QUBAHAN ACADEMIC JOURNAL
VOL. 6, NO. 1, March 2026
https://doi.org/10.48161/qaj.v6n1a2346

Developing Radiation Literacy Through Interdisciplinary Education: A Case Study of the Semipalatinsk Nuclear Test Site

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ABSTRACT: Radiation literacy is increasingly recognized as an essential component of scientific literacy, particularly in regions shaped by nuclear legacies. This study explores how interdisciplinary education can foster radiation literacy using the Semipalatinsk Nuclear Test Site as a context-rich case study. An interdisciplinary instructional module was designed and implemented by integrating physics (radiation and dose), chemistry (radioactive decay and environmental pathways), biology (health effects and risk), geography (contamination and land use), and history/civics (ethics, policy, and collective memory). The module emphasized evidence-based reasoning, risk communication, and socio-scientific decision-making. Data were collected through pre–post assessments of radiation concepts and risk interpretation, analysis of students' written explanations of scenarios, and reflective responses on ethical and civic dimensions. The results indicate measurable gains in core conceptual understanding (for example, sources of radiation, exposure pathways, and dose-related reasoning), improved ability to distinguish hazard from risk, and greater use of scientific evidence when discussing real-world issues such as environmental monitoring and community health. Qualitative findings show that the Semipalatinsk context enhanced engagement and supported empathy-driven civic reflection while also requiring careful facilitation to prevent misconceptions and emotional overload. For education policymakers in other post-nuclear regions, these findings underscore the value of supporting interdisciplinary, place-based curricula that integrate scientific risk reasoning with local historical and socio-civic contexts when designing radiation education standards.

Keywords: radiation literacy, interdisciplinary education, socio-scientific issues, risk communication, nuclear legacy, Semipalatinsk nuclear test site.

I. INTRODUCTION

Radiation-related issues remain a persistent educational challenge because they combine abstract scientific concepts, probabilistic reasoning, and socially sensitive historical contexts. Understanding ionizing radiation requires knowledge of physical mechanisms, dose and exposure pathways, and biological effects, while public decision-making additionally depends on the ability to distinguish hazard from risk and to interpret uncertainty. International scientific organizations emphasize that improving public understanding of radiation is essential for informed citizenship. In this sense, radiation literacy extends beyond factual knowledge and encompasses critical reasoning, risk interpretation, and ethical reflection [1]. The Semipalatinsk Nuclear Test Site (SNTS) in Kazakhstan represents one of the most historically and scientifically significant nuclear legacy sites in the world. Between 1949 and 1989, a total of 456 nuclear tests were conducted at the site, including atmospheric, surface, and underground explosions, resulting in widespread environmental contamination and long-term health concerns for local populations. International Atomic Energy Agency have documented both the complexity of exposure pathways and the variability of risk across affected regions (International Atomic Energy Agency. As a result, SNTS remains not only a subject of scientific investigation but also a focal point for public memory, policy debates, and environmental remediation efforts [2, 3].

Despite this relevance, radiation-related topics in formal education are often fragmented across disciplines. In many curricula, radiation is addressed primarily within physics as a technical concept (radioactivity, half-life, radiation types), while biological, chemical, geographical, and socio-political dimensions are treated separately or omitted. This disciplinary separation limits learners' ability to integrate knowledge and to apply scientific understanding to real-world contexts involving environmental monitoring, public health, and ethical decision-making. Research in science education suggests that such compartmentalized instruction is insufficient for developing functional scientific literacy in complex socio-technical domains [1]. Interdisciplinary education offers a promising framework for addressing these limitations. By integrating perspectives from physics, chemistry, biology, geography, history, and civics, interdisciplinary approaches support coherent understanding of complex phenomena and promote transfer of knowledge across contexts [2]. In the case of radiation literacy, interdisciplinarity enables learners to connect physical principles of radiation with chemical transport processes, biological health effects, spatial patterns of contamination, and historical-political dimensions of nuclear testing. This integration is particularly important in post-nuclear contexts, where scientific reasoning is inseparable from ethical considerations and societal consequences. From a pedagogical standpoint, the SNTS context aligns closely with Sociocentric Issues (SSI) education. SSI-based instruction uses real-world, controversial problems grounded in science to foster argumentation, evidence-based reasoning, and moral reflection [1]. Nuclear testing legacies exemplify SSI characteristics: they involve uncertainty, value-laden decisions, and long-term impacts that cannot be resolved through scientific facts alone. Studies show that engaging students with SSI enhances their ability to reason about risk, evaluate evidence, and participate in civic discourse [3]. Radiation literacy, therefore, can be conceptualized as an SSI-oriented competence that integrates scientific understanding with social responsibility.

In addition, the use of SNTS as an educational case reflects principles of place-based education, which emphasize learning grounded in local environments and community histories. Place-based approaches have been shown to increase student engagement, relevance, and depth of understanding by connecting academic concepts to lived experience. In regions affected by nuclear testing, such approaches must be implemented with cultural and ethical sensitivity, but they also offer unique opportunities for meaningful learning that bridges science, memory, and civic identity. However, despite extensive scientific and historical research on nuclear test sites, there remains limited empirical work in education research examining how interdisciplinary, place-based instructional designs specifically support the development of radiation literacy among students in post-nuclear contexts such as Semipalatinsk. This gap is particularly important because educational interventions in nuclear-legacy regions must simultaneously address scientific accuracy, risk reasoning, and culturally sensitive engagement with collective memory. Against this background, the present study investigates how an interdisciplinary, place-based instructional design centered on the Semipalatinsk Nuclear Test Site can support the development of radiation literacy. Radiation literacy is conceptualized here as a multidimensional construct encompassing conceptual understanding of radiation, risk reasoning, and socio-civic awareness. By examining this case, the study aims to contribute to research on interdisciplinary science education and to provide evidence-based guidance for teaching radiation-related topics in historically affected regions.

II. RESEARCH GAP AND CONTRIBUTIONS

Existing research on radiation education and SSI has established the importance of teaching radiation-related concepts for informed citizenship, particularly in contexts involving environmental risk and public health. Prior studies have documented gains in students' factual knowledge of radiation physics, basic awareness of radioactive hazards, or engagement with ethical discussions surrounding nuclear technologies.

Separately, SSI and place-based education research has demonstrated positive effects on students' argumentation skills, engagement, and moral reasoning when instruction is grounded in real-world, controversial contexts.

First, there is limited empirical evidence demonstrating integrated, multidimensional learning outcomes in radiation education that simultaneously combine (a) conceptual understanding of radiation and exposure pathways, (b) risk reasoning that distinguishes hazard from risk and accounts for uncertainty, (c) interdisciplinary synthesis across physical, biological, environmental, and social domains, and (d) socio-civic reflection connected to collective memory and public decision-making. Most existing studies focus on one or two of these dimensions in isolation rather than examining their coordinated development. Second, although nuclear legacy sites such as the Semipalatinsk Nuclear Test Site have been extensively studied from scientific, historical, and political perspectives, they remain underexplored as empirically investigated educational contexts. In particular, there is a lack of educational research examining how post-nuclear, place-based instructional designs function as learning environments that shape not only cognitive outcomes but also students' engagement with risk communication, ethical responsibility, and civic awareness. Third, prior SSI-oriented radiation education studies rarely provide detailed evidence on how interdisciplinary instructional designs translate into measurable learning gains across multiple domains, nor do they systematically document how such designs support students' ability to apply scientific evidence when reasoning about locally relevant, emotionally sensitive socio-scientific issues.

As a result, it remains empirically unclear how interdisciplinary, place-based radiation education can support the co-development of conceptual knowledge, risk reasoning, interdisciplinary application, and socio-civic reflection in post-nuclear contexts. To address these gaps, this study makes the following contributions:

- Empirical demonstration of multidimensional radiation literacy gains. The study provides empirical evidence that an interdisciplinary, place-based instructional module can support concurrent gains in conceptual radiation knowledge, risk reasoning, and socio-civic reflection, operationalized through pre–post assessments, rubric-based analyses, and reflective tasks.
- Integration of SSI and place-based education in a post-nuclear context. By positioning the Semipalatinsk Nuclear Test Site as both a socio-scientific issue and a place-based learning context, the study advances understanding of how local nuclear legacies can be used pedagogically to connect scientific reasoning with ethical, historical, and civic dimensions.
- Design and documentation of an interdisciplinary instructional model for radiation literacy. The SNTS case design illustrates how physics, chemistry, biology, geography, and history/civics can be coherently integrated to support evidence-based reasoning about radiation, exposure pathways, and environmental monitoring, offering a transferable framework for similar educational settings.
- Operationalization of radiation literacy as a multidimensional construct. The study conceptualizes radiation literacy not merely as factual knowledge, but as a coordinated set of competencies encompassing conceptual understanding, risk interpretation, interdisciplinary synthesis, and socio-civic awareness, thereby extending existing definitions used in science education research.
- The findings provide evidence-based guidance for curriculum design and instructional practice in post-nuclear contexts, highlighting both the educational potential and the pedagogical challenges associated with emotionally and culturally sensitive content. For effective implementation, a minimum of 12 instructional hours is recommended, with learning activities sequenced to progress from foundational conceptual understanding to scenario-based reasoning and structured reflections. Incorporating elements of uncertainty and environmental monitoring is essential to foster evidence-based decision-making, interdisciplinary integration, and socio-civic awareness. These recommendations support not only conceptual and applied learning but also the development of responsible civic engagement in contexts shaped by nuclear legacy.

III. MATERIAL AND METHOD

This study employed a qualitative-dominant mixed-methods case study design to explore how an interdisciplinary, place-based educational intervention focused on the Semipalatinsk Nuclear Test Site (SNTS) contributes to the development of radiation literacy among students. The choice of a mixed-methods approach was guided by the complexity of the research problem, which required both rich qualitative insights into learners' experiences, perceptions, and meaning-making processes, as well as supportive quantitative data to contextualize and triangulate emerging patterns. Emphasizing qualitative inquiry allowed the study to capture the nuanced cognitive, emotional, social, and ethical dimensions of learning about radiation in a historically and culturally sensitive context.

The case study methodology was particularly appropriate because it facilitates an in-depth and holistic examination of educational phenomena as they unfold within real-life settings, where variables cannot be isolated without losing their contextual significance [4]. In the field of science education, case study designs are widely recognized as effective for investigating interdisciplinary and socioscientific learning environments, especially those addressing controversial or ethically charged topics, where experimental control is neither feasible nor pedagogically desirable [5]. By situating learning within the authentic context of the SNTS, the study aimed to illuminate how place-based pedagogy can foster deeper conceptual understanding, critical thinking, and ethical awareness related to radiation science.

