

Fostering Chemical Literacy through a Non-Formal Forensic Chemistry Module for 13-Year-Old Students

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Received: 08-25-2025

Abstract

Traditional chemistry education often struggles to engage students due to abstract content and limited contextual relevance. This study explores the impact of a non-formal forensic chemistry module (NFFCM) designed to foster chemical literacy among 13-year-old students through context-based, inquiry-oriented, and student-centred learning. The module included hands-on, problem-driven activities in forensic scenarios, assessed with a mixed-methods pre-post design. Results indicated significant gains in chemical literacy, supported by logical reasoning, self-concept, and motivation. Both situational and individual interest increased, highlighting motivational engagement. Qualitative data emphasized three key pedagogical features: narrative-driven inquiry, active experimentation, and collaborative group work. Students worked safely and independently, applying results to solve the forensic case. Findings suggest that well-structured, open non-formal modules can complement formal education by fostering chemical literacy, deepening conceptual understanding, and enhancing student engagement.

Keywords: Chemical literacy; non-formal education; inquiry-based learning; context-based learning; forensic chemistry

1. Introduction

Concerns about declining student engagement and achievement in science education have led to louder calls for pedagogical innovation. According to PISA 2022 results, average science scores in OECD countries have gradually declined since 2006, although performance stabilized between 2018 and 2022.^{1–3} This trend reflects the challenges of traditional science education and highlights the need for more student-centred, interdisciplinary, and hands-on approaches. Chemistry education has long struggled with traditional teaching methods that present abstract content with limited context and perceived relevance, which in turn diminish student motivation, engagement, and conceptual understanding.^{4–6} Recent research further highlights how these traditional approaches, embedded in rigid curricular structures and didactic instruction, continue to hinder meaningful learning in chemistry classrooms.⁷ Research consistently shows that young people often perceive chemistry as disconnected from everyday life, which reduces their interest and limits their understanding of key scientific concepts.⁸

In response, science education researchers are increasingly advocating for inquiry-based, student-centred

and context-rich pedagogy that considers both the cognitive and affective dimensions of learning.^{9,10} Non-formal educational environments, which are structured learning experiences that take place outside the formal curriculum, are particularly well suited for this purpose. These settings offer students the opportunity to explore scientific ideas in a flexible, hands-on way, which fosters curiosity, autonomy and deeper understanding.¹¹ Structured non-formal science learning environments, such as student laboratory initiatives (Schülerlabor) in Germany and science camps in Finland, illustrate how extracurricular programs can foster meaningful engagement with scientific content.¹² These models emphasize key features such as experimental work, interdisciplinary themes, student autonomy and relevance to everyday life, all of which also form the foundation of the Non-Formal Forensic Chemistry Module (NFFCM) presented in this research. The need for such approaches is further underscored by recent frameworks that call for the development of critical chemistry literacy, linking chemistry education to climate empowerment, agency, and social responsibility.¹³ In this context, forensic science has emerged as a particularly engaging theme for chemistry education due to its interdisciplinary nature and

strong connection to real-world problem solving. Studies have shown that crime scene-based modules can significantly increase students' situational and individual interest in chemistry while promoting a positive attitude towards group work and inquiry-based learning.^{14,15} Moreover, the integration of dynamic visualisations and sub-microscopic representations in these contexts has been shown to support concept development and chemical reasoning.¹⁶ Building on this work, the present research introduces and evaluates a NFFCM designed to enhance chemical literacy of 13-year-old lower secondary school students. The module is based on the PROFILES pedagogical framework^{17,18} and was implemented in five 90-minute sessions that took place outside the formal curriculum but within the school.

2. Theoretical Framework

This research is grounded in self-determination theory (SDT),¹⁹ which posits that students' intrinsic motivation is fostered when the learning environment supports their need for autonomy, competence, and relatedness. The NFFCM was explicitly designed to provide such conditions: students were given opportunities for independent inquiry (autonomy), scaffolded tasks with achievable challenges (competence), and collaborative group work embedded in meaningful forensic narratives (relatedness). In addition, the collaborative design of the module draws on social interdependence theory,²⁰ which emphasizes that shared goals, mutual support, and positive interdependence enhance students' engagement and learning.

The concept of chemical literacy has emerged as a central educational goal, increasingly defined not merely as the accumulation of factual knowledge but as the ability to apply chemical concepts to real-world contexts, make informed decisions, and critically engage with socio-scientific issues.^{13,21} This broader understanding of chemical literacy reflects a global shift from traditional, content-heavy instruction toward more functional, interdisciplinary, and socially meaningful learning goals. Research consistently shows that to perceive chemistry as relevant, students need opportunities to actively construct knowledge, apply it to authentic problems, and recognize its significance in their everyday lives.^{9,22,23} To support these aims, pedagogical approaches such as Inquiry-Based Science Education (IBSE) and context-based learning have gained prominence. IBSE fosters scientific reasoning and problem-solving by engaging learners in authentic investigations where they ask questions, gather evidence, and draw conclusions.^{24,25} In parallel, context-based learning situates abstract chemical concepts within meaningful real-life situations, which not only enhances conceptual understanding but also improves intrinsic motivation and positive attitudes toward science.^{26,27} A growing body of evidence confirms that these strategies can positively impact both cognitive outcomes and affective factors such as student interest, persistence,

and engagement. In addition to reforms within formal education, non-formal learning environments have emerged as valuable complements to traditional classrooms. Settings such as science camps, student laboratories, and extracurricular modules provide flexible, student-centred experiences that nurture curiosity, autonomy, and deeper engagement with scientific content.^{11,12} These environments are particularly effective when they incorporate hands-on experimentation, real-world problem solving, and narrative elements that connect learning to students' lives. Importantly, recent research has drawn attention to the need for inclusivity in these approaches. Students from diverse linguistic backgrounds often face additional barriers to engagement in science learning. Language-sensitive, participatory strategies in non-formal settings can foster equitable access by enabling active participation for all students, regardless of linguistic competence. Such inclusive teaching practices help bridge achievement gaps and contribute to broader efforts to make science education accessible, engaging, and socially responsive.²⁸

