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Chemistry inquiry conducted by secondary school students into material degradation in the context of sustainability

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Chemistry is essential for improving the quality of life and reducing pollution, requiring regulations, green innovations, and sustainable action. In this case, chemistry education is key not only for raising environmental awareness, but also for preparing future scientists and informed citizens capable of driving sustainable transformations through green and sustainable chemistry. An inquiry-based learning approach can link chemistry education with sustainability, allowing students to develop scientific skills, environmental awareness, and teamwork while experimenting with real-world problems. One significant environmental issue is the degradation of materials, which affects their chemical structure and functionality, requiring solutions to minimize their environmental impact. This study presents an inquiry conducted by ninth-grade secondary school students on material degradation in the context of sustainability. The inquiry is developed as a collaborative project, with students working together throughout most stages, while some tasks such as data collection and analysis were performed individually to encourage autonomy. Furthermore, the inquiry spans a full quarter, enabling students to observe long-term changes, deepen their understanding of the studied processes, and engage more deeply with the environmental issue. Among their key findings, students concluded that a period of 100 days is insufficient for the complete degradation of paper, cardboard, plastic, and metal, with the latter two showing minimal changes despite exposure to environmental conditions that favor photodegradation (solar radiation), thermal degradation (temperature fluctuations between day and night), hydrolytic degradation (humidity variations on rainy days), biodegradation (fungal growth), and chemical degradation or corrosion. Additionally, they developed explanatory models on material degradation, considering environmental factors and their impacts, which allowed them to reflect on sustainability, responsible consumption, and the importance of green chemistry. This study reveals that the students indirectly reflected on five principles of green chemistry through these findings, namely, waste prevention (principle 1), less hazardous chemical synthesis (principle 3), use of renewable feedstocks (principle 7), design for degradation (principle 10), and real-time analysis for pollution prevention (principle 11), especially during the planning and conclusion phases of the inquiry. Thus, this study concludes that inquiry-based learning is an effective approach that deepens the understanding of material degradation and its environmental impact while fostering the integration of the principles of green chemistry. This approach was well-received by students and encouraged positive emotions.

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Sustainability spotlight

Understanding the relationship between chemistry and society is crucial for addressing material degradation and its environmental impact. This study highlights the importance of chemistry education in fostering sustainability awareness through inquiry-based learning. Ninth-grade students conducted an inquiry into material degradation, analyzing environmental factors such as photodegradation, biodegradation, and corrosion. Their findings show that materials such as plastic and metal degrade minimally over 100 days, reinforcing the need for sustainable solutions. This approach advances sustainability by integrating scientific inquiry into education, promoting responsible consumption and green chemistry. This study aligns with UN SDGs, particularly Goal 4 (Quality Education), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action), by fostering scientific literacy and ecological responsibility in future generations.

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Introduction

In recent years, the teaching of chemistry has evolved toward active methodologies that encourage student participation in the learning process. Among these approaches, inquiry-based learning (IBL) has been proven to be an effective strategy for developing scientific skills and critical thinking.[1–4] In parallel, green chemistry has emerged as an essential approach to addressing environmental issues through sustainable practices,[5,6] and its integration into IBL has given rise to a new form of inquiry that combines scientific exploration with environmental responsibility.

The introduction of green chemistry into the classroom offers unique opportunities for students to not only learn responsible concepts and practices but also develop a critical awareness of their role in planetary sustainability. This approach fosters transversal competences such as creativity and systemic thinking, which are essential for tackling global challenges. Moreover, early learning about sustainability principles in chemistry allows students to understand that their individual and collective actions can contribute to positive change, whether in their daily lives or in their future professional decisions.[7–9]

In response to the environmental crisis, schools must serve as catalysts for change. Integrating topics of the green chemistry into pre-university education is essential, given that its transformative potential should be embedded throughout the chemistry curriculum.[10] Among the various sustainability-related topics that can be addressed in the chemistry classroom, material degradation stands out due to its direct link to environmental pollution, particularly from plastics and other persistent waste materials.[11] Understanding how different materials degrade in natural environments enables students to critically examine the long-term consequences of consumption and disposal habits. Furthermore, degradation processes integrate key chemical concepts, such as reaction mechanisms, structure–property relationships, and environmental chemistry, making this topic especially suitable for meaningful and interdisciplinary inquiry. By incorporating concepts such as the circular economy, life cycle analysis of materials, and sustainable product design, students can gain the knowledge and skills needed to tackle the current environmental challenges.[7] Ultimately, safeguarding our planet requires a global shift toward more sustainable models, and education must be at the forefront of this transformation.

Although green chemistry inquiry is a direct approach for teaching the principles of green chemistry in the classroom, some authors[5,7,9] suggest that these principles can also be implicitly addressed through other approaches, such as IBL, even when they are not explicitly taught. Although not all studies explore this idea directly, several researchers have noted that by engaging with environmental and sustainability issues through IBL, students can intuitively understand and apply the core principles of green chemistry.[10,12–16]

In this context, this study presents a standard IBL to a relevant environmental topic, material degradation, with Spanish high school students to explore whether the principles of green chemistry can implicitly emerge through the conventional IBL process. This study does not aim to contribute novel findings to the literature on material degradation, but rather bring this topic closer to high school students through discovery within an IBL approach. The novelty of this research lies in several aspects. The first innovative aspect is the duration of the inquiry, which lasts a full quarter. This extended timeframe allows students to observe long-term changes and deepen their understanding of the processes studied, facilitating greater immersion in the environmental issue. The second innovative aspect is that the inquiry is developed as a group and collaborative project in the classroom, where all students cooperate closely in the various stages of the inquiry, from planning to interpreting results and drawing conclusions, although some stages, such as data collection and analysis, were done individually to promote autonomy in learning. In this way, the benefits of teamwork, as practiced by scientists, impact both individual and larger group learning.[17] This method is considered innovative given that it is uncommon in chemistry classrooms, where inquiries are typically individual activities without the opportunity for collaborative decision-making. The final innovative aspect is the analysis of the emotions of students throughout the IBL.