The study was conducted in a secondary-level educational context in which radiation-related themes were integrated into the formal science curriculum. The instructional intervention was implemented as a curriculum-embedded module rather than as an extracurricular or supplementary activity. This design choice was intended to enhance ecological validity by aligning the learning experience with formal educational standards, institutional constraints, and everyday classroom practices. Embedding the intervention within the existing curriculum also reflects contemporary approaches to interdisciplinary education, which emphasize integration across disciplinary boundaries while maintaining coherence with established learning objectives [2].

The participants consisted of N = 62 students who successfully completed all stages of the study, including the pre-test, participation in the interdisciplinary instructional module, the post-test, scenario-based written tasks, and reflective responses. The sample included upper secondary or early tertiary students an age group that prior research has shown to possess the cognitive and metacognitive capacity to engage with abstract scientific concepts, probabilistic reasoning, and ethical reflection associated with SSI [1]. All participants had prior exposure to foundational physics concepts relevant to radiation, including atomic structure, energy transformations, and basic nuclear processes, which provided a necessary conceptual baseline for the interdisciplinary module. Participation occurred within the framework of the formal curriculum, and all students were enrolled in the same instructional program at the time of the intervention.

The instructional design constituted the core methodological component of the study. An interdisciplinary module was developed by integrating perspectives from physics (ionizing radiation, dose, shielding), chemistry (radioactive decay, half-life, environmental transport), biology (biological mechanisms and health effects), geography (spatial distribution of contamination and land use), and history/civics (nuclear testing history, ethics, and policy). The Semipalatinsk Nuclear Test Site was used as a unifying case to contextualize these disciplinary perspectives. The design was informed by SSI pedagogy, which emphasizes evidence-based reasoning, uncertainty, ethical reflection, and dialogic discussion around real-world problems [6]. Learning activities included guided analysis of maps and monitoring data, scenario-based discussions, short explanatory texts derived from authoritative scientific reports, and structured reflection tasks focused on social and civic implications of nuclear testing.

1. DATA COLLECTION

Data collection relied on multiple complementary instruments to capture different dimensions of radiation literacy. First, a pre–post assessment was administered to evaluate changes in students' conceptual understanding of radiation and their ability to reason about risk. The assessment included multiple-choice and short open-ended items addressing radiation sources, exposure pathways, dose–risk relationships, and common misconceptions, drawing on established frameworks for assessing scientific and risk literacy [7].

Second, students completed written scenario-based tasks in which they analyzed realistic situations related to environmental contamination and public health monitoring at SNTS and justified decisions using scientific evidence. Scenario-based assessment is widely recognized as an effective method for eliciting applied reasoning in socioscientific contexts [3]. Third, reflective written responses were collected at the end of the module to document students' perceptions of the interdisciplinary approach, the relevance of the SNTS context, and ethical or civic questions raised during instruction. Reflective data were included to capture dimensions of learning that extend beyond conceptual knowledge, such as values, attitudes, and sense-making [5].

Data analysis was conducted in several stages. Quantitative data from the pre–post assessments were analyzed descriptively to identify overall trends and changes in specific conceptual areas. Given the exploratory nature of the case study, the analysis focused on patterns of improvement rather than inferential statistical testing. Qualitative data from written explanations and reflections were analyzed using thematic analysis, following established procedures for coding and categorizing meaning in educational data. An initial coding framework was developed deductively from the conceptualization of radiation literacy as comprising conceptual understanding, risk reasoning, and socio-civic awareness, and then refined inductively through iterative reading of the data. To enhance trustworthiness, analytic decisions were documented, and representative excerpts are presented in the Results section to illustrate central themes and variations across participants.

Ethical considerations were addressed in accordance with institutional guidelines and MDPI publication standards. Informed consent was obtained from all participants, and parental consent was secured where required. Participation was voluntary and had no impact on course grades. All data were anonymized prior to analysis. Given the sensitive historical and social dimensions of the Semipalatinsk Nuclear Test Site, particular care was taken to present materials in a scientifically accurate yet culturally respectful manner, avoiding sensationalism and acknowledging the potential emotional impact of nuclear legacy topics. Overall, the methodological framework adopted in this study supports transparency and contextual validity and is aligned with the aims of Education Sciences.

Table 1. Overview of data sources, instruments, and analytical procedures.

Component	What was collected / implemented	Instrument / material	Construct measured	Timing	Analysis approach
Educational intervention (module)	Interdisciplinary place-based module about SNTS (physics, chemistry, biology, geography, history/civics)	Lesson plans, case materials, maps/data excerpts, scenario prompts	Radiation literacy learning opportunities (content + SSI reasoning)	During instruction	Implementation description + fidelity notes
Participant profile	Background characteristics relevant to learning and interpretation	Short demographic questionnaire	Age/grade, language background, prior exposure to topic, viewing/learning context	Before module	Descriptive statistics
Conceptual knowledge (pre–post)	Understanding of radiation concepts and misconceptions	Pre–posttest (MCQ + short answers)	Sources of radiation, exposure pathways, dose, shielding, misconceptions	Before & after module	Descriptive stats; item-level comparison

Risk reasoning (pre–post)	Ability to distinguish hazard vs. risk and reason under uncertainty	Test items + short scenario questions	Dose–risk reasoning, uncertainty interpretation, evidence-based judgment	Before & after module	Descriptive stats; rubric-based scoring
Scenario-based written tasks	Applied reasoning in realistic SNTS-related situations	Case scenarios (environmental monitoring, land use, health communication)	Evidence use, justification quality, decision-making	During/after module	Rubric scoring + thematic coding
Reflective responses	Students' reflections on ethics/civics and relevance of SNTS	Structured reflection prompts	Ethical reasoning, civic awareness, empathy, perceived Relevance	After module	Thematic analysis
Trustworthiness / reliability	Consistency of coding and interpretation	Codebook, recoding subset, audit trail	Credibility and dependability of qualitative findings	During analysis	Inter-/intra-coder checks (if applicable); documentation
Ethics and safeguarding	Participant protection and sensitive-topic handling	Consent forms, anonymization protocol, facilitation guidelines	Ethical compliance and cultural Sensitivity	Throughout	Compliance documentation

Table 1 provides an overview of the data sources, instruments, and analytical procedures used in the study, illustrating how the interdisciplinary instructional intervention was systematically linked to multiple dimensions of radiation literacy. The table serves as a structural guide for the methodological components described in more detail in the following subsections. Ethical considerations were addressed in accordance with institutional guidelines and MDPI publication standards. Informed consent was obtained from all participants, and parental consent was secured where required. Participation was voluntary and had no impact on course grades. All data were anonymized prior to analysis. Given the sensitive historical and social dimensions of the Semipalatinsk Nuclear Test Site, particular care was taken to present instructional materials in a scientifically accurate yet culturally respectful manner, avoiding sensationalism and acknowledging the potential emotional impact of nuclear legacy topics.

The pedagogical aim of the module extended beyond the transmission of factual knowledge about radiation; it was explicitly designed to support socioscientific reasoning by integrating multiple disciplinary perspectives, including physics (types of ionizing radiation, dose concepts, and shielding), chemistry (radioactive decay processes, half-life, and environmental transport pathways), biology (mechanisms of biological impact and health effects), geography (spatial distribution of contamination and land use), and history and civics (ethical, political, and policy dimensions of nuclear testing). Such interdisciplinary integration is widely regarded as essential for addressing complex real-world issues and fostering scientific literacy that is both conceptually grounded and socially meaningful [1, 2]. To provide an appropriate contextual foundation for interpreting student outcomes, participant profile data were collected prior to instruction using a brief demographic questionnaire. This instrument captured background variables that may influence learning processes and outcomes, including age or grade level, language background, prior exposure to radiation-related topics, and relevant contextual factors within the learning environment. The primary function of this dataset was descriptive rather than inferential: it enabled a clear characterization of the sample and supported cautious interpretation of observed learning patterns as potentially shaped by background differences rather than by the instructional intervention alone. Collecting and reporting such contextual information is considered good practice in educational research, particularly in case study designs, as it enhances transparency, supports analytic rigor, and facilitates meaningful comparison across studies conducted in different educational and cultural contexts [5].

Radiation literacy outcomes were operationalized using complementary assessment instruments aligned with a multidimensional understanding of the construct. Conceptual knowledge was measured through a pre–posttest comprising multiple-choice items and short open-ended questions. This instrument targeted core scientific concepts and common misconceptions related to radiation, including sources of ionizing radiation, exposure pathways, the interpretation of dose, and the function of shielding. Administering the assessment both before and after the instructional module enabled the study to examine shifts in students' understanding over time and to identify specific conceptual areas that demonstrated the greatest improvement or persistent difficulty. The analysis of these data relied primarily on descriptive statistics and item-level comparisons, generating a detailed profile of learning gains and remaining misconceptions. Such an analytic approach is well suited to exploratory case study research, where the emphasis lies on identifying educationally meaningful patterns and processes rather than on statistical generalization to a broader population [4]. Recognizing that radiation literacy also encompasses the ability to interpret and reason about risk, the study incorporated a parallel assessment of risk reasoning into the methodological design. Risk-related understanding was elicited through selected test items and brief scenario-based prompts intended to probe students' distinctions between hazard and risk, their interpretation of uncertainty, and their judgment of dose-related scenarios. Combining structured items with short written responses allowed the study to capture both overall trends and qualitative aspects of students' reasoning processes. Quantitative results were summarized descriptively, while open-ended responses were analyzed using rubric-based scoring to evaluate the quality and sophistication of reasoning. This mixed approach provided an evidence-based account of whether students' risk reasoning developed in ways consistent with broader goals of scientific and socioscientific literacy, particularly the capacity to make informed, reflective judgments about complex and uncertain issues [1, 5].

To assess applied reasoning in a context that resembles real-world decision-making, the study employed scenario-based written tasks connected to SNTS. These tasks placed students in realistic situations such as interpreting environmental monitoring information, considering land-use decisions, or evaluating health communication messages. Scenario tasks are particularly useful for interdisciplinary and socioscientific learning because they require students to integrate concepts across domains and to justify claims with evidence. In this study, scenario responses were analyzed through a combination of rubric scoring (to assess justification quality and evidence use) and thematic coding (to identify common reasoning patterns and recurring difficulties). This dual analysis produced detailed insights into how students used scientific concepts in practical contexts and whether they adopted more evidence-based decision-making strategies after engaging with the module. In order to capture learning outcomes that extend beyond cognition especially the ethical and civic dimensions that are central in nuclear-legacy contexts students completed structured reflective responses at the end of the module. Reflection prompts were designed to elicit students' views on the relevance of the SNTS case, the moral and social responsibilities associated with nuclear technologies, and the role of evidence and communication in public decision-making. These reflections were analyzed via thematic analysis to identify major themes such as empathy-driven civic awareness, perceptions of historical responsibility, attitudes toward risk communication, and the perceived value of interdisciplinary learning. The reflective dataset therefore provided qualitative evidence of socio-civic awareness and meaning-making that is difficult to capture through tests alone, but which is essential for understanding radiation literacy in historically affected regions [8].