Affective and cognitive dimensions in chemistry learning

Research within SDT¹⁹ highlights that learning environments which nurture students' sense of autonomy, competence, and relatedness are particularly effective in fostering such motivation, thereby supporting persistence and deeper engagement.²⁹ In chemistry education, such motivation is often nurtured through active learning, experimentation, and inquiry-based problem solving. Closely intertwined with motivation is students' self-concept in science, which refers to their beliefs about their ability to succeed and strongly influences their engagement, resilience, and persistence in learning.^{30,31} Recent research highlights that both students' perceived competence in science and the quality of their classroom experiences play a crucial role in shaping a strong chemistry self-concept, with particular emphasis on supportive relationships with teachers and the accessibility of chemistry-specific language.^{32,33} In parallel, formal logical reasoning plays a crucial role in students' ability to grasp abstract chemical concepts, formulate hypotheses, and evaluate scientific evidence (Tobin and Capie, 1981). These higher-order thinking skills, closely linked to Piaget's formal operational stage, are essential for navigating complex socio-scientific issues and for developing scientifically informed decision-making. Educational strategies that include inquiry-based tasks, guided reflection, and problem-solving have been shown to effectively promote the development of logical reasoning.³⁴ Another significant factor is collaborative learning, which has been widely recognized for its cognitive, social, and emotional benefits in science education. Collaborative inquiry approaches emphasize shared goals, mutual support, and the co-construction of knowledge, which have been shown to enhance both con-

ceptual understanding and social skills in science education.²⁰ Recent empirical evidence confirms that structured collaborative inquiry, such as Process Oriented Guided Inquiry Learning (POGIL), can significantly enhance students' conceptual understanding in science topics like the particulate nature of matter.³⁵ Finally, students' perception of the motivational quality of the learning environment exerts a considerable influence on their attitudes, engagement, and learning outcomes. Environments that offer contextual relevance, clear goals, opportunities for exploration, and timely feedback have been shown to promote active participation and positive emotional responses.³⁶ Rather than being determined solely by individual characteristics such as gender, research emphasizes that engagement is shaped more profoundly by the psychological and pedagogical features of the learning context.³⁷

Non-formal education in chemistry: Insights from the literature

In response to ongoing calls for innovation in science education, non-formal learning environments have emerged as valuable complements to formal instruction. By simultaneously promoting conceptual understanding, emotional engagement, and social inclusion, these settings help bridge gaps often present in traditional classrooms.^{9,11} Settings such as science centres, museums, student laboratories, and residential science camps enable experiential learning that often goes beyond what is feasible in traditional classrooms.^{38,39} A systematic literature review using the PRISMA methodology identified several key characteristics of effective non-formal chemistry education.⁴⁰ These include inquiry-based tasks, hands-on experimentation, and the integration of real-life contexts, which are pedagogical strategies consistently associated with enhanced conceptual understanding, logical reasoning, increased motivation, and greater interest in science learning.^{24,41} From a cognitive perspective, non-formal environments have been shown to enhance chemical literacy and strengthen students' logical reasoning skills by embedding abstract chemical concepts within meaningful problem-solving situations.²⁴ Simultaneously, such learning settings not only stimulate situational and individual interest but also contribute to a stronger science self-concept by linking experimentation to meaningful contexts.³⁷ Beyond these affective gains, the collaborative structure of non-formal programs provides opportunities for teamwork and shared problem-solving, with students' perceptions of a supportive and motivating environment further reinforcing engagement and persistence in learning.^{7,36}

The role of narrative and forensic contexts in chemistry education

Storyline-based learning has been shown to enhance emotional involvement and knowledge retention by pre-

senting science in meaningful, life-connected, and socially relevant ways.⁴² Forensic science provides a particularly engaging context for chemistry education due to its interdisciplinary nature and strong connection to applied scientific reasoning. Activities such as crime scene analysis, evidence interpretation, and chemical investigation stimulate curiosity while offering concrete opportunities to apply key chemical concepts, including substance identification, reaction analysis, and the interpretation of experimental data. These learning environments align naturally with inquiry-based learning by positioning students as active participants in authentic inquiry. Research confirms that modules built around forensic narratives can significantly enhance both situational and individual interest in science, while also supporting the development of conceptual understanding and collaborative skills.^{14,15} Recent studies also show that forensic-themed media, such as CSI, strongly shape students' interest in forensic science, though often accompanied by misconceptions about the role and rigor of chemistry and analytical science.⁴³ These findings highlight the dual role of forensic narratives in both attracting learners and necessitating careful curriculum design to align expectations with academic realities. The integration of dynamic visualizations and submicroscopic representations within these contexts further strengthens students' chemical reasoning.¹⁶ The pedagogical value of forensic contexts is also supported by SDT,¹⁹ which emphasizes that intrinsic motivation is fostered when learners experience autonomy, competence, and relatedness, all of which are naturally present in carefully designed forensic investigations. In these environments, students develop critical thinking, collaboration, and evidence-based decision-making, while narrative-driven modules integrate socio-scientific issues that foster reflection on ethical, environmental, and societal dimensions of science. Such contexts thus support learning and cultivate scientific agency by encouraging engagement with challenges like sustainability, climate change, and responsible citizenship.¹³

3. Research Questions

Based on the research problem, the research was guided by the following research questions:

RQ1: Which aspects of the NFFCM do students perceive as most impactful for their learning experience in chemistry?