Theoretical framework

Chemistry and environment

The relationship among chemistry, society, and the environment is undeniable. Our lifestyle and environmental degradation are closely linked.[18] A clear example is the enhanced quality of life enabled by the knowledge chemistry contributes to society across various fields, including health, food, and materials.[19,20] The consumption of raw materials and the relentless production to meet societal demands generate massive amounts of single-use materials,[21] many of which ultimately end up in nature.[22] In the past few decades, the production of materials and chemicals lacked environmental and health impact assessments.[23] Although regulations in the chemical industry have improved, it remains one of the largest sources of pollution and environmental hazards.[24,25] High carbon dioxide emissions, resource consumption, and waste production are the three main pillars of the environmental degradation problem.

The current climate emergency is urgent. The planet faces unprecedented environmental challenges, with climate change and human-induced alterations as the primary drivers.[26–28] Rising temperatures, extreme weather events, biodiversity loss, and ocean acidification are some of the devastating effects of this crisis.[29,30] Communities worldwide are experiencing direct impacts, ranging from floods[31–33] and droughts[34] to forced migration due to environmental degradation. Addressing the climate emergency requires urgent action, a global and coordinated effort to reduce greenhouse gas emissions, adopt more sustainable practices, and develop innovative solutions to protect our planet and future generations.[35] Awareness and immediate action are essential to tackle this global crisis.

To address this challenge, the United Nations,[36] through the 2030 Agenda, established an ambitious and universal framework with 17 Sustainable Development Goals (SDGs), broken down into 169 specific targets. These targets focus on critical areas such as climate action, sustainable cities and communities, and responsible production and consumption, which are measured through a series of indicators. The SDGs are interconnected and based on the principle of "leaving no one behind", meaning that all countries and all people must participate in the pursuit of sustainable development.

Another significant effort in this area is driven by green chemistry, a framework for chemistry that establishes a relationship among chemistry, the environment, and society.[5,6,37] One of the principles of green chemistry establishes that chemical products should be designed in such a way that at the end of their function, they break down into innocuous degradation products and do not persist in the environment.[5] The 12 principles are as follows: (1) waste prevention rather than post-treatment; (2) atom economy to maximize material efficiency; (3) the synthesis of less hazardous products to reduce toxicity; (4) the use of safer chemicals; (5) the reduction of auxiliary substances; (6) energy efficiency by conducting processes under optimal conditions; (7) the use of renewable raw materials instead of non-sustainable resources; (8) the minimization of unnecessary steps in production (reduction of derivatives); (9) the promotion of catalysts over conventional reagents; (10) the design of biodegradable products; (11) real-time monitoring to prevent pollution; and (12) the development of inherently safer processes, avoiding substances that can cause accidents or environmental harm. Together, these principles enable more efficient, safer, and sustainable chemistry. Green chemistry research has fostered the development and use of renewable raw materials,[24,25] creating chemical processes that consume less energy and finding and promoting safer alternatives to widely used hazardous materials.[24]

To ensure a more sustainable future, current generations must live in a way that preserves resources and opportunities for those to come.[38] Some examples include various alternatives for energy production and use, innovative products derived from chemistry that can help preserve natural resources, or the interaction of the chemical industry with the local and regional economy and society.[39]

Degradation of materials

In this context, it is essential for citizens to reflect on the fate of materials when they are carelessly discarded into nature. Over time, the physical and chemical properties of these materials change due to the action of various factors, such as solar radiation, temperature fluctuations, chemical reactivity with different substances or solutions, physical stress, and contact with water. These factors, either individually or in combination, trigger different types of degradation processes that impact both the structure and functionality of materials. Posada[40] and Vasile[41] identified the following types of degradation:

• Physical degradation, or changes in the physical properties of materials that occur as a result of mechanical forces, such as wear, deformation, and fracture.[42,43]

• Chemical degradation, also known as corrosion in the context of metallic materials, refers to the deterioration or decomposition of a material due to chemical agents. This process involves an electrochemical reaction that dissolves the material in the presence of an electrolyte, such as moisture or a saline solution.[42,44]

• Hydrolytic degradation, a chemical decomposition process in which water is added to a compound, leading to the breaking of chemical bonds.[45]

• Photodegradation, a chemical degradation process induced by light, particularly ultraviolet radiation, which results in changes in both physical and chemical properties. Although it affects various materials, it is particularly significant in plastics due to the absorption of high-energy photons.[46]

• Thermal degradation, referring to the deterioration or decomposition of a material due to exposure to heat.[47,48]

• Biodegradation, a process involving the action of microorganisms. Although many synthetic polymers are resistant to this degradation, there is growing interest in developing biodegradable plastics for applications in agriculture, medicine, and packaging.[49]

The effects of degradation on materials vary depending on their composition and chemical structure. Physical degradation leads to material wear, while chemical degradation involves processes such as corrosion and hydrolysis. Biomaterials, such as paper, cardboard, and wood, are particularly susceptible to microbial degradation. Metals are mainly affected by oxidation–reduction processes. Polymers and ceramics are especially prone to fatigue and fractures.[50] In particular, polymers, such as different types of plastics, are chemically difficult to break down, which means they primarily undergo surface deterioration. Their lightweight nature and resistance to both mechanical and thermal stress allow them to persist intact in ecosystems for long periods.[11]

Chemistry education for the ecological transition

Improving the educational level of society is a key driver in the transition toward more sustainable practices, given the strong connection between environmental preservation and education, both broadly and within chemistry education. Li *et al.*[51] highlighted how the interaction between green innovation and government intervention, together with the role of education, helps reduce carbon emissions. Their findings show that education significantly lowers harmful pollutant emissions, while the mechanisms of green innovation and government intervention further reinforce its positive impact on the green transition. Similarly, Voumik and Ridwan[52] emphasized that population growth and industrialization cause long-term damage to the natural environment, whereas the relationship between carbon dioxide emissions and educational expenditures is significantly inverse in the short term. This connection between education and environmental sustainability underscores the idea that investing in knowledge is an investment in a more prosperous and ecologically responsible future. Thus, addressing socio-scientific issues related to chemistry enhances scientific literacy and prepares citizens with a deep understanding of chemistry, which can be applied to improve society.[53,54]