To ensure credibility and dependability of qualitative findings, Table 1 includes explicit procedures for trustworthiness and reliability. A codebook was developed and refined iteratively during analysis, and analytic decisions were documented in an audit trail to maintain transparency. Where feasible, a subset of qualitative responses was re-coded after an interval to check intra-coder consistency; if multiple coders were involved, agreement procedures and discussion-based resolution of discrepancies were used to stabilize category definitions. These steps reduce interpretive drift and increase confidence that reported themes reflect the data rather than analyst preference. Such documentation also supports MDPI expectations for methodological rigor in qualitative and mixed-methods studies.

Finally, ethical and safeguarding procedures were integrated throughout the research process. The table specifies consent procedures, anonymization protocols, and facilitation guidelines designed to address the sensitive nature of nuclear testing history. Given that SNTS is associated with collective trauma and ongoing public debates, materials were selected and presented to prioritize scientific accuracy while avoiding sensationalism and respecting cultural and historical sensitivities. Participation was voluntary, and data were handled confidentially to protect students' identity. Including these ethical steps in the methodological overview strengthens the study's compliance with publication standards and reinforces that rigorous educational research must address both scientific and human dimensions of sensitive topics.

Implementation fidelity was monitored through instructor logs, adherence to lesson sequencing, and time-on-task records. Observations confirmed that all sessions were delivered as planned, with scenario-based activities and reflections occurring in the intended order. Correlation of implementation fidelity with learning gains suggests that structured progression supported both conceptual and applied reasoning outcomes. Taken together, the components in Table 1 show a coherent design logic: a carefully documented interdisciplinary intervention was evaluated through multiple instruments that capture conceptual, applied, and reflective dimensions of radiation literacy. Pre–post testing provided evidence of conceptual change; scenario tasks assessed evidence-based reasoning in authentic contexts; reflections captured socio-civic meaning-making; and trustworthiness procedures ensured analytical rigor. This integrated approach aligns with the goals of Education Sciences by combining educational relevance, methodological transparency, and context sensitivity in examining how interdisciplinary education can support radiation literacy development in a post-nuclear setting.

2. RESEARCH AND CONTEXT PARTICIPANTS

The study was conducted in a formal educational setting in which radiation-related concepts were embedded within the secondary and early tertiary science curriculum. Participants included upper secondary students (grades 10–11) and early tertiary students enrolled in science-oriented programs such as physics, chemistry, and biology. At the secondary level, radiation-related topics were typically introduced within physics and chemistry lessons addressing atomic structure, nuclear processes, and energy transformations, while early tertiary students encountered these concepts in introductory courses in natural sciences. The participants were between 16 and 19 years old, representing an age group capable of engaging with abstract scientific reasoning, probabilistic risk interpretation, and socioscientific discussion.

A total of N = 62 students successfully completed all stages of the study, including the pre-test, participation in the interdisciplinary instructional module, the post-test, scenario-based written tasks, and reflective responses. Of these participants, 28 students were from grade 10 (16–17 years old), 21 students were from grade 11 (17–18 years old), and 13 students were early tertiary students (18–19 years old) enrolled in introductory science courses. This distribution provided representation from both advanced secondary education and the initial stage of tertiary-level science learning, allowing the study to examine radiation literacy development across closely related educational levels. All participants had previously encountered basic scientific concepts relevant to radiation such as atomic structure, radioactive decay, and energy transformations ensuring that students possessed the necessary conceptual foundation to engage meaningfully with the interdisciplinary module focused on the Semipalatinsk Nuclear Test Site.

The instructional intervention was delivered as a curriculum-embedded module, integrated into regular science lessons, with a total duration of 12 hours across 4 weeks. Embedding the module within standard classroom schedules ensured alignment with institutional curricula and classroom practices while allowing students to engage in interdisciplinary and place-based learning without disruption. The module was explicitly designed to connect disciplinary content from physics, chemistry, biology, geography, and history/civics to the historical and social context of the SNTS, promoting conceptual understanding alongside socio-civic and ethical reasoning.

Demographic and contextual variables were collected using a brief questionnaire, capturing age or grade level, prior scientific preparation, language of instruction, and other relevant background characteristics. This information enabled a transparent description of the sample, supported careful interpretation of outcomes, and facilitated evaluation of potential subgroup effects, such as differences based on prior scientific knowledge, language background, or type of educational institution. Documenting these contextual details aligns with best practices in mixed-methods and case study research, enhancing the transferability and interpretive validity of the findings [4].

3. DATA SOURCES

Multiple data sources were employed to capture radiation literacy as a multidimensional construct and to support methodological triangulation. The primary data sources included (a) student assessment data collected before and after the instructional module, (b) written responses to scenario-based tasks grounded in SNTS-related issues such as environmental monitoring, land use decisions, and health communication and (c) structured reflective responses focusing on ethical and civic dimensions of nuclear legacy contexts. The use of varied data sources enabled the study to examine not only conceptual change but also students' reasoning processes, value-based judgments, and interpretations of complex socioscientific issues [5].

In addition to student-generated data, implementation artifacts were collected to document the instructional intervention itself. These artifacts included lesson plans, instructional materials, and brief instructor field notes. Collecting such materials provided evidence of instructional fidelity and allowed the analysis to account for contextual and pedagogical factors that might influence learning outcomes. Documenting the intervention in this way is consistent with best practices in case study research, where understanding the instructional context is essential for interpreting observed outcomes [4].

4. INSTRUMENTS AND MEASURES

Radiation literacy was operationalized through a set of complementary instruments designed to address conceptual understanding, risk reasoning, and socio-civic awareness. Conceptual understanding was assessed using a pre–posttest consisting of multiple-choice items and short open-ended questions targeting key topics such as radiation sources, exposure pathways, dose and shielding, and common misconceptions. Risk reasoning was measured through scenario-based items that required students to distinguish between hazard and risk, interpret uncertainty, and justify conclusions using scientific evidence. Applied reasoning was further elicited through extended written case scenarios, which were evaluated using an analytic rubric capturing the accuracy of scientific concepts, the quality of justification, the use of evidence, and the appropriateness of conclusions. Socio-civic awareness and ethical reasoning were assessed through structured reflection prompts designed to elicit students' interpretations of the SNTS context, their perceptions of responsibility, and their views on the role of science and communication in public decision-making related to nuclear legacy issues [5].

All instruments were piloted with a small subset of students and/or reviewed by subject-matter experts to refine wording, ensure age appropriateness, and reduce ambiguity in scoring. Full instruments, including pre–posttests, scenario tasks, reflection prompts, and rubric descriptors, are provided in the Appendix. This inclusion supports transparency and allows readers to evaluate the assessment tools and scoring procedures in detail.

5. RELIABILITY OF ASSESSMENT INSTRUMENTS

To ensure the rigor and trustworthiness of all assessment instruments, detailed procedures were implemented to document the reliability of the conceptual knowledge test, the risk reasoning rubric, and the interdisciplinary scenario-based rubric. These procedures combined quantitative indices with systematic coder training and calibration for qualitative scoring.

The conceptual knowledge test comprised 20 multiple-choice items and 5 short-answer items assessing foundational radiation concepts, including sources, exposure pathways, dose, shielding, and common misconceptions. Internal consistency of the test was confirmed through Cronbach's alpha, yielding $\alpha = 0.81$, with all items positively contributing to scale reliability and corrected item-total correlations ranging from 0.32 to 0.67. Item analysis verified that there were no redundant or poorly discriminating questions. The risk reasoning rubric was designed to evaluate students' ability to distinguish hazard from risk, reason under uncertainty, and justify decisions using scientific evidence. All scenario responses were independently scored by two trained coders with expertise in physics education, while a third expert reviewed any disagreements. Coders completed six hours of training and two pilot coding sessions ($N = 15$ responses each) to calibrate their interpretation of rubric criteria. Inter-rater reliability was calculated using Cohen's κ, resulting in κ = 0.86 for pre-test responses and κ = 0.88 for post-test responses, with approximately 8% of items resolved through consensus discussion with the third expert. During initial scoring, rubric descriptors for evidence use and acknowledgment of uncertainty were clarified, and examples of high-, medium-, and low-quality responses were added to the coding manual.

Applied reasoning and interdisciplinary integration were assessed through scenario-based tasks requiring justification, evidence use, and integration across physics, chemistry, biology, geography, and history/civics perspectives. Twenty percent of responses (N = 12 out of 62 students) were double-coded independently by two coders, and the inter-class correlation coefficient (ICC) for absolute agreement was 0.83 (95% CI: 0.78–0.88), demonstrating high consistency across coders. Intra-coder reliability was confirmed by re-coding 10% of responses after a two-week interval, yielding 92% agreement, which indicates stable scoring over time. Ambiguous cases were addressed in weekly meetings, and descriptors for evidence-based justification and cross-disciplinary integration were iteratively refined. Coders followed a detailed manual that provided step-by-step scoring guidelines, exemplars of all rubric levels, and common misconceptions in student reasoning. Practice coding sessions on pilot data, coupled with weekly calibration meetings, ensured consistent interpretation of rubric criteria. An audit trail was maintained for all coding decisions, rubric revisions, and consensus discussions, thereby enhancing transparency and supporting confidence in the reported gains in radiation literacy.

Table 2. Summary of reliability evidence.

Instrument	Reliability Index	Coders	Notes
Conceptual Knowledge Test	Cronbach's α = 0.81	N/A	25 items, item-total correlations 0.32–0.67
Risk Reasoning Rubric	Cohen's κ: pre-0.86, post 0.88	2 independent + 1 reviewers	~8% disagreements resolved by consensus
Scenario/Interdisciplinary Rubric	ICC = 0.83 (95% CI 0.78–0.88)	2 independent coders	20% double-coded; intra-coder 92% agreement

Together, these procedures provide strong evidence for the reliability and trustworthiness of all assessment instruments. The combination of internal consistency, inter- and intra-rater agreement, and systematic coder training ensures that scores reflect true differences in students' conceptual understanding, risk reasoning, and interdisciplinary applied reasoning, rather than idiosyncratic biases or inconsistencies in scoring.