RQ2: Does participation in the NFFCM lead to a statistically significant improvement in students' chemical literacy?

RQ3: Does students' situational and individual interest in learning chemistry change significantly during the NFFCM implementation?

RQ4: Which factors including motivation, logical reasoning, chemistry self-concept, attitudes toward

collaborative learning, perceptions of the motivational learning environment, and gender significantly predict the development of students' chemical literacy during the NFFCM?

4. Experimental

This research employed a quasi-experimental pre-test-posttest design without a control group⁴⁴ within a mixed-methods research framework to evaluate the effectiveness of NFFCM in fostering chemical literacy among lower secondary school students. The combination of quantitative and qualitative methods enabled a comprehensive analysis of cognitive development, affective responses, and social learning processes. Quantitative data were collected through standardized tests and validated questionnaires measuring chemical literacy, logical reasoning, motivation, situational and individual interest, self-concept in chemistry, attitudes toward collaborative learning, and perceptions of the learning environment. Qualitative insights were gathered through semi-structured interviews, classroom observations, and workbook analyses. Methodological triangulation strengthened the reliability and validity of the findings by enabling cross-verification from multiple data sources, although a control group was not implemented in this research design.^{45,46}

Participants

The research was conducted during the 2023/2024 school year with a purposive sample of 100 eighth-grade students (mean age: 13 years) from five Slovenian primary schools. The selection of schools was based on voluntary participation. The sample comprised 48 girls and 52 boys. The NFFCM sessions were delivered after regular school lessons and took place weekly over five 90-minute meet-

ings. All students participated voluntarily with informed parental consent.

Instruments

Eight quantitative instruments and three qualitative methods were used to evaluate students' progression in chemical literacy during the NFFCM implementation. Quantitative instruments measured chemical literacy, logical reasoning, situational and individual interest, self-concept in chemistry, motivation, attitudes toward collaborative learning, and perceptions of the learning environment. Qualitative methods (interviews, workbook analysis, and classroom observations) complemented these data by providing deeper insights into students' engagement and reasoning processes.

The pre-test was a paper-and-pencil assessment consisting of 12 open-ended tasks (maximum 39 points) designed to measure students' chemical literacy prior to the NFFCM, based on knowledge developed in formal education. Tasks covered the Slovenian grade 8 chemistry curriculum, including: (a) chemistry as the study of substances, (b) atoms and the periodic system, (c) bonding, and (d) chemical reactions. Items were mapped onto Bloom's taxonomy to ensure a range of cognitive demands. The test demonstrated good reliability (Cronbach's $\alpha = 0.875$), content validity confirmed by expert review, and objectivity ensured through standardized administration.

The post-test consisted of 10 open-ended tasks (maximum 33 points) aligned with the same core chemical literacy indicators (conceptual understanding, application in context, and reasoning), while also integrating extended content and forensic contexts introduced in the NFFCM. Tasks addressed, for example, separation techniques, chemical safety, and introductory organic chemistry. The same scoring rubric was applied to ensure comparability. Reliability was high (Cronbach's $\alpha = 0.890$), and validity was supported by expert review.

Table 1. Overview of instruments, purpose, timing, and psychometric properties

Instrument	Purpose	Items / Scale	Timing	Reliability (Cronbach's α)
Pre-test on chemical literacy	Assess baseline chemical literacy before NFFCM	12 items, paper-pencil	Before NFFCM	0.875
Post-test on chemical literacy	Assess chemical literacy after NFFCM	10 items, paper-pencil	After NFFCM	0.890
TOLT ³⁴ (Test of Logical Thinking)	Formal-logical reasoning	10 items, dichotomous	Before NFFCM	0.850
SI ⁴⁷ (Situational Interest questionnaire)	Situational interest	10 items, 5-point Likert	After each of 5 sessions	0.860
liSC ⁴⁹ (Individual Interest and Self-Concept questionnaire)	Individual interest and self-concept	10 items, 5-point Likert	After each of 5 sessions	0.941
MoLE ⁴⁹ (Motivational Learning Environment questionnaire)	Perceptions of learning environment	38-items, 7-point Likert	After 1st and 5th session	0.934
MO ^{50,51} (Motivational Orientation questionnaire)	Motivation	25 items, 5-point Likert	Pre- and post-intervention	0.824
CL ⁵² (Collaborative Learning Attitudes questionnaire)	Attitudes toward group work	53 items, 5-point Likert	Before NFFCM	0.933

Although the pre- and post-test items were not identical, both tests assessed the same core chemical literacy concepts acquired in formal education, which allowed for valid comparison of students' progress. The post-test additionally included extended tasks reflecting the forensic contexts and content introduced through the NFFCM, thereby linking students' formal knowledge with new experiences from the non-formal learning environment. It is important to emphasize that forensic science tasks and those assessing concepts taught during the implementation of the NFFCM cannot be included in the pre-test, as students would not yet be able to solve them. The pre-test should therefore focus only on the concepts necessary for students to understand the new content introduced through the NFFCM and were learned in the previous lessons.

An overview of all quantitative instruments, their purpose, timing, and psychometric properties is presented in Table 1.

