindergarten' includes children aged 4-5; 'Grades 1-2' includes children aged 6-8.

Ocean Literacy Principle / Finding	Greece (n=40)		Cyprus (n=12)		Poland (n=44)		Portugal (n=13)	
	Kinder- garten (n=8)	Grades 1-2 (n=32)	Kinder- garten (n=3)	Grades 1-2 (n=9)	Kinder- garten (n=18)	Grades 1-2 (n=26)	Kinder- garten (n=8)	Grades 1-2 (n=5)
P1: Earth Has One Big Ocean with Many Features								
Familiar with term 'ocean'	100%	100%	100%	100%	100%	100%	100%	100%
Named a specific ocean	0%	6%	0%	0%	0%	85%	50%	0%
Correctly attributed waves to wind	75%	55%	67%	78%	56%	96%	80%	80%
Seabed drawn / described as flat	100%	100%	100%	100%	100%	100%	100%	100%
P2: The Ocean Shapes the Features of Earth (Erosion & Sand Formation)								
Sea causes coastal erosion	38%	28%	0%	0%	81%	65%	25%	20%
Understood sand formation through erosion	25%	28%	0%	0%	50%	58%	13%	20%
P3: The Ocean Influences Weather and Climate (Water Cycle)								
Rain comes from clouds	25%	22%	33%	0%	67%	73%	50%	60%
Described evaporation / full water cycle	13%	33%	0%	0%	56%	65%	13%	40%
Rainwater returns to sea / natural sources	25%	33%	33%	22%	72%	73%	38%	72%
P4 & P5: The Ocean Supports Biodiversity								
Named iconic marine animals (fish, shark, turtle, dolphin…)	100%	100%	100%	100%	100%	100%	100%	100%
Mentioned marine plants spontaneously	63%	0%	0%	0%	6%	100%	13%	40%
Mentioned plankton spontaneously	0%	0%	0%	17%	0%	0%	0%	0%
P6 & P7: Human-Ocean Connections and Conservation								
Ocean essential for life	63%	100%	100%	100%	100%	100%	100%	100%
Recognised pollution as a threat	0%	67%	0%	44%	78%	85%	38%	78%
Predicted serious consequences if we no longer have the ocean	100%	100%	100%	100%	78%	100%	88%	80%
Proposed protective actions	0%	56%	33%	44%	33%	58%	50%	60%

priorities; (2) material creation, in which the four toolkit components (Teacher's Handbook, Educational Activities Guide, Board Game, and 360° Underwater Videos) were drafted by project partners with relevant expertise; and (3) cross-partner review, in which all materials were reviewed by the full project team for scientific accuracy, developmental appropriateness, and cross-cultural applicability before finalization.

Three key design principles guided development, each derived directly from the research findings: (a) the need for age-appropriate, experiential learning materials connecting abstract ocean concepts to children's lived experiences; (b) the importance of building on children's existing curiosity and emotional connection to the ocean while systematically addressing documented misconceptions; and (c) the necessity of supporting teachers with ready-to-use, curriculum-aligned resources that compensate for limited marine science training. All four toolkit components are freely available in four languages (English, Greek, Polish, and Portuguese) at the project website (https://teachblue.eu/results/).

Teacher Training and Evaluation

Training Program Structure

Recognizing that educational materials alone are insufficient to ensure effective integration of OL into classroom practice, the Erasmus+ TeachBlue project implemented a comprehensive professional development program designed to build teachers' content knowledge, pedagogical skills, and implementation confidence. The program followed a cascading model whereby trained educators would become ambassadors of OL in their respective countries and educational contexts (Kennedy, 2014; El-Hamamsy *et al.*, 2024).

A five-day intensive training workshop was conducted in Cyprus, bringing together 25 participants from the four partner countries: Portugal (8 participants), Cyprus (7), Poland (5), and Greece (5). The participant group comprised 20 primary school teachers and 5 early childhood education and care (ECEC) educators, representing diverse levels of teaching experience. Notably, 10 participants had 0-10 years of teaching experience, 2 had 11-20 years, and 13 had over 20 years, providing a valuable mix of early-career and veteran educators whose perspectives enriched the training experience and subsequent feedback.

The workshop was structured to balance theoretical understanding with practical application, incorporating multiple pedagogical approaches to model best practices in OL education. This structural combination mirrors key design principles identified in the professional development literature as essential for achieving meaningful gains in teacher confidence and competence within new subject areas (Garet *et al.*, 2001; Desimone, 2009; Darling-Hammond *et al.*, 2017). Participants engaged in presentations on the seven essential principles of OL and their relevance to early childhood education, hands-on exploration of all toolkit components (handbook, activity guide, board game, and 360° videos), collaborative lesson planning sessions where teachers designed implementation strategies for their own classroom contexts, experiential learning activities including a field and museum visit to connect OL concepts with local marine environments and cultural heritage, and opportunities for peer exchange and networking across countries and educational levels (Fig. 3).