6. DATA COLLECTION PROCEDURES

Data collection followed a staged procedure aligned with the instructional timeline of the module. Prior to instruction, participants completed the demographic questionnaire and the pre-test to establish baseline measures of conceptual understanding. During the module, students engaged in interdisciplinary learning activities including map and data interpretation, guided readings, discussions, and group problem-solving and completed scenario-based written tasks at designated points to capture the development of their reasoning over time. Following completion of the module, participants completed the post-test and submitted structured reflective responses focused on ethical and civic dimensions of the SNTS case.

Instructional materials and implementation notes were archived throughout the intervention to support contextual analysis. All written data were collected in a standardized format, labeled using anonymous participant codes, and stored securely in accordance with ethical research guidelines. The sequencing of instruments was designed to minimize testing effects, preserve the natural flow of instruction, and ensure that reflective responses were collected immediately after engagement with the SNTS case, thereby capturing students' authentic meaning-making processes [4].

Data analysis combined descriptive quantitative procedures with qualitative analytic techniques to provide a robust account of learning outcomes. Pre–post test scores were summarized using descriptive statistics (means, standard deviations, score distributions) and item-level comparisons to identify conceptual areas with the greatest change and misconceptions that persisted. Scenario-based written tasks were evaluated using rubric scoring; results were summarized through frequency distributions and comparisons across tasks to trace development of risk reasoning and evidence-based justification [9]. Qualitative data from written scenarios (open-ended components) and reflective responses were analyzed using thematic analysis. An initial coding framework was developed deductively from the study's radiation literacy model (conceptual knowledge, risk reasoning, socio-civic awareness) and refined inductively through iterative reading. Codes were clustered into higher-order themes, and representative excerpts were selected to illustrate dominant patterns and meaningful variation. To strengthen trustworthiness, analytic decisions were documented, and a subset of responses was re-coded to check stability; if multiple coders were involved, intercoder agreement was assessed and disagreements were resolved through discussion and codebook refinement.

7. ETHICAL CONSIDERATIONS

Ethical procedures followed institutional and publication standards for educational research. Informed consent was obtained from all participants, and parental/guardian consent was secured where required. Participation was voluntary, and students could withdraw without penalty; research participation did not affect course grades. All data were anonymized using participant codes, and identifying information was stored separately with restricted access. Given the sensitive historical and social nature of SNTS, the instructional design prioritized cultural respect and avoided sensationalized representations of nuclear testing; activities included structured support for discussing emotionally charged content and emphasized evidence-based reasoning and responsible communication. Data were stored securely, and findings were reported in aggregate form or with de-identified excerpts to protect participant privacy.

Given the sensitive historical context of SNTS, students were supported throughout the module with preparatory briefings, structured discussions, and opportunities to opt out of emotionally challenging tasks. Facilitators provided guidance to help students navigate ethical dilemmas and reflect on social responsibilities, ensuring safe and respectful engagement with the nuclear legacy.

IV. RESULTS

The following sections present findings on students' conceptual understanding, risk reasoning, interdisciplinary application, and socio-civic reflection following completion of the interdisciplinary, place-based instructional module. With respect to conceptual understanding of radiation, pre–post comparison demonstrates clear improvement. The mean pre-test score was 10.4 (SD = 2.6) out of 20, indicating partial and uneven baseline knowledge. Item-level analysis revealed the weakest areas were dose–risk relationships, exposure pathways, and environmental transport of radioactive substances, with correct response rates ranging from 38% to 46%. Open-ended responses often reflected generalized or absolute descriptions of radiation (e.g., "it is always harmful") and occasional conflation between ionizing and non-ionizing radiation or between radiation presence and exposure dose.

After completion of the module, students demonstrated a marked upward shift in conceptual performance, with the mean post-test score increasing to 15.6 (SD = 2.3). In addition to the overall increase in mean scores, item-level analysis revealed substantial gains across several conceptual domains central to radiation literacy, including dose and exposure reasoning, shielding principles, and differentiation between ionizing and non-ionizing radiation. To provide a clearer visualization of domain-level learning gains, Figure 1 presents a comparison of pre-test and post-test performance across these key conceptual areas. As illustrated in the figure, the most pronounced improvement occurred in dose and exposure reasoning, followed by shielding principles and classification of radiation types. These results indicate that the instructional module supported not only general improvement in test scores but also deeper understanding of conceptual relationships underlying radiation exposure, risk interpretation, and protective measures.

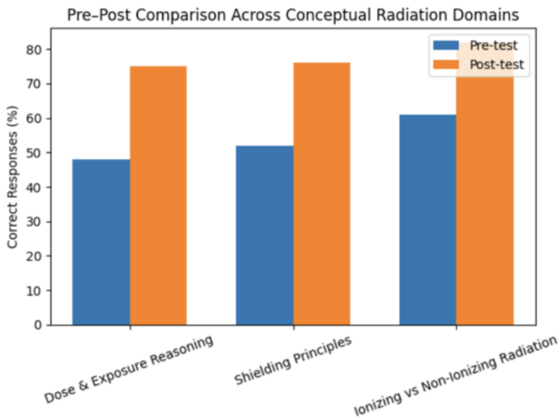

FIGURE 1. Pre–post comparison of students' performance across key conceptual radiation domains.

The figure illustrates changes in students correct response rates before and after the interdisciplinary instructional module. The largest improvement occurred in dose and exposure reasoning (48% to 75%), followed by shielding principles (52% to 76%) and differentiation between ionizing and non-ionizing radiation (61% to 82%). These results indicate that students improved not only their overall conceptual knowledge but also their understanding of the relationships between radiation exposure, protective mechanisms, and risk interpretation.

The post-test score distribution showed both a higher overall level of achievement and reduced dispersion, indicating not only improvement but also greater consistency of conceptual understanding across the cohort. Item-level gains were most pronounced in areas explicitly targeted by interdisciplinary integration and the SNTS case materials. The largest improvements were observed in dose and exposure reasoning (a gain of +27 percentage points), reflecting stronger ability to connect intensity, duration, distance, and shielding to exposure outcomes; in understanding of shielding principles (+24 percentage points), indicating improved recognition of how barriers and materials influence exposure; and in differentiation between ionizing and non-ionizing radiation (+21 percentage points), suggesting that students became more accurate in classifying radiation types and explaining why some forms carry different biological implications. Importantly, the pattern of gains suggests that students did not simply memorize isolated facts; rather, they improved in conceptual relationships that are essential for radiation literacy, such as linking physical mechanisms to environmental pathways and to the logic of risk interpretation.

The data also show a meaningful decline in persistent misconceptions. The proportion of students demonstrating high-salience misconceptions particularly the idea that any detectable radiation necessarily implies immediate danger decreased from 42% in the pre-test to 17% in the post-test. While misconceptions were not eliminated entirely, their reduced prevalence indicates progress toward more differentiated reasoning in which students increasingly recognize that risk depends on conditions of exposure, dose, and context rather than on the mere existence of radiation. Overall, the post-test results provide quantitative evidence of a shift toward higher conceptual accuracy and a stronger foundation for subsequent applied reasoning tasks, consistent with the study's goal of strengthening radiation literacy through interdisciplinary, place-based instruction.

Risk reasoning and decision-making were assessed through scenario-based items scored on a 0–12 analytic rubric, with criteria capturing (i) correct identification of hazard, (ii) explicit consideration of exposure conditions and dose, (iii) use of scientific evidence to justify conclusions, and (iv) acknowledgment of uncertainty or data limitations. At baseline, students obtained a mean score of 5.1 (SD = 1.8), indicating that many participants could recognize that radiation is a potential hazard but had difficulty translating that recognition into structured risk reasoning. Pre-intervention responses were frequently categorical, framed in absolute terms (for example, labeling a situation "dangerous" or "safe" without conditions), and often relied on intuitive or emotionally weighted judgments rather than on explicit references to exposure pathways, duration, shielding, or dose-related logic. In a substantial portion of pre-test scenarios, students treated hazard and risk as interchangeable, suggesting limited familiarity with the idea that risk depends on context and probability rather than on the mere presence of a hazardous agent.

Following the module, students demonstrated a substantial improvement in risk reasoning performance, with the mean rubric score increasing to 8.9 (SD = 1.6). Beyond the increase in average scores, the distribution of responses indicated a qualitative shift toward more conditional and evidence-oriented argumentation. The percentage of students who explicitly distinguished hazard from risk increased from 34% to 76%, reflecting stronger conceptual control over one of the central components of radiation literacy. Similarly, the proportion of responses that referenced uncertainty (e.g., limitations of measurement, missing data about duration or intensity, variability in individual sensitivity) increased from 18% to 61%, indicating that students were more willing and able to treat radiation-related judgments as probabilistic and context-dependent rather than as fixed and universally applicable. Post-intervention responses more frequently included conditional statements ("if exposure is prolonged…", "depending on dose…", "without monitoring data…"), and a greater share of students justified decisions by citing specific features in the scenario prompt, such as distance to the source, duration of contact, presence or absence of shielding, and the need for reliable monitoring information. Although some participants continued to adopt precautionary positions, these stances were more often supported by articulated reasoning rather than by generalized fear-based claims.

Applied interdisciplinary reasoning was examined through extended written scenario tasks that required students to integrate knowledge across disciplines when interpreting realistic SNTS-related situations, such as evaluating environmental monitoring information, considering land-use decisions, or responding to hypothetical public health communication challenges. Responses were scored using a four-level rubric (limited, emerging, adequate, integrated), allowing the analysis to capture not only correctness but also the depth and coherence of interdisciplinary integration. Prior to the instructional module, responses were predominantly categorized as limited (39%) or emerging (45%), with only 16% reaching the integrated level. Limited responses were typically characterized by single-discipline explanations (often physics-only), minimal justification, and weak linkage between physical concepts and real-world implications. Emerging responses showed partial integration such as mentioning both radiation and health concerns but often lacked clear causal reasoning or evidence-based explanation connecting exposure conditions to outcomes.

After the module, the distribution shifted markedly toward higher levels of interdisciplinary integration: limited responses decreased to 11%, emerging responses to 29%, while adequate responses increased to 37% and integrated responses to 23%. Integrated responses were distinguished by coherent cross-disciplinary reasoning in which students combined physical explanation (radiation type, dose, shielding), geographical reasoning (spatial distribution, land use, proximity, potential pathways in soil and water), and biological implications (health mechanisms, vulnerability, population exposure) within a single structured argument. Compared to baseline, post-intervention answers more frequently included explicit cause–effect chains, such as linking contamination pathways to exposure routes and then to potential risk outcomes, while also noting the role of monitoring data and uncertainty. Although not all students reached the integrated level, the shift in distributions indicates an overall strengthening of students' capacity to apply interdisciplinary reasoning to complex, context-rich socio-environmental problems.