To complement the quantitative data and gain deeper insights into students' experiences with the NFF-

CM, three qualitative data collection methods were employed: semi-structured interviews, document analysis, and systematic student observations. These methods were selected to explore students' perceptions, engagement, collaborative processes, and conceptual development, thereby contributing to a holistic understanding of the intervention's impact. Individual semi-structured interviews were conducted with 21 purposively selected students following the completion of the NFFCM. The sample was stratified based on observed engagement and performance to ensure the inclusion of diverse perspectives, ranging from highly engaged students to those with moderate or lower participation. The interviews followed a flexible protocol with pre-formulated open-ended questions aimed at eliciting students' views on the learning experience, their involvement in group work, and their overall impressions of the program. Interviews were audio-recorded with consent, lasted approximately 3–5 minutes, and were transcribed verbatim. A thematic analysis approach was applied, combining inductive cod-

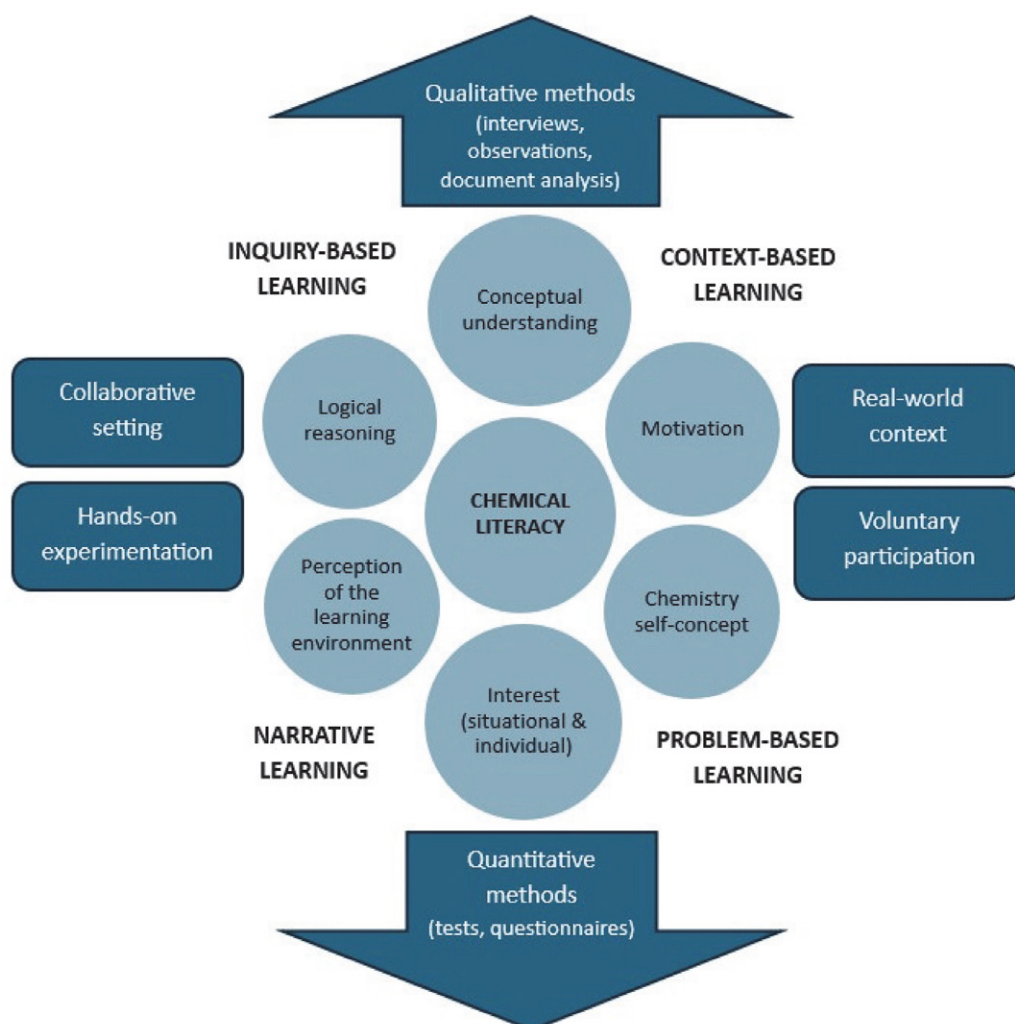


Figure 1: Conceptual model of non-formal chemistry education

ing with deductive coding based on the research's theoretical framework to identify recurring themes and patterns.⁵⁴

In parallel, students individually completed the *Chemical detective* booklet throughout the five-session module. This structured workbook functioned both as a learning guide and as a qualitative data source. Systematic analysis of 100 completed booklets provided insights into students' conceptual understanding, inquiry processes, problem-solving strategies, and reflective thinking. Written responses were coded to assess the accuracy of observations, reasoning, and depth of reflection, offering a complementary perspective on students' learning progression and engagement.

Finally, systematic student observations were carried out during all five NFFCM sessions using pre-designed observation sheets. The focus was on specific behavioural indicators, including adherence to safety protocols, autonomy and competence in experimental work, collaborative interactions, and overall task engagement. Detailed field notes and structured assessments captured both individual and group dynamics. Thematic coding was applied to identify patterns of behaviour and changes in participation over time. Data from these sources were triangulated to strengthen validity and provide a more comprehensive understanding of the module's impact. All qualitative data were coded by the first author using a coding scheme informed by both inductive categories emerging from the data and deductive categories derived from the theoretical framework. To enhance trustworthiness, the coding protocol was systematically applied across data sources, and triangulation of methods was used to support the credibility of the findings.

Research design

To visualize the conceptual underpinnings of this research, Figure 1 presents a model of effective non-formal chemistry education that integrates key pedagogical strategies, cognitive and affective learning goals, and supportive learning environments.

This framework guided the development, implementation, and evaluation of the non-formal forensic chemistry module (NFFCM), designed to foster chemical literacy by embedding real-world forensic contexts into chemistry learning.