In summary, chemistry education is key to the ecological transition because it provides students with solid environmental knowledge and awareness, enabling them to understand environmental challenges and the importance of sustainability, particularly through understanding the behavior of materials when exposed to the environment.[55] By exploring environmental issues from multiple perspectives, students are empowered to become informed citizens who make decisions and take actions to promote a change in society's attitudes.[56] In this way, chemistry education can empower students as future citizens to participate in policy-making and environmental decisions, while also preparing them for careers in sustainability-related sectors, thereby contributing to a green economy.

Inquiry-based learning as an approach to sustainability

The urgent environmental issues make effective approaches necessary in the teaching and learning processes of chemistry.[57–59] IBL, recognized by the European Commission[2] as a relevant approach in science education, can empower students to acquire scientific skills to study natural phenomena and solve problems.[1,3,4,60,61] IBL allows students to apply relevant scientific knowledge in meaningful socio-scientific issues, thereby connecting theory with real-life situations and practices.[38] However, IBL is not synonymous with laboratory practice,[17,62,63] given that it requires the active participation of students, who must reflect on both the processes and scientific knowledge.

IBL offers students the opportunity to design and conduct their own investigations on a problem and interpret them according to their own knowledge.[64–66] The proposal by the National Research Council[67] (NRC) understands inquiry through the following stages: (a) posing science-oriented questions that allow active student participation, (b) collecting evidence by students that enables the development and evaluation of their own explanations to the posed questions, (c) developing explanations to answer the questions based on the evidence collected, (d) evaluating the explanations, which may include alternative explanations that reflect scientific understanding, and (e) communicating and justifying the proposed explanations. The comparative study by Franco-Mariscal[13] on different inquiry approaches concluded that IBL helps develop scientific competences in the areas of problem formulation, information handling, planning and designing research, data collection and processing, data analysis, and drawing conclusions, communicating research results, and fostering critical reflection and teamwork.

Although IBL is not a widely practiced approach in the chemistry classroom,[60] an increasing number of studies have been reported in the literature on chemistry and the environment with secondary school students.[10,55] One example is the work by Mandler *et al.*[15] in the environmental context of water quality and its effects on daily life, where students designed and conducted experiments and evaluated their findings. Learning environments for secondary school students that connect formal and non-formal learning are another opportunity to develop chemistry inquiries on sustainability. For instance, Garner *et al.*[14] proposed inquiries on sustainability, such as the production of biodiesel from vegetable oils, where the role of the teacher was limited to support and consultation. During the inquiry, students reflected on the characteristics of fuels, the social debates surrounding this topic, and learned about national regulations such as subsidies. Another interesting inquiry is the one reported by Franco-Mariscal[13] on the corrosion phenomenon, using urban furniture as a starting point, such as completely rusted steel traffic signs compared to aluminum windows showing few signs of deterioration. This inquiry allowed students to develop critical reflection and awareness of the environmental issues caused by corrosion, as well as the associated economic losses.

The learning of topics related to green chemistry through an IBL approach is gaining increasing attention in the literature.[10,12–16] Green chemistry inquiry represents a specific case of IBL, characterized by distinct content, values, and objectives centered on sustainability and responsible chemistry. Table 1 presents a comparison of the main features of IBL and green chemistry inquiry.

Duangpummet *et al.*[68] carried out a laboratory-based inquiry unit focused on the application of lipase as a catalyst, with the aim of promoting the understanding and perception of greener chemistry. Nahlik *et al.*[9] strived to bring industrial and manufacturing green chemistry closer to a more suitable version for primary and secondary school students through educational proposals in which students conduct open and self-directed experiments, encouraging them to formulate questions, make decisions about materials and procedures, and draw conclusions based on their evidence. Consequently, they not only engage students but also foster a more sustainable mindset. In upper-level chemistry courses, alternatives to traditional laboratory experiments are also being explored, where students learn about stoichiometry by applying the principles of green chemistry through scientific inquiry.[69] Meanwhile, the Department of Chemistry at the University of California, Berkeley, was a pioneer in redesigning general chemistry laboratory courses to introduce green chemistry concepts, using them simultaneously as a relevant context for learning. Armstrong *et al.*[7] analyzed the effectiveness of these proposals, concluding that the principles of green chemistry can be integrated into the classroom through inquiry. Moreover, the green chemistry curriculum effectively introduced new, purely chemical concepts to students.

Additionally, several authors proposed that the principles of green chemistry can be integrated implicitly within pedagogical approaches such as IBL, even in the absence of explicit instruction.[70] Research has shown that when students explore environmental and sustainability issues through IBL, they often develop an intuitive understanding and application of green chemistry[70] with the potential to influence their comprehension of key chemistry concepts, attitudes, motivations for pro-environmentally action, and pro-environmental values.[71] The IBL approach, particularly when centered on socio-