The training followed the recognition and validation framework established by Europass and the European Qualifications Framework (EQF), with participants re-



Fig. 3: TeachBlue teachers' training in Cyprus. (A) During a classroom activity; (B) Playing the board game. Photo credit: Stando LTD, TeachBlue project.

ceiving formal certification upon completion. Beyond skill development, the workshop served as the first pilot testing phase of the toolkit, enabling systematic collection of feedback for refinement and improvement of the educational materials.

Evaluation Methodology

To assess the training's effectiveness and gather formative feedback on the toolkit, a comprehensive questionnaire was administered to all participants upon completion of the workshop (post-training evaluation). The 26-item instrument combined Likert-scale questions, multiple-choice items, and open-ended responses, organized into seven thematic sections: personal information and teaching background, knowledge and content understanding, skills development, toolkit component evaluation, professional development and networking, overall workshop satisfaction, and qualitative reflections on experiences and suggestions. The questionnaire was developed by the research team based on validated instruments used in prior teacher professional development studies in environmental and science education (e.g., Freitas *et al.*, 2025). Face validity was established through expert review by two researchers external to the project prior to administration.

The mixed-methods evaluation approach allowed for both quantitative analysis of general trends and patterns in teachers' perceptions, and qualitative analysis using thematic coding to capture nuanced feedback and detailed insights (Creswell & Creswell, 2018). Likert-scale items were summarized using descriptive statistics (frequencies and percentages) (Boone & Boone, 2012). Open-ended responses were analyzed thematically using an inductive approach (Braun & Clarke, 2006), with two researchers independently generating initial codes and establishing inter-coder agreement on final themes through discussion (O'Connor & Joffe, 2020). Participation was voluntary and anonymous, ensuring candid responses that would inform both toolkit refinement and future professional development initiatives.

Results

The results are organized into two sections corresponding to the two research phases: (1) field research with children, and (2) teacher training evaluation. Prior desk research established the evidence base informing both the field research and the toolkit development described below (Król *et al.*, unpublished data).

Field Research Findings

Table 1 summarizes the key quantitative findings by OL principle and country. The narrative below describes cross-country patterns and developmentally significant findings in detail.

Children's Understanding of Ocean Geography and Physical Properties (Principle 1)

Children across all four partner countries were familiar with the word 'ocean' and associated it with a large body of water, even at the kindergarten stage (100% in all groups and countries) (Table 1). However, knowledge of specific ocean names was limited across all countries, particularly among younger children. In Greece, no kindergarten child and only one child out of 18 first-graders (6%) could name a specific ocean. In Cyprus, no specific ocean names were provided by either age group. In Poland, no kindergarten child could name a specific ocean. Among Grades 1-2 children, 85% named specific oceans including the Atlantic, Pacific, Indian, and Arctic. In Portugal, 50% of kindergarten children named some ocean names, although they could not locate them on a map; older children showed no such recall.

Regarding wave formation, children across all countries showed intuitive but not fully scientific explanations. In Poland, 96% of older children correctly attributed waves to wind, while younger children showed 56% correct attribution. In Greece, 75% of kindergartners and 55% of Grades 1-2 cited wind, with some experience-based explanations also offered. In Cyprus, 67% of kindergartners and 78% of Grades 1-2 made the wind connection. In Portugal, 80% of both age groups attributed waves to wind. When asked to draw the ocean floor, children across all countries and all age groups consistently depicted it as a flat surface, revealing limited understanding of seafloor topography (100% flat depictions across all groups) (Table 1; Fig. 4).

Children's Perceptions of Coastal Processes (Principle 2)

A consistent cross-country pattern emerged in children's understanding of geological processes. In Poland, 81% of kindergartners recognized that the sea causes coastal erosion, and 65% of Grades 1–2 showed similar awareness (Table 1). In Greece, 38% of kindergartners and 28% of Grades 1–2 identified the sea or water as a cause of coastal erosion, with most others attributing it to unrelated causes. In Cyprus, no children in either age group identified water as a cause of erosion. In Portugal, 25% of kindergarten children and 20% of older children showed some awareness. Understanding of sand formation through erosion followed a similar pattern: 50% of Polish kindergartners and 58% of Polish Grades 1–2, compared to 25–28% in Greece, 13–20% in Portugal, and 0% in Cyprus (Table 1).

