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Microplastics in River Water: Raising Science Competencies and Environmental Awarness in Secondary Education

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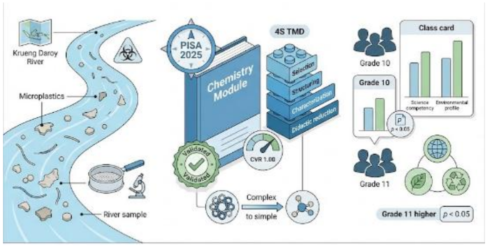
ABSTRACT

Guided by the PISA 2025 science framework, this study aimed to develop and validate microplastics-based chemistry teaching materials using the Four Steps Teaching Material Development (4S-TMD) model and to evaluate their impact on students' science competencies and environmental profiles. The research employed a research-and-development (R&D) design based on the 4S-TMD stages of selection, structuring, characterization, and didactic reduction. The participants were 30 upper-secondary students (15 Grade 10 and 15 Grade 11) from Teuku Nyak Arif Fatih Bilingual School. Additional data were obtained from expert validators who reviewed the teaching materials and assessment instruments, and from microplastics identified in water samples from the Krueng Daroy River as the empirical context. The instruments comprised microplastics-based teaching materials and evaluation sheets measuring students' science competencies and environmental profiles. Expert validation showed that the content validity ratio of the teaching materials and assessment sheets increased to acceptable values (CVR up to 1.00), indicating that all items were essential and aligned with the PISA 2025 framework. Independent-samples t-tests indicated significantly higher science competency and environmental profile scores for Grade 11 than for Grade 10 students ($p < 0.05$). Overall, the microplastics teaching materials developed using the 4S-TMD model were valid and showed potential effectiveness in supporting students' ecological awareness and science competencies in line with the PISA 2025 framework.



Keywords: *PISA's 2025 framework; science competence; environment profile; microplastics; 4S-TMD.*

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INTRODUCTION

Since 2021, the implementation of the Merdeka Curriculum has required students, including those studying chemistry, to respond to global issues and apply chemical concepts in everyday life and local environmental management. By the end of Phase E, chemistry students are expected to observe, investigate, and explain phenomena according to scientific work standards, with a strong emphasis on measurement in scientific activities. These expectations provide a curricular rationale for designing learning activities that engage students with environmental chemistry problems, such as measuring microplastic contamination in water—an issue that aligns closely with the PISA 2025 emphasis on interpreting scientific data and evaluating investigation designs.

Chemistry is an important component of the PISA (Programme for International Student Assessment) 2025 science framework, which now frames science competence as a single integrated competency that combines designing and evaluating scientific investigations with interpreting data and evidence. Therefore, learning should give students experience in interpreting real data and evaluating experimental designs, such as local microplastic measurements in river water. Yet in many science classrooms, students seldom have the opportunity to design or critically evaluate experiments and instead work with decontextualized textbook examples. This lack of authentic, data-rich experiences in environmental contexts motivates the development of teaching materials that use real river microplastic data to strengthen students' scientific reasoning.

The design of science literacy instruction in schools must be modified in light of the shifts in science competency as identified by the PISA 2025 framework in order to promote the enhancement of the quality of education across the country. National education policies, as reflected in the National Medium-Term Development Plan (RPJMN) 2025–2029 and the Sustainable Development Goals (SDGs) 2017–2030, together with Indonesia's relatively low PISA 2022 results compared to the OECD average, indicate the need to improve the quality of science learning, especially in authentic, context-rich tasks. Intervention is required, particularly to enhance the quality of teaching and learning, in order to achieve the targeted increase in PISA scores by 2029.

This research develops chemistry teaching materials based on tests detecting the content and properties of microplastics in the water of the Krueng Daroy River in Banda Aceh City, within the Phase E theme of measurement methods in scientific activity. The river originates in the Mata Ie mountain range and flows through urban green spaces such as Ghairah Park, making it an important ecological corridor for the city. It also has historical value from the period of Sultan Iskandar Muda, when it flowed through the royal Putroe Phang Garden. Today, however, the river is increasingly polluted by household waste along its 38.26-hectare riverbank area, and plastic waste such as bottles accumulates in many sections [1]. This combination of ecological importance and current plastic contamination makes Krueng Daroy a meaningful local context for students to study microplastics and environmental chemistry.

Plastics degrade over time into small fragments known as microplastics (< 5 mm) through various physical, chemical, and biological processes [2-7]. Once formed, microplastics are easily dispersed in aquatic environments and, because of their high surface area and porosity, can adsorb a range of pollutants from the surrounding water [8,9]. High microplastic loads may indirectly affect water quality and aquatic organisms, for example by altering physical conditions and interacting with other pollutants, so communities that rely on contaminated river water can also be impacted. Using data on microplastic contamination in the Krueng Daroy River in chemistry teaching materials gives students an opportunity to engage with a serious, locally relevant environmental problem and to practise interpreting real measurement data in line with PISA-style science competencies.

The risks posed by microplastics have begun to be addressed in education through the development of microplastic-themed modules and web-based learning, which have been shown to improve students' knowledge and awareness about plastic pollution [10-12]. However, these studies mostly focus on general awareness rather than integrating locally measured microplastic data into structured chemistry teaching materials aligned with PISA 2025 science competencies. In Indonesia, very few studies have incorporated local river microplastic data into teaching materials, so many students remain unaware of the actual level of contamination in their own environment. In this study, the experimental findings on microplastic pollution in river water are used as the basis for developing instructional materials and learning media.

Teaching materials created by educators in the classroom also assist this understanding. According to earlier studies, only 62.5% of instructors typically discuss the risks of plastic pollution [13], and they have not particularly addressed microplastics. To raise students' awareness and knowledge, instructional materials that include findings from microplastic content analysis investigations and guide students to analyse and interpret these data must be created. However, microplastics are rarely integrated into teacher-developed chemistry materials, and students have limited opportunities to analyse real microplastic data. Therefore, this study aims to address that gap. Specifically, it aims (1) to develop and validate microplastics-based teaching materials and accompanying cognitive and emotional assessment sheets using the 4S-TMD model, and (2) to evaluate the science competencies and environmental profiles of Grade 10 and 11 students after using these materials, in line with the PISA 2025 framework.