In response to persistent gaps in contemporary chemistry education, the NFFCM was conceptualized to incorporate guided-inquiry and context-based learning approaches, grounded in the PROFILES pedagogical framework^{17,18} and informed by insights from a systematic literature review.⁴⁰ The module comprised five consecutive 90-minute sessions (April–June 2024) implemented across five Slovenian primary schools, involving 100 eighth-grade students. Each session introduced a new forensic case aligned with the curriculum, in which students solved problems using core laboratory techniques (e.g., separa-

tion, pH measurement, chromatography, UV examination, fingerprint/hair microscopy).

A bespoke *Chemical detective* workbook provided the backbone of the intervention, offering safety scaffolds, procedural guidance, reflection prompts, and spaces for recording observations and conclusions. It thus served both as instructional support and as a key qualitative data source. Within this framework, students were encouraged to make decisions about evidence handling, interpret results, and collaboratively solve forensic cases. Tasks combined step-by-step guidance for fundamental laboratory procedures with open-ended questions and problem-solving prompts to stimulate reasoning, discussion, and application of chemical concepts. An example of a workbook activity is illustrated in Figure 2.

Concretely, across the five sessions students: (i) tested three unknowns (yellow powder, grey powder, grey crystals) for solubility, magnetism, and purity; (ii) prepared hair slides and compared cuticle features to references; (iii) dusted, lifted, and classified fingerprints and matched them to suspect cards; (iv) ran quick functional-group tests to classify compounds; and (v) carried out thin-layer chromatography on coffee-cup residue, visualised spots under UV and determined caffeine by comparison with a standard.

All observations and decisions were documented in the workbook and aggregated into a cumulative suspect matrix, which scaffolded group conclusions. Students engaged in both individual and collaborative laboratory work and reflective discussions, while the first author ensured instructional consistency, adherence to safety protocols, and alignment with research procedures.

A mixed-methods pretest–posttest design was employed to evaluate cognitive, affective, and social outcomes. Methodological triangulation combined quantitative and qualitative data, enabling both the measurement of learning gains and the exploration of underlying processes. Data collection was embedded into the instructional flow: prior to the first session, students completed a chemical literacy pre-test, TOLT, MO, and CL; after each session they completed SI and IISC; MoLE was administered after the first and fifth sessions; at the end, students repeated the chemical literacy test and MO.

To capture qualitative dimensions, three additional methods were applied: (1) systematic observations during all sessions, focused on engagement, collaboration, and safety adherence; (2) document analysis of 100 completed *Chemical detective* workbooks, focusing on reasoning, problem-solving, and reflection; and (3) semi-structured interviews with 21 purposively selected students, conducted within one week after the final session. Interviews were audio-recorded (with consent), transcribed verbatim, and thematically analysed. Quantitative data were analysed using descriptive and inferential statistics (t-tests, repeated measures ANOVA, correlation analysis, regression modelling), with effect sizes and confidence intervals calculated.

1. ACTIVITY: FORENSIC IDENTIFICATION OF SUBSTANCES

At the crime scene, you have collected three unknown samples: a yellow powder, a grey powder, and grey crystals. As chemical forensic experts, your task is to carefully examine these substances and determine their identity (see Table 2).

Guiding questions for substance identification



First, carefully examine the substances in front of you. In the table, record the properties you can identify by observing the substances with the help of a magnifying glass. In the second part, design an experiment to test the solubility of the collected substances in water, using the laboratory equipment available to you.

Tabel 2: Collected substances found in the classroom

SUBSTANCE	1 	2 	3 
IMAGE	 Fig. 7: https://www.hempatia.si	 Fig. 8: https://www.widerangemetals.com	 Fig. 9: https://hr.delachieve.com
COLOUR			
AGGREGATE STATE			
PARTICLE DISTRIBUTION SCHEME			
PURE SUBSTANCE/ MIXTURE			
MAGNETISM			
METAL/ NON-METAL			

Figure 2: Example of an NFFCM activity.

Qualitative data were thematically analysed using a hybrid inductive–deductive coding approach, aligned with the conceptual framework.

Ethical approval for this research was obtained from the Ethics Committee of the Faculty of Education, University of Ljubljana (No. 18/2018).

Data analysis

Analyses were structured in accordance with the four research questions (RQ). For RQ1, qualitative data from interviews, workbook entries, and classroom observations were thematically coded using a hybrid inductive–

deductive approach. RQ2 was addressed by comparing pre- and post-test scores on chemical literacy using paired *t*-tests and Wilcoxon signed-rank tests, with effect sizes and confidence intervals calculated. For RQ3, changes in situational and individual interest across the five sessions were examined using repeated measures ANOVA with linear contrasts. RQ4 was analysed using correlations and regression models, with logical reasoning, self-concept, motivation, perceptions of the learning environment, collaborative learning attitudes, and gender included as predictors. All quantitative analyses were conducted with significance set at $p \leq 0.05$.

5. Results and Discussion

Key aspects of students' learning experience in the NFFCM

This section addresses the first research question, which examined which aspects of the NFFCM students perceived as most impactful for their learning in chemistry. Three key aspects consistently emerged as central to students' learning experience: (1) experimental work and hands-on learning, (2) the narrative and forensic storyline, and (3) collaborative group work. The most frequently highlighted aspect was the active, hands-on experimental work. Students repeatedly emphasized that conducting chemical experiments themselves allowed them to better understand and retain the content. The opportunity to manipulate materials, observe changes directly, and draw conclusions was described as both engaging and essential for learning. Typical comments included:

"We actually did the experiments ourselves, not just imagined them like in regular lessons."

"Chromatography was my favourite because we discovered something new."

"When I mixed the chemicals and saw the change, it finally made sense."

"Safety gear made it feel real, and I remembered the steps better."