Table 1 Features of IBL *versus* green chemistry inquiry

Aspect	Inquiry-based learning	Green chemistry inquiry
Definition	An educational approach focused on active learning through question formulation and exploration	A didactic strategy based on inquiry-based learning, applied to environmental issues using the principles of green chemistry
Main objective	To develop critical thinking, scientific skills, and learning autonomy	To understand chemical processes while promoting ecological and sustainable awareness
Content	General and adaptable to any field of knowledge	Chemistry-specific, focused on sustainability and ecological processes
Context	May or may not relate to real-life situations	Always based on real and current environmental issues
Ethics and sustainability	Not a required component of the approach	Central to the approach; ethical and sustainable values are explicitly integrated
Application of principles	Does not involve specific principles beyond the scientific method	Applies the 12 principles of green chemistry as a conceptual framework
Assessment	Focused on the inquiry process and scientific reasoning	Assesses scientific skills as well as environmental and ethical impact
Student motivation	Driven by curiosity and general exploration	Enhanced by connection to real-world problems and a sense of environmental responsibility
Interdisciplinary approach	Varies depending on the design	Highly interdisciplinary (chemistry, ecology, ethics, technology, *etc.*)

environmental issues, can naturally elicit reflections aligned with the principles of green chemistry. As students formulate questions, design experiments, and interpret evidence in real-world contexts, they begin to engage with ideas such as waste minimization, degradation, and pollution prevention. Some research suggests that guiding students through authentic, problem-based inquiry can enhance their knowledge, awareness, and application of green chemistry.[55,70]

Anastas and Warner[5] indicated that many of the principles of green chemistry, such as waste reduction and toxicity minimization, are so deeply embedded in environmental issues that they can be intuitively understood through IBL, without the need for direct instruction. Similarly, Nahlik *et al.*,[9] in their research on green chemistry learning at the primary and secondary levels, emphasized that when students engage in open-ended, self-directed experiments, they can discover and apply green chemistry principles even if they are not explicitly introduced. This suggests that the standard IBL can also serve as an indirect pathway for incorporating these principles into the learning process.

A key aspect of inquiry is collaborative work, which in turn provides the fundamental competence for social responsibility. Huang[72] demonstrated that inquiry develops teamwork skills and collaborative problem-solving. The benefits of teamwork not only positively impact the learning by individual students, but also enhance the learning of a larger group, enriching their collective understanding and fostering mutual support.[17] Furthermore, the level of student engagement in an inquiry and the quality of their learning can be influenced by the emotions that arise during the process.[73–75] IBL allows students to experience and manage a range of emotions, ranging from curiosity to frustration, which not only enriches their learning but also strengthens their socio-emotional skills. Emotions throughout the stages of inquiry are common,[75] particularly during the data collection and analysis phase, when the results do not meet expectations.[15]

Objectives and research questions

The IBL presented is part of a teaching-learning sequence on plastics and pollution for secondary school students,[76] framed within the R&D project TED2021-130102B-I00, aimed at promoting ecological and digital transition in science education. It has been proposed as a pilot study whose objective is to explore the possibilities of this approach and the issue addressed for the development of mobile applications based on educational games.

The main objective of this study is to present and analyze the effectiveness of IBL on material degradation with high school students, exploring their explanatory models related to material degradation, the potential of this experience to elicit green chemistry principles, and its impact on the students' perceptions of their learning experience, collaborative work, and emotional responses.

At the research level, the following research questions (RQ) are posed:

RQ1. How do Spanish secondary school students design and implement an inquiry on the degradation of various everyday materials in the environment?

RQ2. What explanatory models do students use to understand the degradation process and its environmental effects?

RQ3. Which principles of green chemistry underlie the inquiry conducted by the students?

RQ4. What are students' perceptions of the inquiry, their learning experience, collaborative group work, and the emotions they felt?

At the educational level, the objectives of the experience were as follows: (a) to apply the IBL approach to a real-world problem related to chemistry and the environment, specifically, the degradation process of different materials, where students formulate a problem, propose hypotheses, design experiments, observe, collect and analyze data, interpret findings, and draw conclusions; (b) to analyze the degradation of various everyday materials, such as paper, cardboard, plastic, and metal, after 100 days of exposure to environmental conditions; and (c) to understand the degradation process from a chemical perspective to explain its environmental impact, fostering environmental awareness and promoting sustainability.

Research method

Participants

The sample for this study consisted of 25 ninth-grade Spanish students enrolled in the mandatory chemistry course at a public secondary school in Málaga, Spain. Their ages ranged from 14 to 15 years old.

Regarding their prior knowledge, the participants completed various modules on atoms, chemical bonding, chemical elements and compounds, and chemical reactions. However, they had no previous exposure to the concept of green chemistry, its principles, or the different types of material degradation. The IBL was carried out over a full quarter as a cross-cutting activity. Throughout its development, students supplemented their learning with chemistry concepts related to physical and chemical changes, atoms and molecules, and types of chemical bonding. These students were accustomed to a lecture-based approach combined with structured activities. They had previously conducted some laboratory experiments following a predefined protocol but never previously engaged in IBL.

Ethics statement

We obtained ethical approval for this study at the second author's institution (Reference Number 126-2023-H). The formal procedures followed included obtaining informed consent from the students, with the option to decline or withdraw participation.

Data collection instruments

The instruments used for data collection are as follows:

• A written inquiry report completed by each student at the end of the experience, documenting their findings across the different stages of the inquiry. This report included information on the formulated research problems, theoretical background, hypotheses, experimental design (including data collection instruments, selection of samples and variables), collected results and data, visual documentation (*e.g.*, photographs), and the interpretation of results together with the conclusions drawn.

• The teacher's (first author's) observation diary, which tracked students' decisions at each stage and included excerpts from classroom discussions and voting results from whole-group deliberations.