METHODS

1. Research Design

This study used a Research and Development (R&D) design and followed the 4S-TMD (Four Steps Teaching Material Development) model, which consists of four stages: Selection, Structuring, Characterization, and Didactic Reduction (Figure 1). According to [14], this approach is ideal for development research, especially for creating instructional materials.

Selection stage aligned the microplastics topic with relevant PISA 2025 scientific literacy indicators and Phase E curriculum competencies. In the Structuring stage, key concepts, learning objectives, local microplastic data, and assessment tasks were organized into a coherent outline for teaching materials. The Characterization stage involved expert validation of the teaching materials and assessment instruments. Finally, in the Didactic Reduction stage, the content was simplified and refined to match students' cognitive levels and classroom conditions.

The product developed in this study consists of microplastics-based teaching materials and assessment instruments (science competency test and environmental profile questionnaire). The product was then evaluated through expert validation and a student trial.

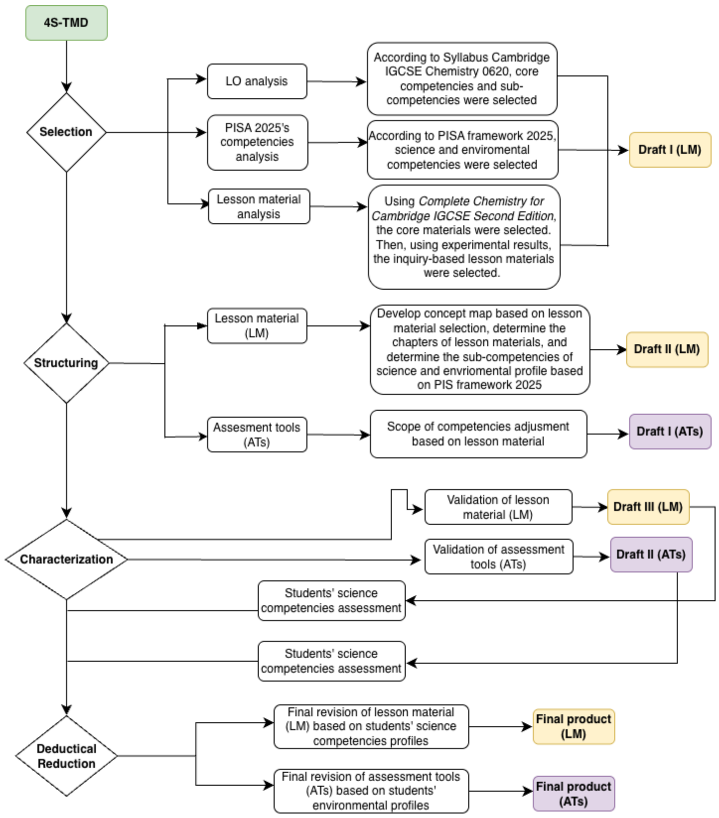


Figure 1. Research flow based on 4S-TMD model

2. Participants and Research Objects

The participants in this study were three expert validators and 30 students. The student group consisted of fifteen Grade 10 students and fifteen Grade 11 students from Teuku Nyak Arif Fatih Bilingual School in Banda Aceh. The students were selected purposively based on grade level and their availability to participate in the learning and assessment activities. The expert validators were responsible for judging the quality of the teaching materials and the science competence and environmental profile assessment sheets.

The research objects in this study were: (1) river water samples from the Krueng Daroy River, which were collected to determine the degree of microplastic contamination and the characteristics of the microplastics; (2) the microplastics-based chemistry teaching materials developed using the 4S-TMD model, which incorporated the experimental results on microplastic abundance; and (3) the science competence and environmental profile assessment sheets used to measure students' cognitive and affective outcomes.

3. Microplastics Samples and Analysis

Surface and near-bottom water were collected at five sampling points along the

Krueng Daroy River using a 3.2 L water sampler (APAL-VHA2). At each sampling point and depth, three replicate grabs were taken at 5 m intervals, resulting in a total volume of 9.6 L per depth and 19.2 L per station. Immediately after collection, the water samples were passed through a 20 µm plankton net to retain potential microplastic particles.

Laboratory processing began by transferring the retained material into Erlenmeyer flasks, followed by the addition of 20 mL of 30% H_2O_2 for 24 h to oxidize organic matter. Centrifugation was then performed at 3,500 rpm for 15 min to support density based separation. Supernatant was carefully decanted and filtered onto Whatman No. 1 filter paper. Drying of the filters was conducted in a Memmert drying oven at 50 ± 2 °C for 24 h.

Dried filters were examined using a stereomicroscope (Olympus SZ51, 40× magnification). Suspected microplastics were visually identified and classified by shape (fiber, fragment, film, pellet), size class (300–500 µm, 500–1,000 µm, 1,000–5,000 µm), and color (black, blue, red, brown, green, purple). Representative particles were characterized using Fourier Transform Infrared spectroscopy (FTIR, PerkinElmer Spectrum Two) and Scanning Electron Microscopy (SEM, ThermoScientific Prisma E) to confirm polymer type and surface morphology. Copper associated with microplastics was quantified using Atomic Absorption Spectrophotometry (AAS, PerkinElmer 900T). Microplastic analysis outputs were incorporated into the teaching materials as contextual data, figures, and interpretation tasks.

4. Development of Teaching Materials

Teaching materials on microplastics were developed following the 4S-TMD stages [14]:

Selection In this stage, key concepts of microplastics (sources, distribution, environmental and health impacts) were identified and aligned with relevant PISA 2025 science competencies and Phase E curriculum competencies. Local data from the Krueng Daroy River microplastic analysis were selected as contextual content.

Structuring The selected content was organized into a teaching module/worksheet consisting of introductory texts presenting the microplastics issue, data tables and graphs based on river sampling results, inquiry-based questions, tasks focusing on interpreting data, explaining phenomena, and evaluating investigations. The structure was designed to gradually guide students from conceptual understanding to application and critical thinking.