Children's Knowledge of the Water Cycle (Principle 3)

Understanding of the water cycle varied considerably across age groups and countries. Regarding basic rain formation, 67% of Polish kindergartners and 73% of Polish Grades 1-2 recognized that rain comes from clouds (Table 1). In Portugal, 50% of kindergarten children and

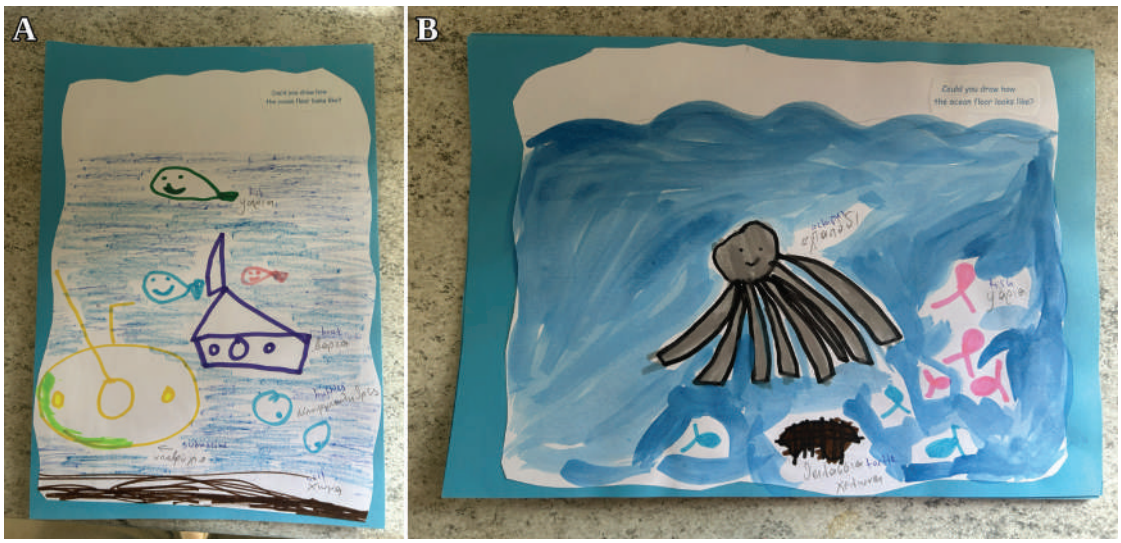


Fig. 4: Children's pictures concerning Principle 1. (A) Sample 1; (B) Sample 2. Children's drawings collected by DUTH during the TeachBlue field research; reproduced with the consent of the children's parents/guardians. Photo credit: DUTH, TeachBlue project.

60% of older children gave correct responses. In Greece, 25% of kindergartners and 22% of Grades 1-2 made this connection. In Cyprus, 33% of kindergartners gave correct responses, while no Grades 1-2 children did so. Understanding of the fuller water cycle (evaporation, condensation, and precipitation) was stronger in Poland (56% of kindergartners; 65% of Grades 1–2) and more limited elsewhere (33% of Greek Grades 1-2; 13% of Greek kindergartners; 13% of Portuguese kindergartners; 40% of Portuguese older children). Knowledge of rainwater returning to natural sources showed a clearer pattern: 72% of Polish kindergartners and 73% of Polish Grades 1-2, 72% of Portuguese older children, and 33% of Greek Grades 1-2 and 25% of Greek kindergartners. Across all countries, the connection between the ocean and the water cycle was rarely made explicit, indicating a gap in understanding the ocean's role in climate regulation (Table 1).

Children's Awareness of Marine Biodiversity (Principles 4 & 5)

Across all four partner countries, all children named iconic large marine animals (100% in all groups and countries) (Table 1). However, awareness of marine plants differed substantially (Fig. 5). In Poland, 6% kindergartners mentioned marine plants spontaneously, while 100% of Grades 1-2 named seaweed. In Greece, 63% of kindergartners mentioned seaweed, while none of the Grades 1-2 children did so. In Portugal, 13% of kindergarten children and 40% of older children mentioned marine plants. In Cyprus, no children in either age group mentioned marine plants spontaneously.

Plankton and microscopic organisms were absent from all spontaneous responses across all countries and age groups, with the sole exception of 17% of Cypriot Grades 1–2 children, who mentioned them, though in Portugal, when shown images, older children confused plankton with tiny shrimp (Table 1).

Children's Understanding of Human-Ocean Connections (Principles 6 & 7)

The ocean was recognized as essential for life across virtually all groups, with 100% agreement in all countries except Greek kindergartners, where 63% considered the ocean essential (37% stated it was not important to their lives) (Table 1). Environmental awareness varied considerably. In Poland, 78% of kindergartners and 85% of Grades 1-2 recognized pollution as a threat. In Portugal, 78% of older children and 38% of kindergartners recognized it. In Greece, 67% of Grades 1-2 identified pollution as a threat, while Greek kindergartners showed no such awareness. In Cyprus, no kindergartners mentioned pollution, while 44% of Grades 1-2 children recognized littering as harmful (Table 1).

Predicted consequences of ocean loss were consistently serious: 100% of Greek kindergartners, Cypriot kindergartners, and Cypriot Grades 1-2 predicted serious consequences, as did 100% of Polish Grades 1-2, 100% of Greek Grades 1-2, 88% of Portuguese kindergartners, 80% of Portuguese older children, and 78% of Polish kindergartners. Proposed protective actions showed a developmental gradient: 0% of Greek kindergartners (who felt humans 'cannot protect' the oceans), rising to 56% of Greek Grades 1-2, 33-58% in Poland, 33-44% in Cyprus, and 50-60% in Portugal (Table 1).