• An inquiry evaluation questionnaire administered at the end of the process, featuring both open-ended and closed-ended questions adapted from validated questionnaires, as follows: (a) rate the activity from 0 to 10 points; (b) through this

Table 2 Principles of green chemistry and expected student inquiry outcomes

Green chemistry principle	Expected outcomes in student inquiry and reports
1 Waste prevention	• Formulate questions related to waste accumulation • Identify environmental problems in their surroundings • Propose strategies to prevent or reduce waste in experimental design or conclusions • Quantify or estimate waste generated during the inquiry
2 Atom economy	Not expected
3 Less hazardous chemical syntheses	• Discuss the impact of certain materials on human health or the environment • Evaluate whether the materials used or released pose low toxicity risks
4 Designing safer chemicals	• Recognize that some materials contain chemical additives that may be released and cause toxicity • Propose the design of materials free from toxic additives
5. Safer solvents and auxiliaries	Not expected
6 Design for energy efficiency	• Reflect on the energy consumption in the production processes of materials • Consider energy use in plastic recycling processes • Propose energy reduction as a sustainability goal
7 Use of renewable feedstocks	• Recognize and justify the use of biodegradable or renewable materials instead of synthetic ones • Compare the origin of materials (biological *vs.* petrochemical) and assess their environmental impact
8 Reduce derivatives	Not expected
9 Catalysis	Not expected
10 Design for degradation	• Analyze and document evidence of material degradation (physical, chemical, or biological) • Relate material properties to their persistence or degradability • Propose how a material can be redesigned for improved degradability
11 Real-time analysis for pollution prevention	• Record data at multiple time points to observe gradual changes • Interpret how environmental factors influence degradation over time • Adjust methodologies based on real-time observations
12 Inherently safer chemistry for accident prevention	Not expected

inquiry, I have learned…; (c) evaluate your knowledge before and after the inquiry on a scale from 0 to 10;[77] (d) Overall, how involved were you in the inquiry? (responses on a four-point Likert scale: not involved, slightly involved, fairly involved, highly involved);[78] (e) Would you like the subject to always be taught through collaborative inquiries such as the one we conducted? (f) Identify your emotional state based on the following pairs (calm–anxious, relaxed–stressed, unconcerned–worried, secure–insecure, comfortable–uncomfortable, confident–unconfident, happy–unhappy, enthusiastic–bored, satisfied–dissatisfied, interested–uninterested), rating each on a seven-point Likert scale of very (+), quite (+), somewhat (+), indifferent, somewhat (−), quite (−), very (−).[79]

Data analysis

To analyze the students' reports, the researchers carefully read each document, identifying the results and discussions that best reflected the findings. They reviewed sections where students explained their observations, interpreted data, and assessed the coherence of their arguments. Additionally, they examined supporting evidence such as photographs and data tables. The researchers also evaluated the students' ability to relate their findings to chemical concepts discussed in class and their capacity to formulate well-supported conclusions. Finally, all reports were compared to identify common patterns and assess the overall level of understanding achieved by the group.

The teacher's observation diary was analyzed to extract the most relevant notes regarding the inquiry process. The researchers analyzed the green chemistry principles underlying the design and implementation of the inquiry. For the analysis, the authors established specific learning standards for each principle that they expected to identify (Table 2) based on previous studies.[7]

The responses from the evaluation questionnaire were analyzed according to their nature. Open-ended questions on learning (question "b") and collaborative methodology (question "e") were categorized independently by the two researchers, who established meaning units. Their analyses were then compared, and any disagreements were resolved through consensus. The frequency of each category was then calculated. In the case of the closed-ended questions on activity assessment (question "a") and knowledge evaluation (question "c"), responses were quantified, and both the arithmetic mean and variance were calculated. The Likert-scale responses on students' level of engagement in the inquiry (question "d") and emotions (question "f") were analyzed by calculating frequencies and percentages for each scale point. A given emotion was considered predominant if the "very" and "quite" levels together accounted for 50% or more of the participants.

Design of the inquiry by students

The inquiry on material degradation was structured into three phases, as follows: (1) planning and design, (2) implementation, and (3) interpretation of results and conclusion drawing.

Phase 1. Inquiry planning and designing

Students worked as a whole group in the classroom over five one-hour sessions to collaboratively plan and design the inquiry. This phase included problem formulation (half a session); theoretical background (two sessions); hypothesis (half a session); selection of variables, experiment design, development of data collection instruments (one session); and data analysis (one session). Throughout this process, the teacher acted as a guide and facilitator.

Firstly, students collaborated to define the research problem by observing and gathering evidence showing that the degradation of everyday materials was an environmental issue in their neighborhood. To support this inquiry, they individually searched for information, and then worked together to construct a theoretical background, integrating their prior chemistry knowledge with newly gathered data. The students reached a consensus on the theoretical background, including only information that was collectively accepted. This process helped them establish connections between chemistry concepts and their inquiry. The teacher reviewed students' contributions to ensure the use of reliable sources and to correct any misconceptions. If an unreliable source was identified, the teacher informed the students, who then replaced it with a higher-quality reference.

To generate the hypothesis, the teacher prompted students with questions about the materials found in local waste and the potential consequences of leaving them uncollected. Through a whole-group discussion, students proposed and debated hypotheses until they reached a consensus.

Next, they collaboratively selected the study samples and the most suitable variables for designing the experiments, resolving disagreements through voting. It was agreed that each student would carry out the inquiry individually using similar materials.

For data collection, students decided to record environmental conditions and observed changes in the samples using an observation table, which they had to complete daily. They conducted visual inspections, examining both sides of each sample without touching or removing the material from its exposure site. The evaluation of properties was carried out qualitatively, given that they decided not to record quantitative data to prevent contact with the material from affecting the results.

Additionally, they agreed to first analyze the data for each material individually before discussing it as a group, giving each student the opportunity to present their observations.

Phase 2. Inquiry implementation

Each student carried out the inquiry at home, beginning simultaneously on the designated date. Throughout the process, they recorded daily observations following the observation protocol. Students collected data on material degradation by documenting their observations and attempting to connect them to the background. For meteorological data, averages were calculated, and tables and figures were created.

Each week, the teacher allocated 10 minutes of a session for students to share their observations and progress in a collaborative setting, fostering idea exchange. This approach not only encouraged communication among students but also provided a space for constructive feedback and mutual enrichment of their individual inquiry experiences. Additionally, the teacher monitored the inquiry process, interacting with each student to track their progress and ensure optimal development. This personalized attention helped address any difficulties encountered and supported effective learning.

Phase 3. Interpretation of results and conclusion drawing

The interpretation of results was first approached individually, with each student analyzing their observations and compiling a written report. Then, over two one-hour group sessions, students engaged in discussions to develop a coherent chemical explanation. This analytical and discussion process ensured the consistency and reliability of the inquiry results.