Characterization A draft version of the teaching materials was evaluated by three experts using a structured rubric (1–5 Likert scale) that assessed construct validity (structure, coherence, pedagogical soundness), content validity (relevance and representativeness), and face validity (readability, appearance, and engagement).

Didactic Reduction Based on feedback from the validators, the materials were revised to improve clarity, reduce unnecessary complexity, and adjust the level of difficulty to match the students' cognitive level. This included simplifying text, refining figures and tables, and adjusting questions and tasks. The final product was a microplastics-based teaching module that integrates local environmental data and targets PISA-oriented science competencies.

5. Instruments

Three main instruments were used in this study, namely: (a) Science Competency Test (Cognitive) was designed to measure students' science competency after learning with the microplastics-based teaching materials. The test consisted of multiple-choice and structured-response items representing key dimensions of science literacy, such as: explaining scientific phenomena, interpreting data and evidence, and evaluating and designing scientific enquiry; (b) Environmental Profile Questionnaire (Affective) was used to assess students' environmental attitudes and profiles related to microplastics and environmental responsibility. The items were arranged on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree) and measured aspects such as awareness, concern, and willingness to act; and (c) Validation Rubric was used by the expert validators to evaluate the quality of the teaching materials and both assessment instruments. The rubric applied a 1–5 Likert scale, with descriptors and descriptions as summarized in Table 1. The same scale was used for lesson materials, the science competency test, and the environmental profile questionnaire, with wording adapted slightly to each instrument.

6. Data and Data Sources

There are particular data collection methods used at each stage of this study. The type of data primary or secondary has a significant impact on the methods employed for data gathering [15]. When gathering unpublished data directly from research participants, primary data collection methods are employed, such as student test scores, questionnaire responses, and expert ratings. Research findings are compared with those of earlier studies using secondary data collection approaches [16], including PISA documents, curriculum documents, and previous research on microplastics.

7. Validation Procedures

The instructional materials and cognitive and affective evaluation sheets were verified using the Content Validity Ratio (CVR) and the Item-level Content Validity Index (I-CVI) following the Selection and Structuring processes [17].

The CVR for each item was calculated using:

$$CVR = \frac{n_e - \frac{N}{2}}{\frac{N}{2}} \quad (1)$$

where N is the total number of experts (N = 3) and n_e is the number of experts who evaluated the item as essential.

The I-CVI for each item was calculated as:

$$I-CVI = \frac{N_r}{N} \quad (2)$$

where n_r is the number of experts who rated the item as *relevant* (i.e., in the highest categories on the 1–5 Likert scale), and N is the total number of experts. I-CVI values approaching 1 indicate that there is a high level of agreement among experts on the relevance of the item.

Three dimensions of instructional materials' validity were tested: (1) Construct Validity (structure, coherence, and pedagogical soundness); (2) Face Validity (readability, appearance, and engagement); and (3) Content Validity (relevance and representativeness). Three experts conducted the validation, and in accordance with the guidelines in Table 1, both the science competency test and the environmental profile questionnaire used the same 1–5 Likert scale, with slightly different wording adapted to each instrument.

Table 1. Validity Descriptor and Description in Characterization Stage

Scale	Validation Description of Lesson Material and Science Competency Assessment		Validation Description of Environmental Profile	
	Descriptor	Description	Analysis	Descriptor
5	Very appropriate	Fully meets the criteria; no revision needed	Excellent	The item is highly valid, precise, and accurately represents the construct
4	Appropriate	Meets most criteria; minor revision needed	Good	The item is clear, relevant, and aligned with the construct
3	Fairly appropriate	Some weaknesses; revision recommended	Fair	The item is acceptable but may need refinement
2	Inappropriate	Major weaknesses; significant revision required	Poor	The item weakly represents the construct or lacks clarity
1	Very inappropriate	Does not meet criteria; should be replaced	Very poor	The item does not reflect the construct or is confusing

8. Implementation Procedures with Students

Expert validation and revision produced the final microplastics based teaching materials, which were implemented in classroom learning with Grade 10 and Grade 11 students at Teuku Nyak Arif Fatih Bilingual School. Implementation followed three steps. Students received the teaching module and participated in learning activities grounded in the microplastics context and local river data. Students completed the science competency test to measure cognitive outcomes at the end of the learning sessions, followed by completion of the environmental profile questionnaire to capture affective aspects such as environmental attitudes and awareness. Test scores and questionnaire responses were used to evaluate the effectiveness of the developed materials and to compare outcomes between grade levels.

9. Data Analysis

A quantitative follow-up test was carried out using statistical techniques because students from two distinct levels took the science competency and environmental profile assessments. Since the test questions were identical for both levels, the Independent Samples t-test (also known as the two samples t-test) was selected [17].

Science competency test hypotheses were defined as follows:

H_0: The average science competency scores of Level 10 and Level 11 students do not differ significantly.

H_1: Level 10 and Level 11 students have significantly different average science proficiency scores.

Environmental profile test hypotheses were defined as follows:

H_0: Level 10's average overall affective score is equivalent to Level 11's.

H_1: Level 10's average overall affective score is lower than Level 11's.

Sample sizes were $n_1 = 15$ for Grade 10 and $n_2 = 15$ for Grade 11. Assumptions of normality and homogeneity of variance were checked prior to conducting the t-tests. A significance level of $p < 0.05$ was used; thus, H_0 was rejected and H_1 accepted when the p-value was less than 0.05 [17].

RESULTS AND DISCUSSION

Following the 4S-TMD approach, the development and evaluation of the microplastics-based teaching materials in this study proceeded through four stages: Selection, Structuring, Characterization, and Didactic Reduction. In this section, we present the main findings from each stage and discuss their implications for science competency and students' environmental profiles.