Professional Development and Teacher Training

The evaluation revealed overwhelmingly positive outcomes across all assessed dimensions (Tables 2-4; see Supplementary File 2 for full Likert-scale response distributions). Participants reported strong content knowledge gains (80–84% across items) and confidence in both designing OL lessons (88%) and using digital tools such as 360° videos (92%). The toolkit components were highly valued, particularly the handbook and activity guide

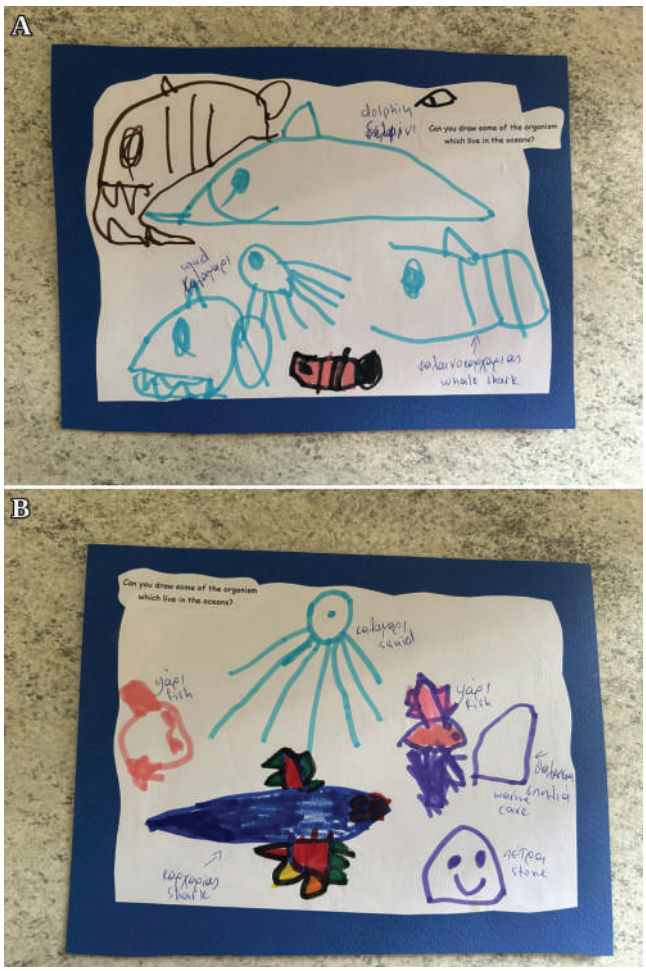


Fig. 5: Children's pictures concerning Principle 5. (A) Sample 1; (B) Sample 2. Children's drawings collected by DUTH during the TeachBlue field research; reproduced with the consent of the children's parents/guardians. Photo credit: DUTH, TeachBlue project.

(96% useful), with consistently high ratings across all four participating countries. Professional development outcomes were equally strong, with most participants reporting valuable new connections with other educators (88%), a positive impact on their professional growth (96%), and high satisfaction with the workshop's structure, delivery, and overall quality (92–96% across items).

Qualitative analysis of open-ended responses revealed several prominent themes, reported narratively rather than quantitatively given the relatively small and unevenly distributed number of responses per theme across countries; the full set of coded responses is provided in Supplementary File 2. Experiential learning emerged as particularly valued, with participants highlighting practical workshops, group activities, and the field visit as the most impactful components. These experiences were consistently described as engaging, effective, and motivating, demonstrating the power of connecting theoretical knowledge with tangible, real-world contexts. The museum visit was specifically noted as a powerful means of linking OL concepts with cultural and environmental heritage.

The educational toolkit received widespread qualitative praise, with most participants describing it as comprehensive and immediately applicable. Teachers particularly valued the practical planning aids provided by the handbook and activity guide, noting that these resources addressed their need for ready-to-use, curriculum-aligned materials. The board game and videos were consistently praised for their potential to engage students and make abstract ocean concepts concrete and accessible. Constructive feedback included suggestions for additional interactive activities, more visual materials for younger learners, and further age-adapted resources.

Discussion

Children's Ocean Literacy: What This Study Adds to Existing Knowledge

The field research findings reveal a consistent picture across four culturally and geographically diverse countries: young children aged 4-8 possess meaningful but partial knowledge of ocean-related concepts, with significant gaps that both reflect and extend what prior studies have reported. Crucially, the cross-country consistency of many findings, despite differences in curriculum frameworks and cultural context, suggests that the knowledge gaps and misconceptions documented here are developmental and educational in nature, rather than merely contextual. This aligns with Mogias *et al.* (2019), who found common knowledge gains and misconceptions among primary school students across three Mediterranean countries with different educational systems, and with broader evidence from science education research showing that children's alternative conceptions about natural phenomena tend to be remarkably consistent across cultural contexts (Vosniadou & Brewer, 1990).