The group discussion was structured by reviewing daily findings and noting them on the blackboard. During each contribution, students explained the observed changes and potential influencing factors. Partial interpretations and conclusions were debated, encouraging comparison between the students' results to verify consistency in their observations and enrich the inquiry. The teacher documented in their diary the discussions that led to the consensus.

Given that each student conducted experimental replications, notable variability emerged when sharing individual results. Although they followed the same procedure, differences in findings sparked discussions on possible causes of these variations. After calculating the frequency of each characteristic for each material on specific dates, the group agreed to represent the results in time ranges, discarding extreme values to focus the analysis on representative trends. All this information was organized into tables and graphs to facilitate comparison and visualization of the findings.

This exchange of ideas enabled the whole group to establish both general conclusions about the problem and material-specific insights, deepening their understanding of the underlying chemical phenomena and enriching the collaborative learning experience.

Results and discussion

This section is organized into two parts. Firstly, the results and discussion of the inquiry conducted by the students across the three phases are presented, and secondly their evaluation of the experience.

Inquiry results and discussion

Phase 1. Inquiry planning and design (RQ1). The following describes the group decisions made during this phase.

Problem formulation. Students identified a major issue in their community, *i.e.*, the alarming accumulation of waste in urban areas, particularly around their high school. This situation concerned them not only because it affected the aesthetics of their surroundings but also due to its environmental and public health implications for the neighborhood. The research problem was formulated in terms of what happens over time to the materials found in street litter in our neighborhood? To support their research problem, students included photographs in their reports illustrating the presence and degradation of materials in their area (Fig. 1). They agreed to study the most common materials found in waste, *i.e.*, paper, cardboard, plastic, and metal.

Fig. 1 Deterioration of different materials in their environment.

Students' theoretical background. Students aimed to gain a deeper understanding of the problem by investigating two key aspects, the chemical composition and properties of various materials, and the different types of degradation that can affect them. Table 3 illustrates the students' insights regarding the internal structure of materials, while Table 4 summarizes the types of degradation, their potential effects, and the corresponding chemical explanations at the submicroscopic level. As observed, the students primarily relied on books and articles in Spanish, given that they were more accessible than specialized international sources restricted to certain databases.

Hypotheses. To address the research question, the teacher asked the whole group to propose hypotheses, establishing key aspects of the problem, including the natural degradation capacity of each material, the estimated time for its decomposition, and its potential environmental impact. Here, an excerpt from the teacher's diary is presented, illustrating how students reached a consensus on the first hypothesis, formulated as: "It is likely that the 100-day period set for this inquiry may be insufficient for many of the materials studied to fully decompose. However, we believe this time frame will provide insight into the main changes occurring during their degradation" (H1):

• Student 1: we need to consider how much time is required to observe changes in the trash discarded on the street.

• Student 2: But what exactly do we mean by "observing changes"?

• Student 1: I think 100 days is enough to notice something, right?

• Student 2: some materials are more resistant. Maybe 100 days won't be enough to see changes in everything.

• Student 3: You're right, plastic can take a really long time to break down. But what about materials like paper or cardboard? I think in 100 days we could see them deteriorate.

Table 3 Information collected by students on the chemical composition of each material

Material	Chemical composition
Paper[80]	Composed of plant fibers made up of cellulose, a natural polymer consisting of numerous glucose molecules linked by covalent bonds between hydroxyl groups. These chains are linear and arranged in parallel. The hydroxyl groups in cellulose give it an affinity for water
Cardboard[80]	Similar in composition to paper, though processed differently to provide greater rigidity. Its manufacturing involves folds, creases, and multiple layers
Plastic[81,82]	Made of synthetic polymers, with composition varying depending on the type of plastic Shopping bags are composed of low-density polyethylene (LDPE), a plastic formed by covalently bonded ethylene units, creating long, branched chains that make it flexible Notebook covers are made of polypropylene (PP), consisting of long, linear chains without branching, giving it strength and rigidity. They are composed of repeating propylene units linked *via* covalent bonds Plastics may contain additives such as colorants and stabilizers to enhance their properties. Plastics do not contain chemical groups with an affinity for water
Metal[81,82]	Composed of metal atoms forming a metallic crystalline lattice. Bonding occurs through metallic bonds, where atoms share their valence electrons, creating an electron cloud The inner lining of milk cartons and soda cans is made of aluminum alloys
Paints and coatings[82]	Highly diverse in composition, including natural pigments, additives, resins, solvents, and more

Table 4 Information collected by students on types of degradation, potential effects, and chemical explanation

Type of degradation	Description	Potential effects	Submicroscopic chemical explanation
Physical degradation[40,82]	Degradation that alters the structure but not the composition of the material	Wear, creases, deformations, wrinkles, loss of elasticity and cohesion, or increased brittleness	Mechanical forces from environmental conditions can impact the material's integrity and physical properties. The loss of internal cohesion may cause the material to fragment or become brittle
Photode-gradation[40]	Degradation caused by prolonged exposure to solar radiation	Changes in the material's physical properties, color fading, texture alterations, loss of gloss, fragmentation, and deterioration of mechanical properties	High-energy solar radiation, such as ultraviolet rays, can trigger chemical reactions that break covalent bonds, leading to material decomposition
Thermal degradation[40]	Degradation caused by temperature changes	Color changes, dimensional alterations, crack formation, *etc.*	Thermal energy can break covalent bonds, leading to material decomposition, reduced elastic recovery, and increased fragility
Hydrolytic degradation[40]	Degradation caused by contact with water or humidity variations	Loss of color, changes in mechanical properties, swelling, particle detachment, decreased cohesion, and mold growth due to the material's hygroscopic nature	Water molecules can interact with other molecules, breaking materials down into fibers. Excessive water absorption can alter the structure of the material, reducing its stability
Biodegradation[40]	Natural degradation of the material due to the action of various biological agents (microorganisms, fungi, bacteria, *etc.*)	Changes in appearance, presence of microorganisms, formation of degradation compounds, color changes, odor development, *etc.*	Microorganisms can use certain materials as a source of food and energy, secreting substances that break down complex molecules into simpler ones
Chemical degradation (corrosion)[82,83]	Destructive attack on a metal due to chemical or electrochemical reactions with the environment	Formation of corrosion products with different colors depending on the metal, thickness loss, formation of crusts and layers, pitting, changes in mechanical properties, *etc.*	Oxidation reaction in which atoms lose electrons, affecting metallic bonds and the material's structure, making it less resistant

• Student 1: So, should we state that 100 days is a period in which some materials will show changes, but others won't?