Overall, the selection stage produced a set of eight core competencies and related sub-competencies aligned with the PISA 2025 framework and environmental profiles. The structuring stage resulted in a three-part teaching module that integrates local microplastics data as contextual material, accompanied by science competency and environmental profile assessment instruments. In the characterization stage, expert validation showed an improvement of CVR and I-CVI values to 1.00 for both the teaching materials and the assessment instruments, indicating strong content relevance and construct representation. Finally, the didactic reduction stage demonstrated that students' understanding of microplastics concepts and related competencies was in the moderate-to-good range, with Grade 11 students outperforming Grade 10 students on both science competency scores and environmental profiles.

1. Selection Stage

The selection stage identified core competencies and subcompetencies, then aligned them with the PISA 2025 science framework and the Environmental Profile constructs (caring, curiosity, critical, reliable, and responsible). The knowledge domain included subcompetencies such as knowledge acquisition and knowledge deepening [18]. These competency targets guided the development of subtopics and themes for the microplastics teaching materials. The selected topics became the main content, while supporting materials were derived from experimental results on microplastics in the Krueng Daroy River.

The eight selected abilities focus on: (1) explaining water contaminants and their impacts; (2) interpreting analytical data related to water quality; (3) designing and evaluating simple investigations on microplastics; and (4) connecting scientific findings to environmental and social consequences. These abilities were mapped to the three PISA 2025 science competencies—explaining phenomena scientifically, evaluating and designing scientific inquiry, and interpreting data and evidence—combined with affective indicators representing students' Environmental Profiles (caring and critical, among others). This mapping ensures that the developed materials do not only target cognitive understanding but also students' attitudes and values toward environmental issues [19,20]. The overall mapping of core competencies, sub-competencies, and major lesson contents is summarized in Figure 2.

The supporting materials selected from the microplastics identification experiment include: (1) microplastic presence at the surface and within the water column of the Krueng Daroy River; (2) microplastic types and colors identified under the stereomicroscope; (3) polymer types confirmed using FTIR; and (4) surface morphology characterized using SEM. These data provide scientifically grounded examples that are later embedded in the teaching materials as figures, tables, and interpretation tasks.

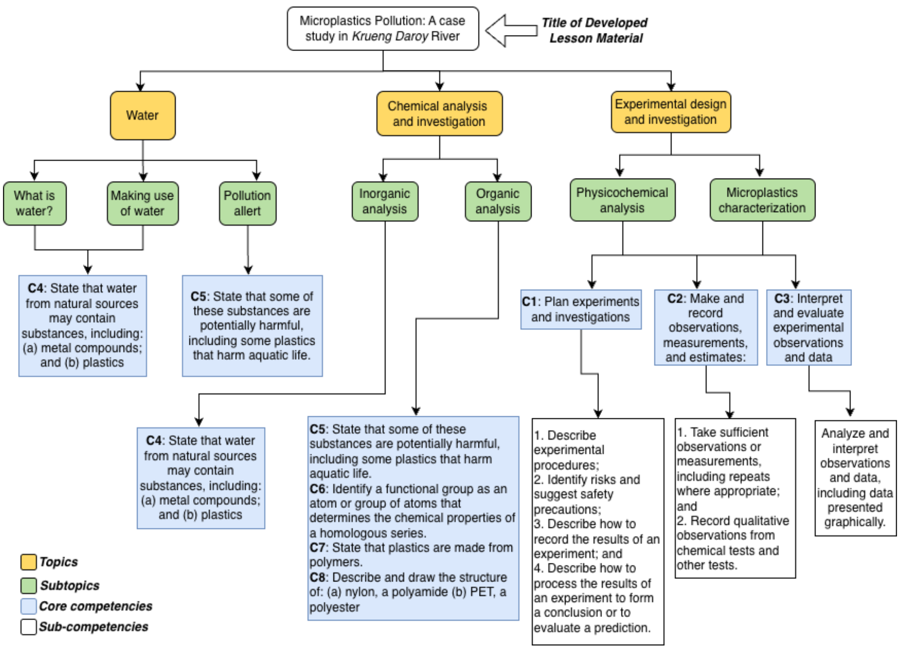


Figure 2. Selection of core competencies, sub-competenicies, and major contents for lesson materials in microplatics

2. Structuring Stage

2.1 Structuring of Learning Materials

The teaching materials were structured around three main concepts: Water, Microplastics, and Water Analysis, adapted from the "Air and Water" chapter of a reference chemistry textbook "Complete Chemistry for Cambridge IGCSE Second Edition" and further expanded with microplastics content and a local river case study. The Water concept covers water sources (surface water, groundwater, and the hydrological cycle), water properties, and water quality indicators, including physical, chemical, and biological pollutants (Figure 3 and Figure 4a).