Regarding ocean geography and physical properties (Principle 1), the consistently low rates of named ocean identification across most countries are likely attributable to a lack of explicit curricular attention to ocean geography at this age level, rather than to proximity to the sea. Although the naming and location of oceans is introduced as early as kindergarten in the OL Scope and Sequence Framework (National Marine Educators Association, 2010), it typically receives more systematic attention in upper primary grades (3-5), leaving early childhood largely without targeted instruction on this topic. This discrepancy is consistent with the terrestrial bias reported elsewhere in the science curriculum literature (Strang *et al.*, 2007), where ocean topics and macro-geographic ocean structures are frequently underutilized or omitted entirely from foundational science education; the present study did not directly compare children's continent- and ocean-related knowledge, and this framing therefore reflects a broader curricular pattern rather than a finding demonstrated by our own data. The higher performance of Polish children on this question likely reflects the specific emphasis on geography in the Polish curriculum, further reinforcing the view that explicit instruction, rather than coastal familiarity, is the key mediating factor. Furthermore, the fact that 100% of children across all countries

Table 2. Teachers' perceptions of knowledge gained, content usefulness, and skills development (N = 25).

Assessment Dimension	Positive Response (N)	Percentage (%)
Knowledge & Content		
Clear understanding of the 7 Ocean Literacy principles	21	84%
Usefulness of theoretical content for classroom practice	20	80%
Confidence in teaching ocean literacy principles	20	80%
Feasibility of integrating ocean literacy into daily practice	20	80%
Skills Development		
Capability to design and implement ocean literacy lessons	22	88%
Confidence in using digital and multimedia tools (360° videos, apps)	23	92%

Table 3. Participants' evaluation of the perceived usefulness and effectiveness of the TeachBlue Toolkit components (N = 25).

Toolkit Component	Positive Evaluation (N)	Percentage (%)
Teacher Handbook	24	96%
Activities Guide	24	96%
Educational Board Game	23	92%
360° Videos	22	90%

Table 4. Professional development outcomes, workshop structure evaluation, and overall training satisfaction (N = 25).

Evaluation Indicator	Positive Response (N)	Percentage (%)
Established valuable connections with other educators	22	88%
Positive impact on professional growth and development	24	96%
Workshop duration was appropriate	23	92%
Effective balance between theory and practical activities	24	96%
Adequate facilities, equipment, and instructor expertise	24	96%
Effective collaborative learning approach	24	96%
Overall training satisfaction (Met expectations)	24	96%

depicted the ocean floor as a completely flat surface reveals a robust initial mental model (Vosniadou & Brewer, 1990). An alternative explanation is that children's drawings prioritized animals and other salient objects over background topology, so the flat-seabed convention observed here may partly reflect drawing style rather than a literal belief that the ocean floor is flat. Because the deep seafloor is perceptually inaccessible to young learners, they tend to project their immediate sensory experiences of sandy shorelines or terrestrial plains onto underwater topography, completely omitting complex geological features like trenches or underwater reliefs.

Children's understanding of wave formation (Principle 2) followed a similar pattern across all countries: most children attributed waves to wind, an essentially correct association, but framed it experientially rather than scientifically. This is consistent with the constructivist view that children develop informal theories about natural phenomena through personal interaction with their everyday physical environment, rather than through scientific reasoning (Driver *et al.*, 1994).

Water cycle understanding (Principle 3) showed considerable variation both within and across countries probably reflecting differences in how water cycle concepts are embedded in national early childhood curricula. Notably, even where children demonstrated basic under-

standing of evaporation and condensation, the connection between the ocean and the water cycle, that the ocean is the primary source of atmospheric water vapour, was almost entirely absent across all countries. This finding echoes Shepardson *et al.* (2009), who found that students across grade levels tended to conceptualise the water cycle narrowly in terms of evaporation, condensation, and precipitation, with little attention to broader water transport and interconnections. This gap is significant, and points to a missed opportunity: the water cycle, precisely because it is already embedded in early childhood curricula across many national contexts and explicitly recommended as foundational content in the OL Scope and Sequence framework (National Marine Educators Association, 2010), represents one of the most accessible entry points for beginning to build the kind of systems thinking that underpins ocean and climate literacy. Early childhood curricula could use the water cycle as a first, concrete step toward understanding how the ocean, atmosphere, and land are connected, laying the groundwork for more complex conceptual understanding in later years.

The biodiversity findings (Principles 4 and 5) were among the most striking and consistent across the study. While children across all countries demonstrated rich knowledge of large, iconic species, such as sharks, dolphins, turtles, and octopus, plankton, microscopic marine organisms, and marine plants were mostly absent from spontaneous responses. This pattern shows a clear gap in children's understanding: they easily recognize familiar charismatic marine animals, but overlook the invisible side of the ecosystem. They do not realize that, according to OL Principle 4, it is microscopic life and marine plants that sustain global habitability. Where marine plants were mentioned at all, children referred exclusively to seaweed, with no reference to seagrasses. Notably, seaweed is technically macroalgae rather than a true marine plant, whereas seagrasses are flowering plants more directly relevant to OL Principle 4; children's exclusive reference to the former, and complete omission of the latter, may therefore understate their limited awareness of true marine plant life. This pattern likely reflects the dominance of charismatic megafauna in children's media, books, and informal learning environments, alongside the limited visibility of non-animal marine life in everyday experience and educational materials, and points to a significant gap in early childhood ocean education that curricula have yet to systematically address. The absence of plankton from children's spontaneous knowledge across all four countries is particularly significant from an ecological literacy perspective and confirms the need for targeted educational interventions.