• Student 2: sounds good to me. That timeframe might not be enough for the complete decomposition of more durable materials, but it should be sufficient to observe the beginning of the process.

• Student 4: the hypothesis would then be: "It is likely that the 100-day period set for this inquiry may be insufficient for many of the materials studied to fully decompose".

• Student 2: we could add: "However, we believe this time frame will provide insight into the main changes occurring during their degradation".

The following are the rest of the formulated hypotheses:

H2: paper will decompose the fastest due to its low cohesion and resistance, breaking down into smaller pieces.

H3: cardboard will decompose easily, aided by rain and humidity, which will soften it and cause it to separate into layers.

H4: Tetra Pak cardboard will be more difficult to break down than regular cardboard due to the aluminum layer inside.

H5: plastic bags will be the material that takes the longest to decompose.

H6: the metal from a soda can will begin to rust quickly due to moisture and rain, but the process will be slow.

Selection of samples and study variables. The students collectively selected 16 samples (Table 5) to ensure a comprehensive representation of the studied materials. Some decisions, such as the choice of plastic bags, sparked debate. Some students believed that including a thin white bag and a thicker one was sufficient, while others argued for adding a colored bag as well. The first group maintained that the difference in thickness already provided enough variability, whereas the second group contended that incorporating a colored bag would not only be easy to obtain but would also enrich the inquiry. Ultimately, with 15 votes in favor, the decision was made to include the colored bag. All participants agreed to reuse materials from their homes as samples. Likewise, they expressed the need to dispose of them in the appropriate recycling bins once the inquiry was completed.

As observed in Table 5, the independent variables considered include the type of material (paper, cardboard, plastic, and metal), differences in thickness (thin or thick), and the presence or absence of printing or color.

Additionally, the students agreed on the controlled variables for the inquiry including material dimensions, duration of the study, exposure location, and number of replicates. Each student conducted the inquiry individually in Málaga city (Spain), using samples measuring 15 × 10 cm. The study lasted 100 days, spanning the autumn and winter seasons (from October to February), a period expected to present adverse weather conditions. The exposure location was each student's outdoor clothesline, where samples were hung vertically through a small hole made at the top of each material. Each student exposed three replicates of each sample to ensure reproducibility and kept a fourth unexposed replicate as a control sample for comparison.

The dependent variables selected include the different properties assessed daily for each sample (Table 6). It is important to highlight the recording of environmental conditions (weather: sunny, cloudy, rainy, windy, or snowy, maximum and minimum temperatures, and precipitation), given that they fluctuate daily and cannot be controlled but significantly influence material degradation.

Collected data. Table 6 provides an example of a student's daily observation record. The records include environmental conditions obtained from mobile applications or specialized agency websites, as well as characteristics of the types of degradation studied in the background. Observations focused on the condition of the materials, documenting changes such as wrinkles, folds, moisture from rain, stains, color changes, separation of parts or fibers, odor development, swelling, and detachment. Additionally, each material was photographed to visually document its evolution.

The results obtained show a significant positive impact on the students' ability to design and plan an inquiry, as supported by other studies such as Gooddey and Talgar[63] and Wang *et al.*[17]

Phase 2. Inquiry implementation (RQ1). The inquiry was conducted under environmental conditions characterized by an average maximum temperature fluctuating between 14.0 °C and 22.5 °C, an average minimum temperature ranging from 5.0 °C to 11.5 °C, and a total accumulated precipitation of 164 mm over the study period. Table 7 provides a breakdown of this information by biweekly intervals.

The prevailing weather conditions included 31% cloudy, 28% sunny, 22% windy, and 19% rainy days. Thus, temperature fluctuations contributed to thermal degradation, while the presence of sunny and rainy days facilitated photochemical and hydrolytic degradation, respectively. Table 8 presents the average time ranges in which changes were observed in the samples.

All paper samples exhibited three main changes, the appearance of wrinkles, creases, and water absorption. The first two changes were caused by ambient humidity and wind, while the third was primarily due to rain. As a result of the latter, stains appeared in some cases, and pieces of paper might detach or completely disintegrate.[50]

As the paper thickness decreased, the changes became more pronounced and occurred within a shorter time (Table 9). Toilet paper, being the thinnest material, was affected by all three changes more frequently than the other paper samples. The shopping bag is particularly noteworthy, given that its behavior was more similar to that of cardboard than paper due to its thickness and composition, consisting of a blue and a white paper layer, which gradually separated over time. As seen in the

Table 5 Description of the samples selected for the inquiry

	Independent variables		
Sample	Material	Thickness	Printing or color
Toilet paper	Paper	Thin	No
80-gram sheet of paper		Thin	No
Graph-paper notebook sheet		Thin	Yes
Advertisement paper		Thick	Yes
Shopping bag		Thick	No
Packaging cardboard	Cardboard	Thin	Yes
Notebook cover		Thick	No
Storage cardboard		Thick	No
Tetra Pak (exterior)		Thick	Yes
White shopping bag (thin)	Plastic	Thin	No
White shopping bag (thick)		Thick	Yes
Colored shopping bag		Thin	Yes
Notebook cover		Thick	No
Tetra Pak (interior)	Metal	Thin	No
Soda can (exterior)		Thick	Yes
Soda can (interior)		Thick	No