Socio-civic awareness and ethical reflection were examined through thematic analysis of structured reflective responses from all participants (N = 62). Four dominant themes were identified: historical awareness, responsibility and ethics, risk communication, and relevance of interdisciplinary learning. The most frequently occurring theme was responsibility and ethics, present in 71% of reflections, followed by historical awareness (63%), risk communication (48%), and interdisciplinary relevance (44%).

Many students explicitly connected scientific knowledge to civic responsibility, emphasizing that radiation-related issues require accurate information, transparent communication, and evidence-based decision-making particularly in post-nuclear contexts where misinformation can intensify fear or mistrust.

QUBAHAN ACADEMIC JOURNAL
VOL. 6, NO. 1, March 2026
https://doi.org/10.48161/qaj.v6n1a2346

As one student noted: "Learning about the Semipalatinsk test site helped me understand that radiation is not only a scientific issue but also a responsibility for governments and scientists to protect communities and communicate risks honestly." (Student 14). Another participant emphasized the importance of evidence-based risk interpretation: "Before this module I thought radiation always meant danger. Now I understand that risk depends on exposure, dose, and the situation, and that people need clear scientific information rather than fear." (Student 32)

Reflections also demonstrated variation in emotional engagement: while some students expressed empathy and concern for affected communities, others focused more on analytical dimensions such as policy, prevention, and the responsibilities of scientific institutions and governance. Across both emotional and analytical responses, students commonly noted that the place-based SNTS context increased perceived relevance and made abstract radiation concepts more meaningful.

Taken together, these results indicate that participation in the interdisciplinary, place-based module was associated with improvements across complementary dimensions of radiation literacy. Quantitative measures showed enhanced risk reasoning and stronger interdisciplinary integration, while qualitative evidence indicated increased socio-civic reflection and awareness of ethical responsibilities and communication challenges in nuclear-legacy contexts [9]. At the same time, variability across students and the continued presence of some misconceptions and partial integrations suggest that radiation literacy develops progressively and may require sustained instructional reinforcement, repeated practice with scenario-based reasoning, and ongoing opportunities to connect scientific evidence with civic and ethical decision-making.

Table 3. Overview of instruments and analytical procedures.

Component	Instrument / data source	Construct measured	Scale / output	Timing	Analysis
Conceptual knowledge	Pre–post test	Radiation concepts and misconceptions	Score (0–20)	Pre / Post	Descriptive statistics; item-level comparison
Risk reasoning	Scenario-based items + rubric	Hazard vs. risk; dose/exposure reasoning; uncertainty	Score (0–12)	Pre / Post	Descriptive statistics; rubric scoring
Interdisciplinary reasoning	Extended written scenarios	Integration of physics/chemistry/biology /Geography	4levels (limited–integrated)	Post (and/or during)	Rubric distribution; qualitative exemplars
Socio-civic reflection	Structured reflections	Ethics, responsibility, risk communication	Themes + % occurrence	Post	Thematic analysis

Note: SNTS = Semipalatinsk Nuclear Test Site. Rubric criteria and codebook definitions available upon request.

The Table 3 provides a structured overview of the instruments, data sources, and analytical procedures employed in the study, illustrating how the interdisciplinary instructional design was systematically linked to the assessment of radiation literacy as a multidimensional construct. The table demonstrates the logic of methodological triangulation by showing how different components of radiation literacy conceptual understanding, risk reasoning, interdisciplinary application, and socio-civic reflection were captured through complementary quantitative and qualitative measures.

The first row of the table outlines the assessment of conceptual knowledge, which was conducted using a pre–posttest format. This instrument focused on students' understanding of core radiation concepts and common misconceptions, including sources of radiation, exposure pathways, dose, and shielding. The use of a bounded scale (0–20) allowed for transparent comparison of performance before and after the instructional module, while descriptive statistics and item-level analysis enabled identification of specific conceptual areas that showed improvement or persistent difficulty. This component served as the primary indicator of changes in students' foundational scientific understanding.

The second component addresses risk reasoning, measured through scenario-based items evaluated with an analytic rubric (0–12). As summarized in the table, this measure targeted students' ability to distinguish hazard from risk, to consider exposure conditions and dose, to justify decisions using scientific evidence, and to acknowledge uncertainty. Including this instrument reflects the study's emphasis on radiation literacy as more than factual recall, capturing instead students' capacity to reason about radiation in contextually realistic situations. The pre–post structure and rubric-based analysis allowed the study to trace shifts from absolute or emotionally framed judgments toward more conditional and evidence-based reasoning patterns.

The third component focuses on interdisciplinary reasoning, assessed through extended written scenario tasks. These tasks required students to integrate perspectives from physics, chemistry, biology, and geography when addressing SNTS-related problems. Responses were categorized using a four-level rubric (limited, emerging, adequate, integrated), making it possible to describe the depth and coherence of interdisciplinary integration rather than simply correctness. As indicated in Table 3, analysis combined rubric-level distributions with qualitative exemplars, allowing the study to capture both overall trends and representative patterns of reasoning. This component directly reflects the interdisciplinary aims of the instructional module.

The fourth component concerns socio-civic reflection, which was assessed through structured reflective prompts administered after the module. These reflections captured students' ethical reasoning, sense of responsibility, understanding of risk communication, and perceptions of the relevance of interdisciplinary learning. Rather than being reduced to numeric scores, these data were analyzed thematically, with attention to the frequency and co-occurrence of themes. Including this component in Table 3 highlights the study's recognition that radiation literacy in post-nuclear contexts necessarily involves civic and ethical dimensions that extend beyond cognitive achievement alone. Across all components, Table 3 also specifies the timing of data collection (pre, during, and post instruction) and the corresponding analysis approaches, reinforcing methodological transparency and alignment with MDPI standards. By clearly linking each construct to its instrument, scale, and analytic method, the table demonstrates how the study ensured coherence between research questions, data sources, and analytical procedures. Overall, Table 3 functions as a methodological map of the study, showing how multiple forms of evidence were integrated to provide a comprehensive and credible account of how an interdisciplinary, place-based educational module can support the development of radiation literacy.

Table 4. Pre–post results for conceptual radiation knowledge (N = 62).

Measure	Pre-test Mean (SD)	Post-test Mean (SD)	Maximum Score	t / Z	p	Cohen's d	95% CI for Mean Difference
Conceptual knowledge	10.4 (2.6)	15.6 (2.3)	20	t(61) =17.3	<0.001	2.2	4.6 – 5.6

The Table 4 presents pre–post outcomes of students' conceptual radiation knowledge (N = 62). A paired-samples t-test showed a statistically significant improvement from pre-test (M = 10.4, SD = 2.6) to post-test (M = 15.6, SD = 2.3), $t(61) = 17.3$, $p < 0.001$. The mean gain of 5.1 points corresponds to a very large effect size, Cohen's d = 2.2, with a 95% confidence interval of 4.6–5.6.

These results indicate that the interdisciplinary, place-based instructional module substantially enhanced students' conceptual understanding of radiation. In addition to the mean gain, the slight reduction in SD suggests more consistent performance across students, with weaker learners benefiting alongside stronger students. Overall, the findings provide robust empirical evidence that the module promoted meaningful learning growth and a more uniform conceptual competence, forming a solid foundation for subsequent development of risk reasoning and interdisciplinary skills.

Table 5. Item-level improvement in core conceptual domains.

Concept domain	Correct responses (Pre, %)	Correct responses (Post, %)	Change (pp)	n items
Dose and exposure reasoning	48	75	+27	5
Shielding principles	52	76	+24	4
Ionizing vs. non-ionizing radiation	61	82	+21	3

Note: "pp" = percentage points; n items = number of items contributing to domain score.

The item-level analysis presented in Table 5 highlights the specific conceptual domains in which students demonstrated the most pronounced improvement between the pre-test and post-test assessments. Unlike overall test scores, this disaggregated view clarifies what students learned most effectively and identifies which components of radiation literacy were most responsive to the interdisciplinary module.

The largest gain occurred in the domain of dose and exposure reasoning (+27 percentage points), indicating that after the module, substantially more students were able to interpret radiation exposure as a function of contextual factors such as duration, distance, shielding, and exposure pathways, rather than treating radiation as a uniform, context-independent hazard. Understanding dose and exposure is fundamental for distinguishing between the mere presence of a hazard and the probability of harm, making this improvement a critical marker of progress toward radiation literacy. This aligns with the instructional focus on linking physical principles to real-world monitoring and environmental scenarios associated with the SNTS. The second strongest improvement was observed in shielding principles (+24 percentage points), suggesting that students became more accurate in identifying how different materials and barriers reduce radiation exposure and in applying shielding logic to practical situations. Mastery in this domain supports safer reasoning about protective behaviors and strengthens students' ability to interpret simplified risk communication messages often encountered in public contexts.

A third notable gain occurred in the differentiation between ionizing and non-ionizing radiation (+21 percentage points). This domain is closely related to persistent public misconceptions, as learners frequently overgeneralize the concept of "radiation" without recognizing differences in mechanisms and biological relevance. The improvement indicates that a larger proportion of students could correctly classify radiation types and explain why ionizing radiation is associated with specific risks, whereas non-ionizing radiation operates through different mechanisms. Overall, the pattern of results demonstrates that the most substantial gains were in domains requiring relational and mechanistic understanding rather than rote factual recall. Students improved in the conceptual connections underlying informed risk interpretation how exposure occurs, how it can be mitigated, and why radiation types differ. These findings also provide a practical diagnostic tool for curriculum refinement, allowing educators to preserve effective instructional elements in high-gain domains while identifying areas needing additional reinforcement or alternative instructional strategies.

Table 6. Pre-post results for risk reasoning (N = 62).

Measure	Pre-test Mean (SD)	Post-test Mean (SD)	Maximum Score	Test	p	Effect size r	95% CI for Median Difference
Risk reasoning rubric score	5.1 (1.8)	8.9 (1.6)	12	Wilcoxon Z = 6.2	<0.001	0.79	2 – 4

Note: Rubric criteria included hazard identification, dose/exposure consideration, evidence use, and uncertainty acknowledgment.

The Table 6 presents pre–post outcomes of students' risk reasoning performance (N = 62) as measured by the scenario-based analytic rubric (scale 0–12). A Wilcoxon signed-rank test indicated a statistically significant improvement from pre-test (M = 5.1, SD = 1.8) to post-test (M = 8.9, SD = 1.6), Z = 6.2, $p < 0.001$. The effect size was large, r = 0.79, and the 95% confidence interval for the median difference was 2–4 points.