Environmental awareness (Principles 6 and 7) was the area of greatest cross-country consistency and the strongest area of children's OL. Universal agreement that the ocean is essential for life, combined with widespread recognition of pollution as a threat, suggests that environmental messaging has permeated early childhood experience across all four countries. This aligns with Spiteri (2021), who found that young children aged 3-7 were already aware of the need to protect the environment and could articulate reasons grounded in their local experience, though their understanding remained tied to familiar, observable contexts rather than broader systemic issues. Consistently with this, children's conservation reasoning in our study was predominantly action-oriented and individual (cleaning beaches, not throwing litter), with little spontaneous mention of systemic threats such as overfishing and habitat destruction — concepts that may exceed what is developmentally accessible without prior instruction at this age. This pattern mirrors findings by Duran (2021), who found that preschool children's proposed solutions to environmental pollution were similarly concrete and individual, such as disposing of litter correctly, with no reference to structural or systemic responses. The absence of systemic reasoning is developmentally expected: research on systems thinking suggests that this is a higher-order cognitive skill that does not emerge spontaneously in young children, but can be scaffolded through targeted inquiry-based instruction (Ben-Zvi Assaraf & Orion, 2005, 2010). By leveraging accessible, already-embedded curricular concepts like the water cycle, educators can provide the necessary pedagogical scaffolding to transition children from these linear, individual actions toward a more holistic, systems-thinking approach. This structured progression is vital, as it underscores the importance of early, targeted ocean education rather than relying on incidental environmental messaging alone.

Evidence-Based Toolkit Development: From Field Research to Classroom Resources

The direct linkage between field research findings and toolkit content is a distinctive feature of the Teach-Blue approach. Rather than developing materials based solely on curriculum standards, the toolkit was designed to address specific, empirically documented knowledge gaps and misconceptions identified across four countries, a constructivist approach to curriculum development whereby instructional materials are anchored in children's actual prior knowledge rather than assumed starting points (Driver *et al.*, 1994). This evidence-to-design logic is most visible in the following areas: lesson plans addressing plankton and microscopic marine life, which directly target the universal absence of this knowledge from children's spontaneous responses; water cycle activities explicitly connecting children's existing understanding of evaporation and condensation to the ocean's global role, a connection absent from responses across all countries; the board game's inclusion of lesser-known species and diverse habitats, designed to broaden mental models beyond the charismatic megafauna that dominated all four country samples; tactile and visual tasks coupled with the 360° underwater videos, which were specifically designed to disrupt the universal misconception of a flat ocean floor by allowing children to visually explore and comprehend seafloor, and an environmental action strand that builds on children's existing pollution awareness while progressively scaffolding more systemic

understanding, responding to the finding that conservation reasoning at this age is predominantly individual and action-oriented (Ben-Zvi Assaraf & Orion, 2005, 2010).

The pedagogical architecture of the toolkit reflects contemporary understanding of how young children learn most effectively, incorporating diverse pedagogical modalities, print resources, hands-on activities, game-based learning, and immersive 360° technology (Zosh *et al.*, 2022). It rests on play-based and inquiry-based learning, both extensively validated for early childhood science education. Play-based learning fosters holistic development across cognitive, social-emotional, and physical domains (Taylor & Boyer, 2020; Pyle *et al.*, 2023), while inquiry-based approaches promote critical thinking and deeper conceptual understanding (Pyle *et al.*, 2023). Crucially, research emphasises that the most effective learning in early childhood occurs at the intersection of the two: purposeful, guided play in which children direct their own exploration while adults provide intentional scaffolding (Weisberg *et al.*, 2013; Zosh *et al.*, 2022). The board game was designed precisely around this principle, with educator-guided gameplay identified as the critical mechanism for maximising learning gains from game-based experiences (Noda *et al.*, 2019; Bayeck, 2020; Alotaibi, 2024). The 360° underwater videos address a different but equally significant barrier: most young children have no direct experience of underwater marine environments, making abstract ocean concepts difficult to grasp through traditional instruction alone. Research indicates that immersive 360° video experiences improve learning performance, motivation, and knowledge retention (Ranieri *et al.*, 2022; Rosendahl & Wagner, 2024), and that for young children specifically, virtual environments facilitate meaningful learning by presenting new content in contexts that feel experientially real (Araiza-Alba *et al.*, 2021). Together, the toolkit components provide complementary, evidence-based pathways into OL content that are developmentally appropriate, multimodal, and accessible to teachers with limited marine science backgrounds.