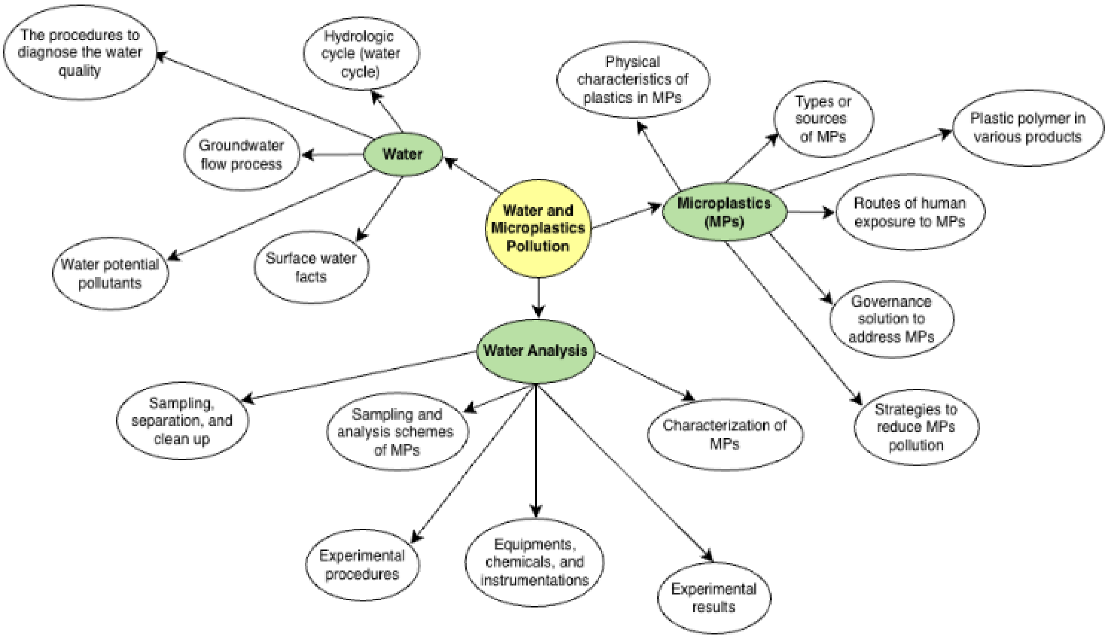
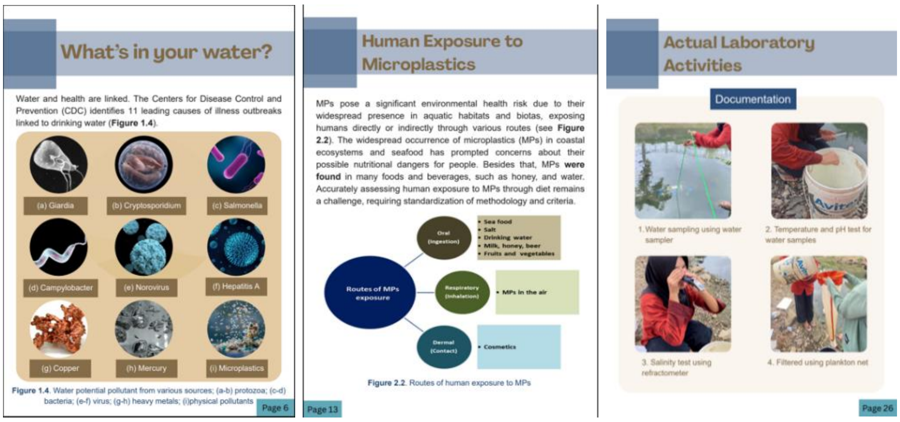


Figure 3. Concept map of lesson material in water and microplastics pollution



a. b. c.

Figure 4. a. The "What's in Your Water?" element of the teaching materials is displayed in Chapter 2; b. Display of teaching materials on the mechanism of human exposure to microplastics; and c. Presentation of Instructional Resources on the Water Sampling Procedure for the Identification of Microplastic

The Microplastics concept addresses definition and composition, primary and secondary microplastics, human exposure pathways (e.g., seafood, table salt, bottled water), and governance strategies for microplastics management (Figure 4b). The Water Analysis concept uses the Krueng Daroy River as a case study and introduces analytical methods for detecting microplastics, including sampling, separation, cleaning, identification, and confirmation (Figure 4c).

The material was organized into chapters that progress from basic concepts

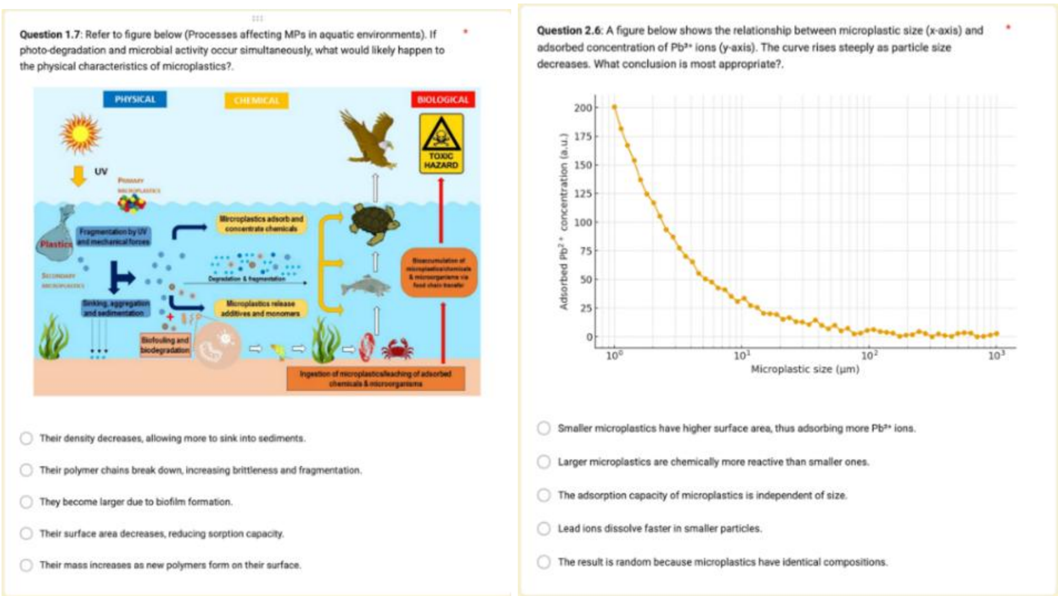
("What is water?" and "What is in your water?") to specific microplastics issues and finally to local water analysis and laboratory activities (Figure 3). This structure is intended to scaffold students from familiar contexts to more complex analytical thinking about environmental contamination.

2.2 Structuring of Assessment Tools

Science competency and Environmental Profile assessment instruments were structured to align with the PISA 2025 science competencies and Bloom's taxonomy across the cognitive hierarchy and affective domain. Table 2 presents an example of the mapping among PISA competencies, Environmental Profile constructs, and Bloom's taxonomy. The same mapping procedure was applied to all instrument items.

Table 2. The mapping of cognitive hierarchy and affective domain and their correlation to PISA's 2025 science and environmental competencies

PISA's 2025 competencies			Bloom's Taxonomy		
Science	**Science sub-competencies**	**Environment Profile**	**Cognitive hierarchy**	**Affective domain**	**Focus of affective**
Explaining phenomena scientifically	Recalling and applying scientific knowledge; explaining the implications of scientific phenomena for society.	Caring	Analysis	Valuing	Identify the cause, connect humans and ecosystems
	Identifying and evaluating models of chemical interaction; explaining the implications for society.		Evaluate	Critical	Evaluate arguments, detect bias



a. b.