These findings align well-established research on IBSE and context-based learning, which underscores the importance of active engagement for the development of both conceptual understanding and positive attitudes toward science.^{24,25,41} The connection to authentic, real-life contexts helped students perceive chemistry as meaningful rather than abstract, addressing longstanding concerns about the perceived irrelevance of science curricula.^{1,22,23} Moreover, classroom observations corroborated these perceptions: over 90% consistently followed safety procedures, 62% worked independently (26% occasional help; 12% frequent guidance), and 62% showed high on-task engagement. Workbook entries moved beyond procedure to evidence-based reasoning, indicating that manipulation of materials and direct observation supported conceptualisation. This reflects the role of autonomy and perceived competence in fostering intrinsic motivation, as described by SDT.^{19,25} The second impactful aspect identified was the narrative context of the NFFCM, which framed chemical investigations within a forensic storyline. Students reported that solving a mystery using chemical evidence to identify a fictional culprit was not only entertaining but also enhanced their motivation and understanding by giving each experiment a clear purpose.

"The story made everything more fun. We weren't just doing experiments-we were detectives trying to solve a case."

"Because of the story we understood what each experiment was for."

"Linking results to the suspect made me check the data more carefully."

"I liked that every test moved the story forward."

This finding is consistent with research emphasizing the motivational power of narrative contexts in science learning.^{14,42} Embedding chemical concepts within a coherent storyline situates learning within a meaningful framework, facilitating both cognitive engagement and emotional involvement.¹⁶ From a theoretical standpoint, this aligns with recent calls for developing "critical chemical literacy" that links science learning to real-life societal issues and decision-making.¹³ By integrating a narrative that mirrors real-world forensic challenges, the module helped students perceive chemistry as both relevant and applicable beyond the classroom. Document analysis showed strong integration of data and narrative, 92% workbooks were fully completed, 84% had correct interpretation of experimental results, and 87% linked findings to the case by identifying the fictional culprit. Many entries explicitly used experimental evidence to justify claims rather than listing steps, signalling purposeful sense-making within the narrative frame.

The third major theme was the importance of collaborative learning. Many students valued working in small groups, noting that this allowed them to exchange ideas, help each other, and make sense of the experimental tasks collectively.

"It was good to work together because when I didn't understand something, someone else explained it, and we figured it out together."

"We shared jobs - one measured, one wrote, one checked the time."

"Hearing other ideas helped me correct my mistake."

These perceptions are consistent with social interdependence theory²⁰ which highlights the role of peer interaction and cooperation in fostering deeper learning and engagement. Collaborative inquiry, as evidenced in POGIL-type approaches,³⁵ has been shown to not only enhance conceptual understanding but also promote essential communication and teamwork skills. While most students viewed group work positively, a minority noted uneven contribution and occasional noise, which are challenges commonly reported in cooperative learning environments.⁵³

"Sometimes not everyone worked, and it got noisy."

"I prefer working alone so we don't argue."

These findings suggest the importance of structuring group activities carefully to ensure equitable engagement, particularly in non-formal settings where students may be less accustomed to collaborative inquiry.

Improvement in students' chemical literacy

This part addresses the second research question, focusing on whether participation in the NFFCM led to a statistically significant improvement in students' chemical literacy. To address this question, students completed two specifically designed and validated assessments: the pre-test on chemical literacy (administered before NFFCM)

and the post-test on chemical literacy (administered after NFFCM).

Descriptive statistics revealed that students' mean chemical literacy score increased from $M = 54.2\%$ ($SD = 22.4\%$) before implementing NFFCM to $M = 68.0\%$ ($SD = 18.4\%$) after completing the NFFCM, representing a substantial gain of 13.8 percentage points, while the decrease in standard deviation indicates greater consistency in students' performance following the intervention. The Shapiro-Wilk test confirmed that both pre-test and post-test results did not significantly deviate from normality ($p > 0.05$), which justified the application of parametric analyses. The paired-sample t-test showed that this improvement was statistically significant ($t(99) = -8.69$; $p \leq 0.001$), with a Cohen's d effect size of 0.87, indicating a large educational effect. The 95% confidence interval for the difference in mean scores (-16.94 to -10.65) did not include zero, further confirming the statistical significance of the observed gains. To strengthen the robustness of these findings, the Wilcoxon signed-rank test was also conducted, producing consistent results ($Z = -8.44$; $p \leq 0.001$), which confirmed the validity of the observed improvement even in the case of minor deviations from normality. Pre-post gains in chemical literacy ($M: 54.2\% \rightarrow 68.0\%$; $t(99) = -8.69$, $p < .001$, $d = 0.87$) together with reduced dispersion ($SD: 22.4 \rightarrow 18.4$) indicate improvement and more even performance. Analysis of task-level results further showed that these gains were evenly distributed across the chemistry concepts assessed. No single content area emerged as disproportionately stronger or weaker, suggesting that the NFFCM supported a broad and balanced development of chemical literacy rather than improvements limited to specific topics. This pattern is consistent with evidence that hands-on, inquiry tasks in authentic contexts enhance conceptual learning^{24,25,41} and with context-based approaches that support transfer to applied problems.^{22,26} The module's autonomy and competence supportive features offer a plausible mechanism in line with SDT.¹⁹

Changes in situational and individual interest

In relation to the third research question, we examined whether students' situational and individual interest in learning chemistry changed statistically significantly over the course of the NFFCM. To address this question, situational interest was measured five times using the situational interest questionnaire (SI), while individual interest in chemistry was assessed concurrently through the individual interest questionnaire (IiSC). Descriptive statistics revealed a consistent upward trend in situational interest throughout the intervention. The mean score increased from $M = 3.58$ ($SD = 0.79$) after the first session to $M = 3.87$ ($SD = 0.71$) after the final session (Figure 3).