Professional Development Outcomes: Building Ocean Literacy Capacity Among Teachers

The overwhelmingly positive outcomes of the teacher training evaluation reflect the effectiveness of a sustained, multi-component professional development model. The five-day TeachBlue workshop was designed to combine content knowledge, hands-on practice with all toolkit components, experiential learning through field visits, and peer collaboration across countries. The significant increase in teachers' confidence confirms the arguments of Desimone (2009) and Darling-Hammond *et al.* (2017) that balancing theory with practical application is critical for effective professional development.

Constructive feedback from participants, including suggestions for additional interactive activities, more visual materials for younger learners, and further age-adapted resources, was incorporated into subsequent revisions of the toolkit prior to broader dissemination.

The finding that 92% of participants felt confident using digital tools including 360° videos is noteworthy, as digital technology integration remains a barrier in many early childhood educational contexts (Ranieri *et al.*, 2022). This result likely reflects both the quality of the training in digital tool use and the intuitive design of the 360° video component. However, literature cautiously notes that increased confidence with technology or toolkits during a structured, supportive training context does not automatically translate into sustained, independent use in the classroom (Ertmer & Ottenbreit-Leftwich, 2010; Sadaf *et al.*, 2012).

The small proportion of neutral or negative responses (up to 12%) may reflect systemic rather than individual barriers, such as time constraints, crowded curricula, limited institutional support, and resource availability, challenges that extend beyond individual teacher capacity and require policy-level responses (Asikin *et al.*, 2025; Freitas *et al.*, 2025). These findings reinforce the argument that teacher-level interventions, however effective, are insufficient on their own to ensure sustained OL integration. Explicit OL objectives in national early childhood curricula and dedicated professional development time for environmental education are necessary complements to toolkit-level resources, a need strongly echoed in recent global educational frameworks (Santoro *et al.*, 2022).

The cascading model adopted by the TeachBlue project, training teachers who will become OL ambassadors in their own schools and regions, has potential for multiplicative impact beyond the 25 direct workshop participants. Cascade models of teacher professional development have been shown to enable rapid and scalable dissemination of educational innovations, provided that trainer-teachers receive adequate preparation and ongoing institutional support (Kennedy, 2014; El-Hamamsy *et al.*, 2024). The high levels of professional networking reported by participants (88% established valuable connections) suggest that the workshop successfully initiated a cross-national professional community of practice, a resource that is empirically proven to sustain educational implementation and mitigate teacher isolation beyond the immediate post-training period (Wenger-Trayner & Wenger-Trayner, 2020).

A Replicable Framework for Evidence-Based Ocean Literacy Curriculum Development

Beyond its specific contributions to OL education, the TeachBlue project demonstrates a replicable methodological framework for developing evidence-based educational materials in domains where children's knowledge and resources are poorly understood. This framework comprises three sequential, interdependent phases: systematic review of existing resources and curricula (Król *et al.*, unpublished data); empirical field research with children to document actual knowledge, misconceptions, and areas of interest; and iterative toolkit development with pilot testing. This iterative process aligns with the

principles of Design-Based Research (DBR) in education, which advocates for a continuous feedback loop between empirical analysis and practical tool design (McKenney & Reeves, 2018). The critical feature of this framework is that each phase directly informs the next: the desk research identified curriculum gaps and established the theoretical foundation (Król *et al.*, unpublished data); the field research documented children's actual knowledge and misconceptions, preventing the toolkit from addressing assumed rather than real needs; and the pilot testing ensured that theoretically sound materials were also practically viable in classroom contexts. This evidence-to-design chain contrasts with curriculum development approaches that begin from standards or content knowledge alone, and it aligns with calls in the early childhood education literature for more participatory and needs-based curriculum development processes (Lind, 1999; Ardoin & Bowers, 2020).

The multi-component design of the toolkit, combining a teacher handbook, activities guide, board game, and 360° videos, also reflects an important design principle: that no single resource type can meet the diverse needs of early childhood educators across different classroom contexts, resource levels, and teaching styles. This architecture aligns with the principles of Universal Design for Learning (UDL), which advocate for providing multiple means of engagement and representation to accommodate diverse educational environments (Meyer *et al.*, 2014). This layered approach to resource design increases the toolkit's accessibility and adaptability, and may have contributed to the high cross-country approval ratings observed in the evaluation. Future iterations of the framework might also consider co-design with teachers from the outset, not only as pilot-testers but as co-developers, which has been shown to increase both the quality and the uptake of educational materials (Cviko *et al.*, 2014; Freitas *et al.*, 2025).