Figure 5. Example of question based on a. the first; and b. the second of PISA's 2025 science competencie

The science competency test consists of 20 multiple-choice questions grouped into three competencies: (1) explaining phenomena scientifically, (2) designing and evaluating scientific investigations, and (3) interpreting data and evidence for scientific decisions. Each item targets higher-order thinking (C4–C6) and is anchored in microplastics-related scenarios. Examples of science competency items developed based on the first and second PISA 2025 science competencies are shown in Figure 5.

The Environmental Profile questionnaire is organized around five profiles—Caring, Curious, Critical, Reliable, and Responsible. Each profile is represented by a contextual scenario related to water pollution and microplastics, followed by Likert-scale statements (1–5) that capture both affective (emotional-empathetic) and analytical (reflective-ethical) dimensions. This arrangement ensures that environmental attitudes are assessed not only as feelings but also as reasoned positions linked to potential actions.

3. Characterization Stage

3.1. Validation of Learning Materials

Three expert validators (V1, V2, and V3) evaluated the teaching materials in two rounds. Their feedback and the corresponding academic implications and revisions are summarized in Table 3. Key recommendations emphasized stronger contextualization through everyday examples, such as consumer products containing microplastics and practical plastic free alternatives, to improve relevance and learning transfer. Technical sections that were judged too dense, including FTIR spectra interpretation and detailed laboratory procedures, were flagged as needing simplification and stronger visual scaffolding to reduce cognitive load. Reflective tasks and guiding questions were also recommended to strengthen metacognitive monitoring and inquiry based learning processes, so students can evaluate claims, interpret evidence, and justify conclusions more systematically.

Revisions increased the CVR of the teaching materials from 0.76 to 1.00, indicating complete expert agreement that all lesson components are essential. The I-CVI also rose from 0.88 to 1.00, confirming that each content element was judged highly relevant to the intended constructs of scientific inquiry and environmental chemistry literacy [21,22]. This gain suggests that the redesigned materials align more closely with the targeted competencies and with students' cognitive level [23]. The pattern is consistent with studies emphasizing alignment among curriculum, assessment, and classroom practice, alongside the role of sustained professional development and adequate school resources in supporting implementation [24]. Stronger I-CVI values also accord with prior evidence in educational measurement showing that high I-CVI reflects expert consensus on item representativeness and construct relevance [25].

Table 3. Experts' feedbacks and revision follow-up

Aspects of validity	Feedbacks	Academic implication	Revision follow-up
Content	Include examples of ordinary products containing microplastics (such as face scrubs and toothpaste), as well as plastic-free alternatives.	The recommendation to incorporate examples of everyday products containing microplastics (e.g., face scrubs, toothpaste) suggests that the lesson plan should focus on contextual and applied components of scientific learning.	Include a brief opening segment or infographic demonstrating common consumer products containing microplastics and eco-friendly alternatives (for example, bamboo toothbrushes and natural exfoliants).
	The topic is appropriate for high school or university students. However, some of the more technical aspects (such as the FTIR spectrum and comprehensive laboratory methods) may necessitate further explanation for beginners.	The feedback that technical topics such as FTIR spectra and specific lab methods may require extra explanation suggests a mismatch between content complexity and learner readiness.	Simplify or augment FTIR-related sections with the following: a visual explanation of FTIR peaks and what they represent, and a step-by-step flowchart for sample preparation and data interpretation.
Face	The language employed is often straightforward and intelligible. However, some technical phrases, such as "BEPP," "polyamide," or "density separation," may necessitate a dictionary or further explanation for middle school students.	The validator's observation that certain technical terminology (e.g., BEPP, polyamide, density separation) may require explanation shows that disciplinary language must be mediated for the learners' cognitive level.	Include a glossary or side notes that define terminology like BEPP, polyamide, and density separation with student-friendly language and visual representations.
	Create a separate page for handling 30% H_2O_2, centrifugation, and other scientific equipment.	Creating a distinct page for handling 30% H_2O_2, centrifugation, and other laboratory gear prioritizes safety, clarity, and ethical education.	Create a separate safety page that includes handling considerations for 30% H_2O_2 and a step-by-step visual guidance for centrifugation. General laboratory safety symbols and emergency protocols.
Construct	Laboratory activities and data analysis help to develop analytical skills. However, they could be improved by include guiding questions that encourage students to think critically and reflect more deeply on their findings.	This emphasizes the need of including metacognitive and inquiry-based scaffolds—questions that assist students in connecting facts to theory, evaluating evidence, and drawing reasoned conclusions.	Include a brief "reflection section" following data analysis in which students explain what they learned, any uncertainties they encountered, and any causes of mistake.

3.2. Validation of Assessment Tools

Table 4. Results of the science competency test validation based on science competencies: analysis and implications

Example of Questions	Analysis	Implication
Competency 1: Explaining Phenomena Scientifically		
Question 1.5: "Microplastics can adsorb toxic organic compounds like PCBs… smaller microplastics were found to accumulate more toxins… Which conclusion is most scientifically valid?"	This question assesses the ability to describe scientific processes using chemical-physical principles (adsorption, surface area ratio, and molecular interactions) in a realistic environmental setting. The cognitive level is C4-C5 (analyzing-evaluating) because students must: (1) relate particle size to its physicochemical attributes, and (2) evaluate the scientific conclusion that is most consistent with basic scientific concepts.	**Before adjustment**, the validator observed that some EPS elements overemphasized idea recall. **After adjustment**, questions such as Question 1.5 exhibit scientific thinking that incorporates ideas, empirical facts, and real-world context, which is congruent with PISA's scientific reasoning framework. So, the increase in CVR (0.69→1.00) can be attributed to all validators agreeing on the item's relevance, scientific accuracy, and high cognitive complexity (HOTS).
Competency 2: Designing and Evaluating Scientific Investigations		
Question 2.2: "A student wants to test whether water temperature affects the rate of microplastic degradation. Which design would best test this hypothesis?"	This question measures the ability to design scientific studies (experimental design) while taking into account control, independent, and dependent variables. The cognitive level is C5 (evaluating), which requires students to: (1) identify the most scientifically legitimate design; (2) evaluate if the design accurately answers the hypothesis; and (3) control variables so that the results can be validly compared.	**Before amendment**, the validator noted that several designs were overly "technical" (using advanced technologies). **Following adjustment**, the experimental environment was modified to be practical in an educational laboratory. **Conclusion**: This revision considerably enhanced cognitive level and scientific accuracy, resulting in an I-CVI score of 1.00. Then, in Question 2.2, it displays high inquiry alignment: pupils are thinking like scientists rather than simply answering factual questions.