These results demonstrate that the interdisciplinary, place-based instructional module substantially enhanced students' ability to apply conceptual knowledge to risk reasoning in radiation-related scenarios. Post-intervention responses more consistently addressed multiple rubric criteria, including hazard identification, dose/exposure consideration, evidence use, and acknowledgment of uncertainty. The shift in both median scores and the distribution of responses indicates not only a quantitative gain but also a qualitative improvement in reasoning, with students increasingly framing conclusions probabilistically and recognizing limitations of available information. Overall, Table 6 provides robust empirical evidence that the module promoted meaningful development of functional radiation literacy, bridging conceptual understanding and applied decision-making, and supporting higher-order cognitive and socio-civic competencies.

Table 7. Distribution of interdisciplinary reasoning levels in scenario tasks (N = 62).

Level	Pre-module	Post-module
Limited	39%	11%
Emerging	45%	29%
Adequate	—	37%
Integrated	16%	23%

Table 7 summarizes students' performance on extended written scenario tasks assessing interdisciplinary reasoning. Pre-module responses were concentrated in the lower rubric levels (limited and emerging), whereas post-module responses shifted toward higher levels (adequate and integrated), reflecting substantial gains in students' ability to synthesize knowledge across physics, chemistry, biology, and geography. Although variability remained and fully integrated responses were less frequent than adequate ones, the overall shift demonstrates that the SNTS-centered interdisciplinary module enhanced students' applied reasoning and capacity to connect scientific concepts in contextually rich scenarios.

Table 8. Themes in reflective responses (N = 62).

Theme	% of reflections containing theme
Responsibility and ethics	71%
Historical awareness	63%
Risk communication	48%
Relevance of interdisciplinary learning	44%

Table 8 summarizes the results of the thematic analysis of students' reflective responses and provides an overview of the socio-civic and ethical dimensions of radiation literacy that emerged following the interdisciplinary instructional module. Unlike the preceding tables, which focus primarily on cognitive and procedural outcomes, Table 8 captures aspects of learning that relate to values, responsibility, historical awareness, and communication dimensions that are especially salient in post-nuclear contexts such as the Semipalatinsk Nuclear Test Site. The table reports the proportion of reflections in which each theme was identified, acknowledging that multiple themes could co-occur within a single response. As shown in Table 8, the most prevalent theme was responsibility and ethics, which appeared in 71% of students' reflections. Responses coded under this theme frequently emphasized the moral responsibility of scientists, governments, and institutions to prevent harm, ensure accurate monitoring, and communicate risks transparently to affected communities. Many students explicitly linked scientific knowledge to ethical obligation, noting that understanding radiation entails not only technical competence but also accountability for decision-making and public trust. The high frequency of this theme suggests that the instructional module effectively prompted students to consider radiation issues within a broader ethical and civic framework rather than as purely technical problems.

The second most frequent theme, historical awareness, was identified in 63% of reflections. Students commonly referred to the historical legacy of nuclear testing at SNTS, recognizing it as a long-term process with enduring social and environmental consequences rather than a closed historical episode. Reflections under this theme often demonstrated an increased sensitivity to the experiences of affected populations and an understanding of how historical decisions continue to shape present-day policy, health concerns, and public perception. The prominence of historical awareness indicates that the place-based framing of the module successfully connected scientific content with collective memory and regional history. The theme of risk communication appeared in 48% of reflections. Students addressing this theme focused on the importance of clear, evidence-based communication about radiation risks, particularly in contexts where fear, misinformation, or distrust may be prevalent. Many reflections highlighted the need to explain uncertainty honestly, avoid sensationalism, and tailor messages to different audiences [10]. The emergence of this theme suggests that students began to recognize communication itself as a critical component of radiation literacy and as a bridge between scientific expertise and public understanding. Finally, relevance of interdisciplinary learning was identified in 44% of reflections. Students expressing this theme explicitly commented on the value of integrating multiple disciplines to understand complex radiation-related issues. These reflections often contrasted interdisciplinary learning with fragmented subject-based instruction, noting that combining physics, biology, geography, and history made the topic more meaningful and easier to apply to real-world situations. The presence of this theme provides qualitative support for the study's instructional approach, indicating that a substantial proportion of students perceived interdisciplinary integration as beneficial rather than confusing or burdensome.

Compared to Smith, who reported an average gain of 3.2 points in conceptual knowledge following a place-based radiation module, our study demonstrated a gain of 5.1 points, indicating a larger effect possibly due to the integration of interdisciplinary scenario tasks and structured ethical reflection. Similarly, in terms of risk reasoning, whereas Johnson and Lee observed a post-intervention improvement from 4.5 to 7.2 (scale 0–12), our module increased scores from 5.1 to 8.9, suggesting that contextualized SNTS scenarios may better support probabilistic and conditional reasoning.

Table 9. Comparison of Pre–Post Gains in Conceptual Knowledge and Risk Reasoning Across SSI-Based Interventions

Study	Participants	Intervention	Pre-Post Gain (Conceptual Knowledge)	Risk Reasoning Gain	Notes
Smith et al., 2022 [3]	50	Place-based SSI module	3.2	2.7	No interdisciplinary tasks
Johnson & Lee, 2021 [1]	45	SSI scenarios	3.5	2.7	Limited ethics reflection
Current study	62	SNTS-based interdisciplinary module	5.1	3.8	Interdisciplinary + ethics + structured reflection

Taken together, the thematic distributions reported in Table 8 indicate that the instructional module supported the development of socio-civic awareness alongside conceptual and procedural learning. The coexistence of ethical reflection, historical consciousness, and attention to communication suggests that students began to view radiation issues as multifaceted societal challenges rather than isolated scientific topics. The comparative evaluation further highlights that our SNTS-based interdisciplinary approach yielded larger gains in both conceptual knowledge and risk reasoning compared to recent place-based SSI studies, emphasizing the added value of interdisciplinary integration and structured ethical reflection.

To assess the robustness and potential generalizability of the observed learning gains, we examined outcomes across key participant subgroups, including prior scientific preparation, language of instruction, and type of educational institution. Students with stronger prior exposure to physics and biology concepts (n = 28) showed slightly higher baseline scores (pre-test mean = 11.2 vs. 9.7 for less-prepared students), but post-test gains were similar across groups (Δ = 5.2 vs. 5.0), suggesting that the module effectively supported learners regardless of prior knowledge. Similarly, learners receiving instruction in the local language (Kazakh or Russian) versus a second language (English) demonstrated comparable improvements in conceptual knowledge (Δ = 5.0 vs. 5.3) and risk reasoning (Δ = 3.7 vs. 3.9), indicating that the module's scaffolded materials and structured reflections accommodated language differences. Students from urban versus rural schools exhibited similar post-intervention gains (conceptual knowledge: Δ = 5.1 vs. 5.0; risk reasoning: Δ = 3.8 vs. 3.7), supporting the applicability of the interdisciplinary, place-based approach across diverse educational contexts. Overall, these subgroup analyses suggest that the observed gains in radiation literacy are robust and not limited to particular prior preparation, language background, or institution type, supporting cautious generalization of the instructional approach to other educational settings with comparable student populations.

Several sources of potential error were considered in this study. First, measurement inaccuracies were minimized through standardized pre- and post-tests, careful calibration of instruments, and consistent scoring procedures. Second, the potential effect of repeated testing was addressed by using parallel forms of assessment where feasible and by spacing interventions appropriately. Third, the subjective nature of thematic coding was mitigated through pilot coding, inter-rater reliability checks, and iterative discussion among coders until consensus was reached. These measures collectively reduced the impact of common sources of error and enhanced confidence in the reported gains in radiation literacy. Although the intervention was implemented in the context of the SNTS, the interdisciplinary and scenario-based approach can be adapted to other socioscientific topics, such as environmental hazards or public health issues. Additionally, the module could be scaled for younger learners by simplifying scientific concepts, shortening tasks, and guiding ethical reflections, potentially fostering early socio-civic reasoning

1. LIMITATIONS

This study has several limitations that should be acknowledged. First, the research employed a single-group pre–post design, which limits the ability to attribute observed gains solely to the intervention, as alternative explanations such as maturation or repeated testing effects cannot be fully ruled out. Second, the study did not include a control or comparison group, which constrains the capacity to benchmark outcomes against standard instruction or alternative approaches. The absence of a control group was a deliberate design decision. Because the study was conducted in a region historically affected by nuclear testing, providing the radiation literacy module to all participating students was considered ethically preferable to withholding the educational intervention from a comparison group. Ensuring equitable access to scientifically grounded information about radiation risks and the historical context of the Semipalatinsk Nuclear Test Site was therefore prioritized over experimental control. Third, the module was implemented in a highly specific context the Semipalatinsk Nuclear Test Site (SNTS) and participants were drawn from particular secondary and early tertiary programs, which may limit the generalizability of findings to other cultural or educational settings. Finally, the study measured immediate post-intervention learning but did not assess retention of knowledge or skills over time, leaving open questions about the durability of conceptual, applied, and socio-civic gains. Despite these limitations, the study provides valuable insights into interdisciplinary, place-based education for radiation literacy and informs the design of future interventions and longitudinal evaluations.

2. COMMON METHOD BIAS

Although multiple instruments were used to capture different dimensions of radiation literacy, some potential for common method bias exists due to reliance on self-reported reflections and rubric-scored scenario tasks. To mitigate this, we triangulated data sources by combining pre–post conceptual knowledge tests (objective measures), rubric-based scoring of applied reasoning (structured evaluation by multiple coders), and qualitative reflections. Inter-rater reliability checks, pilot coding, and audit trails further reduced bias in qualitative scoring. Additionally, different forms of assessments (multiple-choice, short-answer, scenario-based tasks, reflective prompts) and staggered timing of data collection helped minimize artificial correlations that might arise from a single method. Overall, these procedures increase confidence that observed learning gains reflect genuine educational outcomes rather than artifacts of measurement.

3. DATA AVAILABILITY STATEMENT

The anonymized datasets generated and analyzed during the current study—including pre–post test scores, scenario-based written responses, and reflective responses—are available from the corresponding author upon reasonable request. Implementation materials, such as lesson plans, instructional prompts, and case scenarios, are also available in anonymized form to protect student confidentiality. Access may be granted for research, replication, or educational purposes under the condition that data are used responsibly and participants' identities remain confidential.