Median values remained stable at 4, indicating a consistently high level of situational engagement. The reduc-

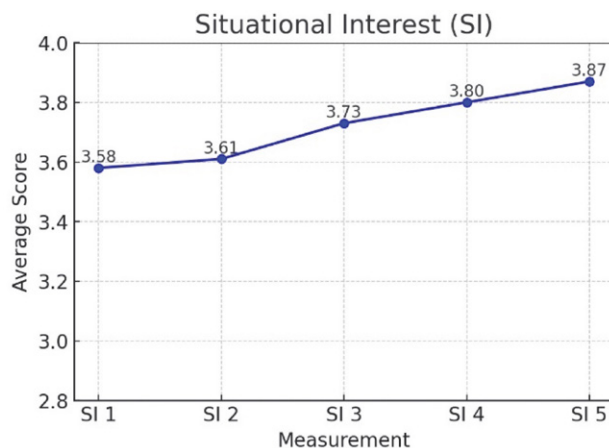


Figure 3: Development of students' situational interest (SI) across the five NFFCM sessions.

tion in standard deviation over time suggests increased uniformity in student responses, with more students expressing higher levels of situational interest as the program progressed. A repeated measures ANOVA confirmed that this increase was statistically significant (Wilks' Lambda = 0.728; $F(4,87) = 8.12$; $p \leq 0.001$; $\eta^2 = 0.27$), indicating a medium effect size. A linear contrast further confirmed a statistically significant positive trend ($F(1,90) = 26.2$; $p \leq 0.001$; $\eta^2 = 0.23$), reflecting a steady enhancement of situational interest across the five sessions. Similarly, individual interest, which reflects students' enduring personal interest in chemistry, also demonstrated a statistically significant improvement. The mean individual interest score increased from $M = 2.98$ ($SD = 0.89$) to $M = 3.42$ ($SD = 0.81$) over the five measurements (Figure 4). Although the median remained stable at 3, the decreasing variability in responses suggests a growing consistency in students' positive attitudes toward chemistry.

The repeated measures ANOVA for individual interest showed a highly statistically significant effect of time

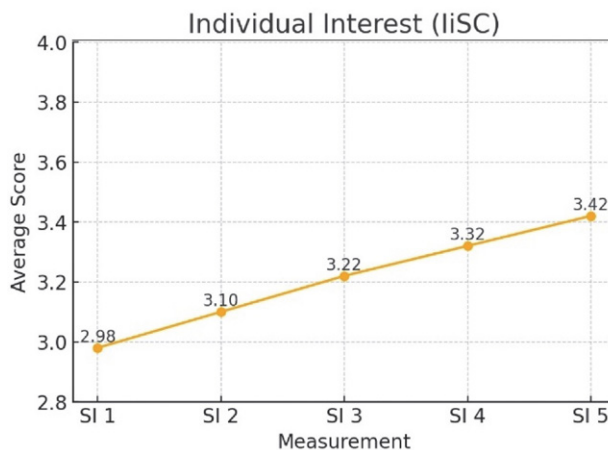


Figure 4: Development of students' individual interest (IiSC) across the five NFFCM sessions.

(Wilks' Lambda = 0.582; $F(4,84) = 15.1$; $p \leq 0.001$; $\eta^2 = 0.42$), indicating a large effect size. A linear contrast further confirmed this growth ($F(1,87) = 54.2$; $p \leq 0.001$; $\eta^2 = 0.38$), reflecting a consistent and meaningful increase in students' individual interest as the module unfolded. These findings align with model of interest development, which posits that situational interest, initially sparked by engaging and meaningful experiences, can evolve into individual interest through repeated positive interactions with the subject matter.⁵⁵ The design of the NFFCM, which integrated hands-on experimentation, collaborative inquiry, and a narrative-driven forensic context, provided precisely the kind of emotionally engaging and cognitively stimulating environment that supports this developmental trajectory. The statistically significant increases in both situational and individual interest underscore the NFFCM capacity to engage students not only cognitively but also emotionally and socially, dimensions that are crucial for sustaining long-term motivation and active participation in science learning.^{4,19}

Predictors of chemical literacy development

Finally, the fourth research question addressed which individual and contextual factors significantly predicted students' development of chemical literacy during the NFFCM. Analyses focused on six predictor variables: logical reasoning, chemistry self-concept, autonomous motivation, perceptions of the learning environment, attitudes toward collaborative learning, and gender.

Correlations showed that students' logical reasoning abilities were most strongly related to post-intervention chemical literacy, with a Spearman's rank correlation coefficient of $r_s = 0.54$ ($p \leq 0.001$). This indicates that students with higher formal reasoning abilities were significantly more likely to achieve better results in chemical literacy, confirming the essential role of cognitive readiness in science learning as highlighted in the literature.³⁴ Similarly, students' chemistry self-concept showed a strong and statistically significant positive correlation with chemical literacy ($r = 0.49$; $p \leq 0.001$), underscoring the importance of learners' beliefs about their competence in shaping academic success. Students' motivation, measured after the intervention, was also significantly related to chemical literacy outcomes ($r = 0.40$; $p < 0.001$), indicating that higher levels of autonomous motivation contributed to better performance. Furthermore, students' perception of the motivational learning environment demonstrated a moderate but significant correlation with post-test results ($r_s = 0.32$; $p \leq 0.001$), suggesting that learning environments characterized by autonomy support, relevance, and collaboration positively influenced achievement. In contrast, students' attitudes toward collaborative learning were not significantly associated with chemical literacy ($r_s = 0.12$; $p = 0.242$), nor did gender significantly predict outcomes, although fe-