Implications for Policy and Practice

The Erasmus+ TeachBlue project carries important implications for educational policy and teacher preparation. First, the findings reinforce calls for the explicit integration of OL into national and regional early childhood curricula (Bastos *et al.*, 2025; Freitas *et al.*, 2025). The high teacher confidence and positive evaluations demonstrated here challenge assumptions that marine science is too abstract for early learners. Crucially, the field research shows that children across all four countries enter school with significant prior knowledge derived from personal experience and popular culture. Because this knowledge is often incomplete or misconceived, early OL education should not start from scratch. Instead, it must systematically scaffold children's existing curiosity and experience-based insights into structured scientific frameworks, a pedagogical approach directly embedded within the TeachBlue toolkit design.

Furthermore, the project highlights the essential role of comprehensive professional development in driving curriculum innovation. The five-day workshop successfully built content knowledge, advanced pedagogical skills, and fostered cross-national communities of practice. This multi-component model directly addresses a well-documented barrier: limited teacher confidence in marine science content, which frequently leads to the avoidance or superficial treatment of ocean topics (Boubonari *et al.*, 2013; Mogias *et al.*, 2015, 2021). By combining deep content exploration with hands-on experience, pedagogical modeling, and ready-to-use resources, the TeachBlue model effectively reduces the preparation burden on educators.

Finally, the consistent success of this transnational collaboration, spanning the four partner countries, demonstrates that OL education can transcend diverse European linguistic and cultural contexts. The shared knowledge gaps and misconceptions documented across these nations are not localized anomalies. Rather, they reflect broader, cross-national patterns in how young children conceptualize the marine environment. This shared reality strengthens the case for making OL a transnational educational priority. It strongly supports the adoption of the OL Principles and the NMEA Scope and Sequence, to structure early childhood curricula across diverse national educational systems (Cava *et al.*, 2005; National Marine Educators Association, 2010; National Oceanic and Atmospheric Administration, 2024).

Limitations and Future Directions

While the TeachBlue project achieved its primary objectives, several limitations warrant acknowledgment. First, the pilot evaluation relied on a relatively small sample of 25 teachers in a single intensive workshop. Crucially, teachers' self-reported confidence and satisfaction, while positive, do not directly demonstrate objective shifts in ocean science content knowledge or actual classroom replication. Literature cautions that self-efficacy in professional development settings does not automatically translate into observed pedagogical competence or long-term behavior change (Akyeampong *et al.*, 2013). Future evaluations should deploy validated instruments to measure objective knowledge gains and include observational or portfolio-based evidence of classroom implementation.

Second, a direct, post-implementation assessment of children's learning outcomes was beyond the scope of this phase. Although the baseline field research documented children's initial OL, this was not repeated after toolkit deployment. Consequently, while the materials are empirically grounded, their capacity to improve children's long-term knowledge and attitudes remains to be demonstrated. Future research must prioritize robust pre-post and longitudinal designs tracking understanding across the 4-8 age range. Given the developmental stage of early learners, these assessments should leverage participatory, age-appropriate methodologies, such as student drawings, focus group interviews, and structured play observations, which have proven highly effective in

mapping emergent marine conceptualizations (Freitas *et al.*, 2026).

Third, the field research sample was not nationally representative. Sample sizes varied significantly across the four participating countries, and within-country cohorts were restricted to single schools or classrooms, limiting generalizability; notably, while schools in Greece, Cyprus, and Portugal were coastal, those in Poland were inland, introducing a further source of variation in children's direct experience with the marine environment that was not systematically controlled for. Future studies should employ larger, geographically diverse samples to account for confounding sociocultural factors, such as socioeconomic status, prior formal environmental education, and geographical proximity to the coast.

Finally, the geographical scope was limited to European, primarily Mediterranean or Atlantic-facing nations, apart from Poland. Testing and adapting the TeachBlue framework in landlocked countries, developing regions, or diverse marine ecosystems would drastically enhance its cross-cultural applicability. Ultimately, this evidence-based development process, multi-modal resource design, and professional development model hold strong potential for replication across other early childhood STEM and environmental education domains where tailored resources are currently scarce.

Conclusions

This study evaluated children's baseline OL, developed an evidence-based educational toolkit, and assessed its professional development impact within the TeachBlue project. Together, these findings make two contributions to the field: original, evidence-based OL teaching materials grounded in children's authentic conceptualizations rather than abstract curriculum standards alone, and a replicable methodological framework that can inform curriculum development in other under-resourced STEM and environmental education domains.

These contributions should be interpreted alongside the study's limitations: teacher evaluations relied on immediate, self-reported measures, and a direct post-implementation assessment of children's learning outcomes has yet to be conducted. Additionally, children completed their drawings in their normal classroom setting without individual isolation, so some convergence in content (e.g., commonly drawn animals) may partly reflect peer discussion rather than independent recall alone. Future research should prioritize pre-post experimental designs to measure children's long-term learning gains, alongside longitudinal tracking of trained educators. By nurturing marine awareness during the critical early childhood period, TeachBlue offers a scalable model for fostering ocean-literate citizens from the earliest years of education.

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Supplementary Data

The following supplementary information is available online for the article:
Suppl. 1: Questions for Field Research.
Suppl. 2: Results from Workshop.