Student science competencies and Environmental Profiles on the topic of microplastics were assessed using two instruments, namely a science competency assessment sheet for the cognitive domain and an Environmental Profile assessment sheet for the affective domain. The science competency assessment is structured around three sub-competencies: (1) explaining phenomena scientifically; (2) designing and evaluating scientific investigations; and (3) interpreting data and evidence for decision-making. The final version of the test consists of 20 multiple-choice questions: seven items for Competency 1, seven items for Competency 2, and six items for Competency 3. Each item was evaluated by three experts based on four criteria: content relevance, cognitive level, scientific accuracy, and clarity of wording. The detailed validation results for the science competency items, including examples of questions, analyses, and implications before and after revision, are summarised in Table 4.

Initial validation produced CVR and I-CVI values of 0.69 and 0.84, indicating that most items were relevant, yet several items did not fully reflect the targeted higher order cognitive demand at C4 and above or were framed in overly technical language. Validators noted, for example, that several items overemphasised recall or used contexts that were not feasible in a typical school laboratory. After revising these items to focus on realistic scenarios, higher-order reasoning, and more accessible experimental designs, both CVR and I-CVI increased to 1.00, showing complete agreement among validators that all items are essential and highly relevant. Table 4 presents examples of revision and analysis for selected science competency items and their implications for improving alignment with PISA 2025 and higher-order thinking skills.

The Environmental Profile assessment sheet was developed to evaluate students' environmental attitudes and values in relation to water contamination, microplastics, and sustainability. It comprises five major profiles: Caring, Curious, Critical, Reliable, and Responsible. Each profile is represented by a contextual scenario (real-world case) followed by five Likert-scale statements (1–5), which jointly measure two dimensions: (1) affective (emotional–empathetic) and (2) analytical (reflective–ethical reasoning). Three experts validated the instrument using four criteria: content relevance, concept coherence, clarity of wording, and representativeness of affective–analytical characteristics. An in-depth analysis of the validation results for several Environmental Profile scenarios and students' response patterns is presented in Table 5.

An in-depth analysis shows that the increase in CVR (0.69 → 1.00) reflects improvements in the substance of the items and better alignment between the targeted competencies. Likewise, the increase in I-CVI (0.84 → 1.00) indicates that all items have fully met the dimensions of content, cognitive, and scientific validity. Systematic revisions have made the assessment not only statistically sound, but also conceptually and pedagogically coherent, as items now integrate scientific knowledge, scientific processes, and socio-ecological contexts, demonstrate the interconnectedness of science, technology, and society (STS literacy), and encourage students to think at evaluative and creative levels (C5–C6). Table 5 presents illustrative examples of validation findings for several Environmental Profile scenarios and students' response patterns in the questionnaire.

Table 5. In-depth analysis of validation results based on Environmental Profile

Examples of Questions	Analysis	Interpretation
Profilel 1: Caring		
Before adjustment: "I feel troubled by how everyday activities such as washing and plastic use can damage the river ecosystem." **After adjustment**: "I feel empathy for local fishermen whose livelihoods are affected by the river's pollution."	These items assess ecological emotions and social empathy, requiring an understanding of the link between human actions and ecosystems.	**Prior to change**, the validator discovered that certain assertions were overly emotional and lacked links to real-world behaviors. **After adjustment**, adding statements like "I believe communities should work together to restore river health..." increases the analytical-action dimension (C5: evaluating and deciding). **Conclusion**: The improvement in validity is mirrored in the growth of CVR because the items now link empathy (Caring) with social responsibility analysis.
Profile 3: Critical		
Before adjustment: "I question commercial claims about environmental safety unless supported by strong scientific evidence." After adjustment: "I believe data from peer-reviewed research is more reliable than promotional advertisements."	This profile assesses the capacity to discriminate between scientific evidence and non-scientific statements, demonstrating scientific reasoning and media literacy.	**Prior to change**, the validator saw that the item frequently shared "curiosity." **After revision**: "I think it's important to evaluate how information sources might have different motives or biases" is one example of how an evaluative judgment element has been included. **Conclusion**: By striking a balance between the affective-skeptical and cognitive-evaluative parts of public assertions, these questions enhance construct validity and now require argumentative examination (C5).

The improvement in validity indices (for example, from CVR = 0.33 → 0.67 and I-CVI = 0.66 → 0.83 in earlier iterations) also suggests a positive modification of the instrument: from merely normative statements to reflective, contextual items;

from passive affective expression to active affective–analytical responses (reflective empathy); and from static attitudes to action-oriented social–emotional competence (SEL and SDG-oriented). These results are consistent with the Environmental Affective–Analytical Model, which posits that ecological attitudes are best assessed through the interaction of empathy (affective) and reasoning (analytical), leading to environmentally responsible behaviour [25].

3.3. Student Science Competencies and Environmental Profile Results

3.3.1. Science Competencies

Students' science competency was measured using the 20-item test, with scores ranging from 0 to 20. Figure 6 shows the average scores for each science competency for Grade 10 and Grade 11 students. Overall, average scores fell within a moderate range, but Grade 11 students obtained higher mean scores than Grade 10 students for all three competencies.