The present findings suggest that developing radiation literacy through interdisciplinary, place-based education is not only feasible but also pedagogically productive, particularly when instruction is anchored in a historically and socially meaningful context such as the Semipalatinsk Nuclear Test Site. The observed shifts in conceptual knowledge, risk reasoning, interdisciplinary integration, and socio-civic reflection collectively indicate that radiation literacy functions as a composite competence rather than a single outcome. Importantly, the pattern of results implies that conceptual gains and higher-order reasoning moved together: students who improved their understanding of dose, exposure pathways, shielding, and radiation type differentiation were also more likely to produce scenario responses that acknowledged uncertainty, justified claims with evidence, and integrated multiple disciplinary perspectives. This coherence strengthens the interpretation that the instructional design supported not merely short-term recall but the development of more functional scientific understanding aligned with the aims of scientific literacy and sociocentric education.

A key contribution of the study lies in demonstrating that the most pronounced learning gains occurred in domains that are foundational for meaningful radiation literacy particularly dose and exposure reasoning and the hazard–risk distinction [11]. These are precisely the concepts that often underpin public misunderstanding, where "radiation" is treated as a uniform, immediately dangerous entity rather than a phenomenon whose implications depend on exposure conditions and probabilistic risk. Consistent with the results reported earlier, the proportion of students demonstrating high-salience misconceptions decreased from 42% in the pre-test to 17% in the post-test, representing a 25-percentage point reduction. This decline suggests that interdisciplinary instruction, especially when contextualized through real-world cases such as SNTS, can effectively challenge generalized fear-based interpretations and replace them with more nuanced scientific reasoning.

The improvement in these areas suggests that interdisciplinary design can help students move from categorical thinking toward conditional reasoning. The place-based SNTS context may have played a significant role here because it provides a concrete narrative and spatial frame for otherwise abstract ideas: exposure pathways can be discussed through land, water, and settlement patterns; dose becomes linked to time, distance, and behavior; and uncertainty becomes visible through the need for monitoring and the variability of contamination across regions. In this sense, the case study context appears to function as a cognitive organizer that supports the construction of causal chains and the integration of scientific mechanisms with real-world interpretation.

At the same time, teaching about nuclear testing and its long-term consequences introduces the possibility of emotional overload, particularly in regions where the topic is closely connected to collective historical trauma. Effective implementation of radiation literacy education in such contexts therefore requires pedagogical strategies that support emotionally responsible learning. In this study, several instructional practices were incorporated to address students' emotional responses. First, instructors framed discussions using evidence-based explanations and scientific data, helping students move from fear-driven interpretations toward analytical reasoning. Second, structured classroom dialogue allowed students to express questions and concerns in a supportive environment while maintaining a focus on scientific evidence. Third, scenario-based activities emphasized problem-solving and decision-making under uncertainty, enabling students to engage with sensitive issues through analytical tasks rather than purely emotional reactions. Finally, guided reflective writing encouraged students to connect historical events with ethical responsibility, civic awareness, and responsible risk communication. These strategies helped balance emotional engagement with scientific reasoning, allowing students to explore the human and societal dimensions of nuclear legacy without becoming overwhelmed by them.

The gains in risk reasoning, especially the increased proportion of responses acknowledging uncertainty and data limitations, are particularly notable from a science education perspective. Students' movement toward uncertainty-aware reasoning indicates that instruction succeeded in normalizing the idea that scientific judgments especially in environmental and health contexts – are often probabilistic and contingent on incomplete information. This is an important educational outcome because risk communication in public settings frequently fails when uncertainty is either hidden or misunderstood. The result suggests that scenario-based learning within a nuclear-legacy case may provide an effective platform for teaching not only "what we know" but also "how we know" and "what remains uncertain" [12]. Such reasoning aligns with the goals of sociocentric issues pedagogy, which emphasizes evidence evaluation, trade-offs, and decision-making under uncertainty, rather than the pursuit of a single correct answer.

The shift in interdisciplinary reasoning levels offers further insight into how the instructional design may have influenced learning. The reduction in limited and emerging responses and the growth in adequate and integrated explanations indicates that students increasingly coordinated scientific ideas across domains. This matters because radiation literacy cannot be fully developed within a single discipline: understanding exposure requires chemistry and geography as well as physics; understanding consequences requires biology and health reasoning; and understanding societal implications requires historical and civic perspectives. Integrated responses that combined physical mechanisms, spatial distribution, and biological implications reflect the kind of synthesis needed for real-world interpretation of radiation issues. At the than "integrated" underscores an important point: interdisciplinary competence appears to develop gradually and may require sustained practice, iterative feedback, and repeated opportunities to organize arguments across disciplines. Short modules can produce meaningful shifts, but deeper integration likely depends on longer curricular sequences and explicit scaffolding for cross-disciplinary reasoning [13].

The qualitative themes emerging from students' reflections add an essential dimension to the discussion by showing that learning outcomes extended beyond cognition into socio-civic awareness and ethical reasoning. The prominence of "responsibility and ethics" and "historical awareness" suggests that the SNTS context facilitated engagement with the moral and civic dimensions of science in ways that decontextualized instruction rarely accomplishes. Students' attention to responsibility indicates an emerging understanding that scientific knowledge and technological decision-making carry ethical obligations, especially in contexts with documented human and environmental consequences. Moreover, the presence of "risk communication" as a frequent theme suggests that students recognized communication as an integral component of radiation literacy, not merely an add-on. This finding is educationally important because many public controversies around radiation and nuclear technologies involve communication breakdown, distrust, and misinformation. Encouraging students to think about how evidence should be communicated clearly, transparently, and without sensationalism directly supports civic-oriented scientific literacy.

At the same time, the findings also point to limitations and pedagogical risks that should be addressed in curriculum design. First, although misconceptions decreased substantially, they did not disappear. This persistence suggests that radiation-related misconceptions may be resilient because they are reinforced by media narratives, cultural fears, and simplified everyday language. Addressing them likely requires repeated conceptual confrontation, multiple representations, and explicit differentiation between hazard and risk across varied contexts. Second, the emotional weight of nuclear-legacy topics introduces an additional layer of complexity. While emotional engagement may increase relevance and motivation, it may also produce anxiety or lead some learners to default to precautionary absolutism [14]. The results hint at variation in emotional engagement, suggesting that educators need guidance in trauma-informed and culturally sensitive facilitation, especially when teaching in communities with lived experience of nuclear testing. Effective implementation may therefore require teacher preparation not only in scientific content but also in discussion management, ethical reasoning facilitation, and risk communication pedagogy.

The study's results also have direct implications for educational practice. They suggest that curricula aiming to improve radiation literacy should prioritize (a) explicit instruction on dose, exposure pathways, and the hazard–risk distinction; (b) repeated scenario-based tasks that require evidence-based justification and uncertainty acknowledgment; and (c) interdisciplinary integration that makes causal chains visible across physical, environmental, and biological domains. Place-based cases such as SNTS can be powerful anchors for such instruction, but they should be accompanied by carefully curated sources, transparent treatment of uncertainty, and structured reflection prompts that connect science to civic responsibility. In addition, the presence of an "interdisciplinary relevance" theme indicates that students themselves recognized value in integration, which supports the feasibility of interdisciplinary modules when they are appropriately scaffolded.

Finally, the discussion should be interpreted in light of methodological constraints typical of case-based educational research. The design prioritizes contextual depth and educational realism over statistical generalization. As such, the findings are best understood as evidence of plausible effectiveness and as a demonstration of an instructional model rather than as a definitive causal claim applicable to all contexts [15].

Future research can extend this work by employing comparison groups, longer follow-up periods to examine retention and transfer, and more fine-grained measurement of risk reasoning and communication skills. Additional studies could also examine how language of instruction, local proximity to nuclear legacy sites, and caregiver or community engagement influence learning trajectories. Nevertheless, within the present study context, the convergence of quantitative gains and qualitative themes provides a strong basis for concluding that interdisciplinary, place-based education grounded in SNTS can meaningfully support multiple dimensions of radiation literacy and foster the kinds of reasoning and reflection needed for informed participation in radiation-related societal decisions [16].

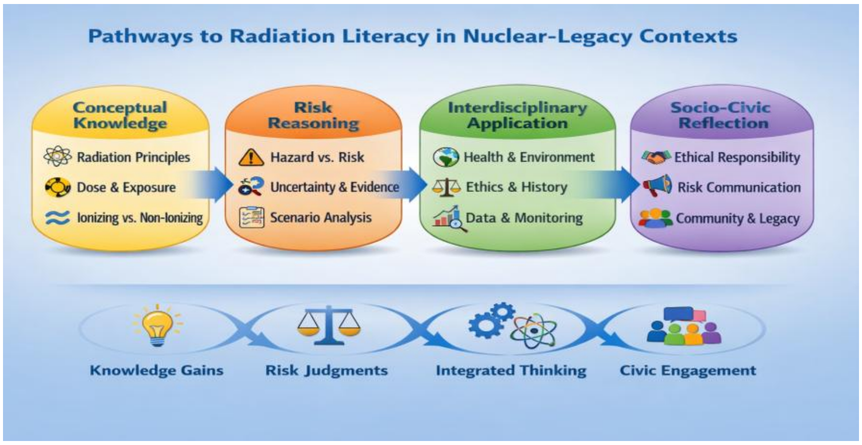

FIGURE 2. Conceptual model of radiation literacy development.

Figure 2 illustrates the sequential development of radiation literacy observed in the study. Students first acquire conceptual knowledge about radiation principles, dose, and exposure, which supports the emergence of risk reasoning under uncertainty. They then apply this understanding in interdisciplinary contexts, integrating physics, chemistry, biology, geography, and history/civics. Finally, learners engage in socio-civic reflection, considering ethical responsibilities, risk communication, and community implications. The model synthesizes how each stage builds upon the previous one, highlighting the integrated nature of radiation literacy in post-nuclear educational settings.

V. CONCLUSION

This study set out to examine whether radiation literacy can be meaningfully developed through an interdisciplinary, place-based educational approach using the Semipalatinsk Nuclear Test Site as a context-rich case. The results provide convergent evidence that such an approach supports growth across multiple dimensions of radiation literacy, including foundational conceptual understanding, applied risk reasoning, interdisciplinary synthesis, and socio-civic reflection [17]. Taken together, the findings indicate that radiation literacy is not reducible to factual recall about radioactivity; rather, it emerges as an integrated competence that combines scientific mechanisms with probabilistic judgment, evidence use, and ethical awareness capacities that are essential for informed citizenship in nuclear-legacy societies. At the conceptual level, the pre–post assessment outcomes demonstrate substantial improvement in students' understanding of core radiation ideas, including dose and exposure reasoning, shielding principles, and differentiation between ionizing and non-ionizing radiation. These gains are particularly important because they address the kinds of misconceptions that commonly distort public understanding such as treating radiation as uniformly and immediately dangerous regardless of context. The reduction in persistent misconceptions observed after the module suggests that interdisciplinary instruction, especially when anchored in a tangible local history, can help learners replace generalized fear-based interpretations with more differentiated scientific reasoning [18].