male students achieved slightly higher mean scores ($M = 71.46\%$) compared to their male peers ($M = 64.74\%$), with this difference failing to reach statistical significance ($t(98) = -1.848$; $p = 0.068$). To further explore these relationships, simple linear regression analyses were conducted. Logical reasoning abilities accounted for the largest proportion of variance in chemical literacy ($R^2 = 0.30$; $p \leq 0.001$), followed by chemistry self-concept ($R^2 = 0.24$; $p \leq 0.001$) and post-intervention autonomous motivation ($R^2 = 0.16$; $p \leq 0.001$). The perception of the learning environment explained 11.6% of the variance ($R^2 = 0.12$; $p \leq 0.001$). Neither students' attitudes toward collaborative learning ($R^2 = 0.0020$; $p = 0.242$) nor gender ($R^2 = 0.034$; $p = 0.068$) emerged as significant predictors of chemical literacy development. These findings confirm the strong role of formal reasoning in mastering abstract chemical concepts and engaging effectively in problem-solving, consistent with prior research.³⁴ Chemistry self-concept and autonomous motivation also contributed substantially, in line with SDT accounts linking competence beliefs and autonomous regulation to achievement.^{19,29} Perceptions of the motivational learning environment played a smaller role but aligned with context-based evidence that relevance, structure, and autonomy support enhance learning.^{26,36} In contrast, general attitudes toward collaborative learning were not predictive, suggesting that such measures may not capture in-situ group dynamics and that structured group roles might be required.⁵⁴ Gender did not emerge as a significant predictor.

6. Conclusions

This research evaluated the effectiveness of implementing a non-formal forensic chemistry module (NFFCM) through inquiry-based and context-based learning approaches in fostering chemical literacy among 13-year-old students. The results indicate that participation in the NFFCM was associated with improvements in students' chemical literacy, situational and individual interest, and affective engagement with science learning. By integrating hands-on experimentation, narrative-driven contexts, and collaborative inquiry, the module appeared to support not only cognitive development but also emotional engagement and motivation, both of which are important for immediate engagement and long-term interest in chemistry.

Qualitative findings were particularly valuable in highlighting three pedagogical features as central to students' learning experience: active experimentation, narrative-driven inquiry, and collaborative group work. Predictive analyses further suggested that logical reasoning, chemistry self-concept, and autonomous motivation contributed substantially to students' chemical literacy outcomes, whereas general attitudes toward collaborative learning and gender did not. These findings are consistent

with self-determination theory and prior research emphasizing the importance of both cognitive readiness and affective dimensions in science learning.

For practice, the module's principles can be translated into actionable steps. In schools, short, narrative-anchored practicals with explicit scaffolds for reasoning and structured group roles may be embedded within existing lessons, while non-formal contexts can adopt similar problem-driven activities. Given that stronger gains were linked to higher levels of logical reasoning, chemistry self-concept, and autonomous motivation, instruction may benefit from deliberately cultivating these through routine reasoning tasks, competence-focused feedback, and carefully framed choices with clear goals to support durable improvements in chemical literacy.

7. Limitations and Further Research

While the findings are promising, several limitations point to directions for future research. First, the quasi-experimental pretest-posttest design without a control group limits causal inference; future studies should employ randomized or matched-comparison designs. Second, the purposive and voluntary sample (students from elective chemistry clubs in five Slovenian schools) likely included more motivated participants, reducing generalizability. Replication with larger and more diverse cohorts would strengthen external validity. Third, the durability of observed gains is unknown; longitudinal follow-ups should examine whether short-term improvements in interest and literacy persist and influence subsequent STEM choices. Fourth, all qualitative coding was conducted by a single researcher; future work should involve independent coders and report inter-rater reliability. Finally, although group work was generally well received, it did not emerge as a predictor of outcomes. More structured role assignments and targeted collaboration training may enhance its effectiveness. Scaling NFFCM-type interventions and integrating them into formal curricula remain important avenues for further inquiry.

8. Data availability

The data collected in this research involves 13-year-old students and, although informed consent was obtained from guardians and the research was approved by an ethics committee, the data are not publicly available due to confidentiality considerations. Some of the instruments used (TOLT, SI, IiSC, MoLE, MO, CL) were developed by other authors and are cited accordingly. Figure 1 originates from the workbook *Chemical detective*, developed and authored by the first author. Figure 2 was created by the first author, based on concepts drawn from the referenced literature.

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Povzetek

Tradicionalno poučevanje kemije se pogosto sooča z izzivi zaradi abstraktne vsebine in pomanjkanja povezave z življenjskim kontekstom. Raziskava preučuje vpliv neformalnega modula forenzične kemije (NFFCM), zasnovanega za spodbujanje kemijske pismenosti pri 13-letnikih s kontekstualnim, raziskovalnim in na učenca usmerjenim pristopom. Modul je vključeval praktične, problemsko zasnovane dejavnosti v forenzičnih scenarijih, vrednotene s kombiniranim pred- in potestnim načrtom. Rezultati so pokazali pomemben napredek v kemijski pismenosti, podprt z logičnim sklepanjem, samopodobo in motivacijo. Povečal se je tako situacijski kot individualni interes, kar kaže na motivacijsko vključenost. Kvalitativni podatki so izpostavili tri ključne pedagoške značilnosti: pripovedno zasnovano raziskovanje, aktivno eksperimentiranje in sodelovalno skupinsko delo. Učenci so dosledno upoštevali varnostna pravila, samostojno delali in rezultate uporabili pri razrešitvi primera. Ugotovitve kažejo, da lahko dobro strukturirani, a dovolj odprti neformalni moduli dopolnjujejo formalno izobraževanje z razvijanjem kemijske pismenosti, poglobljanjem razumevanja in večjo vključenostjo učencev.



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