Figure 6. Average score of science Competencies

The independent samples t-test yielded t(28) = −2.41, p = 0.023, indicating a statistically significant difference in overall science competency between Grade 10 and Grade 11 students. Eleventh-grade students had a higher mean science competency score (M = 11.80, SD = 2.65) compared to tenth-grade students (M = 9.80, SD = 1.82). The effect size (Cohen's d = 0.88) suggests a large practical difference in science competency between the two grade levels. This pattern is consistent with previous studies reporting that competency demands and performance generally increase with educational level and accumulated learning experiences [26,27].

These findings indicate that the developed materials and assessments are sensitive enough to detect grade-level differences in science competency. They also suggest that Grade 10 students may require additional scaffolding, particularly in tasks that demand higher-order reasoning (C4–C6).

3.3.2. Environmental Profile

The Environmental Profile was assessed using a scenario-based Likert questionnaire. Scores were summed across the five profiles, yielding a total score that reflects the strength and consistency of students' environmental attitudes and analytical reflection. Figure 7 displays the average profile scores for both grade levels. While all profiles show relatively positive attitudes, Grade 11 students generally achieved higher total Environmental Profile scores than Grade 10 students.

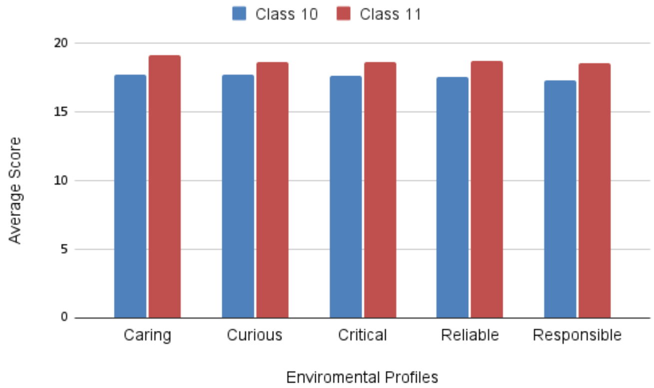


Figure 7. Average score of students' environmental profiles

The independent samples t-test for Environmental Profile scores resulted in $t(28) = -4.77$, $p = 5.2 \times 10^{-5}$, indicating a statistically significant difference between grade levels. Tenth-grade students obtained a lower mean Environmental Profile score ($M = 88.07$, $SD = 3.59$) than eleventh-grade students ($M = 93.80$, $SD = 2.96$). This result is consistent with the one-tailed hypothesis specified in the Methods, namely that Grade 10 students would have lower environmental profile scores than Grade 11 students.

These findings suggest that older students not only demonstrate stronger cognitive science competencies but also more developed environmental attitudes and reflective–ethical reasoning related to microplastics and water pollution. This aligns with research indicating that environmental literacy and affective–analytical competencies tend to increase with age, educational exposure, and contextualized learning experiences.

4. Didactic Reduction Stage

The didactic reduction stage focuses on simplifying and recontextualizing complex microplastics concepts so that they remain scientifically accurate while being accessible to high school students' cognitive levels. Concepts such as microplastic identification, polymer structure, degradation, ecological impact, and mitigation strategies are reconstructed into local and relatable contexts (e.g., river pollution near the school, everyday plastic use) and supported by visualizations and inquiry-based activities [28].

Students' understanding of the teaching materials was evaluated using comprehension criteria grouped into three competencies (C1, C2, and C3), which represent progressively higher levels of conceptual and procedural understanding of microplastics. Table 6 presents the percentage of students in each class who met the understanding criteria for these competencies.

Table 6. Understanding criteria of students

Classes	Undestanding criteria (%)		
	C1	C2	C3
10	44.76	49.52	53.33
11	61.90	56.19	58.89

These results indicate that students in both grade levels achieved moderate levels of comprehension, with Grade 11 students showing better overall understanding. The upward trend across competencies in Grade 10 suggests that the progression of ideas in the teaching materials effectively supports learning, even for younger students. For Grade 11, higher comprehension of fundamental concepts (C1) combined with slightly lower scores in more advanced competencies (C2 and C3) indicates that further reinforcement may be needed in scientific reasoning and data interpretation tasks.

This pattern is consistent with previous findings that link improvements in science literacy to environmental context-based learning experiences [29] and emphasizes the importance of reasoning and evidence-based interpretation skills as highlighted in the PISA 2025 scientific literacy framework [30]. The didactic reduction strategies used in this study—such as incorporating local environmental contexts, visualizing phenomena through figures and experimental data, and engaging students in inquiry-based activities—appear to support both conceptual understanding and environmental awareness [31].

Overall, the results of the didactic reduction stage suggest that the developed microplastics teaching materials meet didactic and functional requirements for enhancing science competency and Environmental Profiles. However, future iterations of the materials should further strengthen Competencies C2 and C3, especially by integrating more basic experimental tasks and structured, data-driven scientific discussions. These refinements are expected to better support students' transition to higher-order competencies (C5–C6) and deepen their engagement with real-world environmental challenges.

CONCLUSION

The validation results of the microplastics-based teaching materials show an improvement in both CVR (from 0.76 in Stage I to 1.00 in Stage II) and I-CVI (from 0.88 to 1.00), indicating full agreement among experts that the revised materials are essential, relevant, and aligned with the targeted science competencies and Environmental Profile dimensions under the PISA 2025 framework.

The results of the science competency assessment demonstrate that Grade 11 students outperform Grade 10 students. The independent samples t-test yielded t(28) = –2.41, p = 0.023, indicating a statistically significant difference in science competency between the two grade levels.

Similarly, the Environmental Profile assessment shows that although all five profiles are generally positive for both groups, Grade 11 students have higher overall Environmental Profile scores than Grade 10 students. The independent samples t-test produced t(28) = –4.77, p = $5.2x10^{-5}$<0.05, confirming a significant difference in environmental attitudes and reflective–ethical reasoning between grade levels.

Overall, these findings indicate that the developed teaching materials and assessment instruments are valid and capable of distinguishing competency levels between students, supporting their potential use in strengthening science literacy and environmental awareness related to microplastics.

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