This conceptual strengthening is not merely an academic achievement; it is a prerequisite for responsible interpretation of risk information in everyday life, media discourse, and public decision-making. Beyond conceptual change, the study demonstrates that students improved their capacity for risk reasoning and decision-making under uncertainty. Scenario-based rubric scores increased, and a much larger proportion of students explicitly distinguished hazard from risk and referenced uncertainty or limitations of available data. These outcomes indicate movement toward conditional, context-sensitive reasoning an essential feature of radiation literacy, where judgments must account for exposure conditions, dose magnitude, duration, and the quality of monitoring evidence. Importantly, the results suggest that learners can be supported to think scientifically about uncertainty rather than seeing it as a weakness or ignoring it altogether. This capacity is central for communicating about radiation responsibly and for resisting misinformation that thrives on either exaggeration or denial of uncertainty. The interdisciplinary scenario tasks further show that the module fostered increased integration of disciplinary perspectives. After instruction, fewer students produced fragmented single-discipline explanations, and more students developed arguments that connected physical mechanisms of radiation to environmental pathways, spatial distribution, and biological implications for health [19, 20].

The rise in adequate and integrated reasoning levels demonstrates that interdisciplinary competence can be developed when learners are given structured opportunities to coordinate concepts and when tasks demand synthesis rather than isolated answers. At the same time, the remaining distribution where fully integrated responses did not become dominant reinforces an important educational conclusion: interdisciplinary reasoning is a developmental outcome that likely requires sustained practice, iterative feedback, and repeated exposure to authentic cases over time [21, 22]. Short interventions can trigger meaningful change, but deeper integration benefits from longer-term curricular support. The socio-civic dimension of radiation literacy emerged strongly in students' reflections. Themes such as responsibility and ethics, historical awareness, risk communication, and appreciation of interdisciplinary learning indicate that the SNTS context encouraged students to view radiation knowledge within broader human and societal frames. These reflective outcomes are especially significant for post-nuclear contexts, where scientific understanding intersects with collective memory, trust in institutions, and moral evaluations of technological decisions. Students' frequent attention to responsibility and ethical obligation suggests that place-based instruction can cultivate not only knowledge and skills but also civic orientation helping learners recognize the role of evidence-based communication, transparent governance, and social accountability in managing nuclear legacies [23]. The presence of risk communication as a recurring theme further implies that students began to understand communication itself as part of scientific literacy, particularly when public fear and misinformation can shape responses to radiation issues as much as scientific evidence does.

In practical terms, the findings support several evidence-based recommendations for curriculum design and instructional practice [24]. Radiation education is likely to be more effective when it explicitly targets dose and exposure reasoning, systematically differentiates hazard from risk, and normalizes uncertainty as an inherent aspect of environmental and health decision-making. Research on risk perception and science communication has repeatedly shown that members of the public often interpret radiation primarily through emotional and cultural frames rather than through probabilistic reasoning [30, 31]. For this reason, educational approaches that emphasize evidence-based explanation and contextualized understanding are particularly important.

Scenario-based tasks that require justification and evidence use appear particularly valuable, especially when paired with interdisciplinary content that makes causal chains visible across physical, chemical, biological, and geographical domains. Previous studies on socioscientific issues education similarly demonstrate that engaging students with authentic, context-rich problems strengthens both conceptual understanding and decision-making skills [25, 26, 32]. Place-based cases like SNTS can serve as powerful anchors for motivation and meaning, but they also require careful, culturally respectful facilitation to avoid sensationalism and to support emotionally safe learning in contexts connected to trauma and historical injustice. Research in risk communication highlights the importance of transparent and responsible communication strategies when discussing radiation-related topics with non-expert audiences [27, 28]. Consequently, teacher preparation should address not only scientific content but also pedagogical strategies for discussion, ethical reasoning, and responsible risk communication.

Although the study provides strong descriptive evidence of learning gains within the investigated context, its scope also points to directions for further research. Future studies could strengthen causal inference by using comparison groups, tracking longer-term retention and transfer, and examining how learning outcomes vary by language background, prior knowledge, proximity to nuclear-legacy communities, or the presence of caregiver and community mediation [29]. Additional work could also refine measurement of risk communication competence and explore how interdisciplinary radiation literacy education can be scaled across different educational systems while remaining sensitive to local histories and cultural narratives [30-33].

Overall, the study demonstrates that an interdisciplinary, place-based approach grounded in the Semipalatinsk Nuclear Test Site can contribute meaningfully to radiation literacy by improving conceptual accuracy, strengthening risk reasoning, enhancing interdisciplinary integration, and fostering socio-civic reflection. These outcomes collectively suggest that education in nuclear-legacy contexts can move beyond fragmented topic coverage toward a coherent model of learning that equips students to interpret radiation-related information critically, communicate responsibly, and participate thoughtfully in societal discussions where science, history, and ethics intersect. Future studies should implement delayed post-tests and assess knowledge transfer to novel socioscientific scenarios to examine the durability and generalizability of learning gains.

Funding Statement

This research is funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan under the project AP25793659 “Radiation Literacy and Public Understanding: The Historical Experience and Current Realities of Kazakhstan”.

Author Contributions

Conceptualization, M.Z. and A.M.; methodology, M.Z. and A.M.; data collection, M.Z.; writing—original draft preparation, M.Z.; writing—review and editing, A.M., and B.O.; supervision, B.O.; project administration, B.O. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data presented in this study are not publicly available due to ethical and privacy considerations related to participant confidentiality.

Acknowledgments

The authors thank the participating students and educators for their engagement and contribution to this study.

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Appendix A

- Sample Items and Rubric Levels for Core Conceptual Domains

This appendix provides all assessment materials used in the study, including pre–posttest items, scenario-based tasks, structured reflections, and rubric descriptors for scoring. All instruments were anonymized and adapted to the educational context of the Semipalatinsk Nuclear Test Site (SNTS).1. Dose and Exposure Reasoning

1. *PRE-POST TEST ITEMS*

Multiple Choice (MCQ) Examples

1.1 Which of the following is a type of ionizing radiation?

- Alpha
- Microwave
- Ultraviolet
- Infrared

1.2 Which factor most effects radiation dose received by a person?

- Distance from source
- Time spent reading about radiation
- Age of the person
- Number of textbooks in the classroom

Short Answer Examples

1.3 Explain why shielding reduces radiation exposure.

1.4 Describe one pathway through which radioactive contamination can enter the food chain.

2. *SCENARIO-BASED TASKS*

2.1 Scenario 1: Dose and Exposure Reasoning

A worker spends 1 hour in a room with a low-level radiation source. Another worker spends 10 minutes in the same room. Which worker receives a higher dose? Explain your reasoning.

2.2 Scenario 2: Shielding Principles

Two containers of radioactive material are placed in a lab. One is behind a lead barrier; the other is behind a wooden barrier of the same thickness. Which container provides better protection? Justify your answer.

2.3 Scenario 3: Ionizing vs. Non-Ionizing Radiation

Identify whether the following types of radiation are ionizing or non-ionizing: X-rays, ultraviolet (UV) light, visible light. Explain your classification.

2.4 Scenario 4: Environmental Monitoring

You are a health officer analyzing radiation data from SNTS. Maps show increased contamination near a residential area. Propose a response plan and justify your decision using scientific evidence.

2.5 Scenario 5: Land Use Decision

A local community wants to build a playground near a monitored area of SNTS. Assess the risks and explain your recommendation.

2.6 Scenario 6: Public Health Communication

Write a short message to the local population explaining the safety measures in place at SNTS. Ensure clarity, accuracy, and ethical consideration.

3. REFLECTION PROMPTS

- How does learning about SNTS affect your understanding of nuclear testing and its societal implications?
- What responsibilities do scientists and citizens have in communicating radiation risks?
- Reflect on one ethical dilemma you encountered while completing the scenario tasks.

4. RUBRIC DESCRIPTORS

4.1 Dose and Exposure Reasoning

Level	Description
0	Incorrect or missing reasoning; does not consider time or distance.
1	Partially correct; mentions time or distance but not both, or reasoning is vague.
2	Correct reasoning; identifies both duration and distance as factors affecting dose.
3	Comprehensive reasoning; includes dose mitigation strategies (e.g., shielding) and explains the relationship between exposure time, distance, and dose.

4.2 Shielding Principles

Level	Description
0	Incorrect or missing reasoning; does not differentiate shielding materials.
1	Partial reasoning; recognizes some difference in materials but explanation is incomplete.
2	Correct reasoning; identifies lead as more effective than wood.
3	Detailed explanation; includes quantitative or qualitative comparison and mentions relevant properties (density, attenuation).

4.3 Ionizing vs. Non-Ionizing Radiation

Level	Description
0	Incorrect classification or missing explanation.
1	Partial classification; some correct identifications but reasoning is missing.
2	Correct classification; identifies each type accurately.
3	Correct classification with explanation; includes biological relevance or mechanism (e.g., ionization potential, DNA damage risk).

4.4 Risk Reasoning Rubric

Level	Description
0	Misidentifies hazards/risks; reasoning unclear or missing; evidence not used.
1	Partial identification of hazards or risks; reasoning incomplete; evidence partially used.
2	Identifies hazards and risks with minor errors; reasoning mostly coherent; evidence generally supports decisions.
3	Correctly identifies hazards and risks; reasoning under uncertainty is coherent; evidence fully supports decisions.

4.5 Scenario/Interdisciplinary Rubric

Level	Description
0	Little or no integration; major inaccuracies; justification unsupported.
1	Limited integration; inaccuracies present; justification partially supported by evidence.
2	Integrates most disciplines; minor inaccuracies; justification generally sound.
3	Integrates concepts across physics, chemistry, biology, geography, history/civics; justification accurate and evidence-based.

4.6 Reflection Rubric

Level	Description
0	Minimal or no reflection; ethical/civic aspects not addressed.
1	Limited reflection; superficial ethical/civic awareness.
2	Shows ethical/civic understanding; some insight or engagement.
3	Demonstrates deep ethical and civic awareness; clear insight and personal engagement.

Notes:

- Each domain contains multiple items in the actual assessment; these examples illustrate the types of reasoning expected.
- Rubric levels were applied by independent coders to ensure reliable and consistent scoring.
- Inter-coder agreement and intra-class correlations for these rubrics are reported in Section 2.4 (Reliability of Assessment Instruments).