Table 6 Observation record completed by a student

Date: November 16

Meteorological data: cloudy, maximum temperature: 17.9 °C, minimum temperature: 8.1 °C, precipitation: 21 mm

		Characteristics								
Material	Sample	Wrinkles	Bends	Gets wet from rain	Stains/dirt appears	Color changes	Separates into parts or fibers	Odor develops	Swells	A piece detaches/disintegrates
Paper	Toilet paper	Yes	Yes	Yes		Yes				
	80-gram sheet of paper	Yes	Yes	Yes	Yes					
	Graph-paper notebook sheet	Yes	Yes	Yes	Yes					
	Advertisement paper	Yes	Yes	Yes	Yes	Yes				
	Shopping bag	Yes	Yes	Yes						
Card-board	Packaging cardboard	Yes		Yes						
	Notebook cover	Yes		Yes						
	Storage cardboard	Yes	Yes	Yes			Yes			
	Tetra Pak (exterior)			Yes			Yes			
Plastic	White shopping bag (thin)	Yes	Yes							
	White shopping bag (thick)	Yes	Yes			Yes				
	Colored shopping bag	Yes	Yes							
	Notebook cover									
Metal	Tetra Pak (interior)	Yes					Yes			
	Soda can (exterior)	Yes								
	Soda can (interior)	Yes								

Table 7 Average meteorological data by biweekly intervals over the 100 days

Period	Average weather	Average maximum temperature (°C)	Average minimum temperature (°C)	Average accumulated precipitation (mm)
Oct 25–Oct 31	Sunny	22.5	11.5	0
Nov 1–Nov 15	Sunny/rainy and windy	20.4	10.0	107
Nov 16–Nov 30	Cloudy	17.9	8.1	21
Dec 1–Dec 15	Sunny	15.7	6.5	13
Dec 16–Dec 31	Rainy and windy	15.0	5.5	1
Jan 1–Jan 15	Rainy and windy	14.0	5.0	1
Jan 16–Feb 1	Windy	16.6	5.0	21
Total precipitation				164

Table 8 Days or periods in which students observed changes in each material on average

Material		Wrinkles	Bends	Gets wet from rain	Stains/dirt appears	Color changes	Separates into parts or fibers	Odor develops	Swells	A piece detaches/ disintegrates
Paper	Toilet paper	2	3–9	11	29–35	6–16				20–80
	80-gram sheet of paper	6–11	6–11	11	6–11					35–80
	Graph-paper notebook sheet	6–11	6–11	11	6–11					
	Advertisement paper	6–11	6–11	11	6–11	7–11				60–90
	Shopping bag	4–9	10–15	11			35–42			30–42
Cardboard	Packaging cardboard	15–29	27–32	11		33–36	30–35			30–90
	Notebook cover	18–23	38–40	11	60–67	32–36	30–35			32–89
	Storage cardboard	8–35	19–67	11	82–87		16–57			
	Tetra Pak (exterior)		55–60	11			21–35			20–59
Plastic	White shopping bag (thin)	2	11–15		31–35	38–42				
	White shopping bag (thick)	2	9–12			6–9	85–89			
	Colored shopping bag	2	9–11			67–71				
	Notebook cover	35–47								
Metal	Tetra Pak (interior)	29–31					21–35			
	Soda can (exterior)	18–24			32–42					
	Soda can (interior)	18–24			32–42					

images (Table 9), except for the thick shopping bag, the paper samples degraded significantly before reaching 100 days.

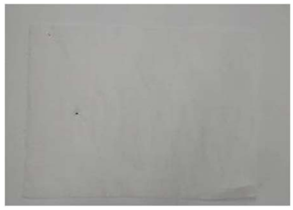
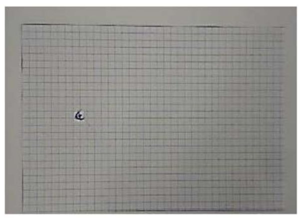
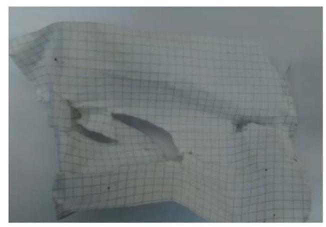
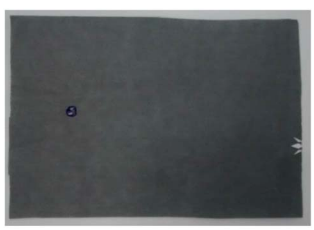
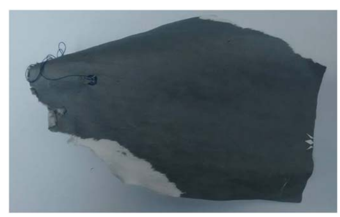
The behavior of the cardboard samples was similar to that of paper (Table 10), given that both are biomaterials.[80] Wrinkles and creases appeared, water was absorbed, and some stains formed. The main difference observed compared to paper was the separation of the cardboard into layers (two in some samples and three in others). In the case of the Tetra Pak, the initial separation of the cardboard from the metallic layer was noted. Layer separation was also observed in the printed samples, together with color loss. Unlike paper, all the studied cardboard samples withstood the weather conditions for the full 100 days.

The plastic samples developed wrinkles and creases (Table 11). Given that plastic is an impermeable material,[81] it was not affected by rain when wet, preventing it from softening and eventually breaking, as happened with paper and cardboard. It was also observed that thin plastic exhibited more wrinkles and creases than paper or cardboard. However, thicker plastic, such as that from notebook covers, only developed minor wrinkles and did not bend. Another change detected in some plastics was the appearance of small black spots, likely caused by mold formation, which may have been facilitated by rain or material damage. Plastics with printing only experienced a slight loss of information. Table 11 presents the initial and final state of each plastic sample, showing that 100 days were insufficient for either full or even partial degradation.

The metallic materials exhibited minimal changes (Table 12). Some folds and a slight separation of the metal from the attached cardboard were observed in the aluminum lining of the Tetra Pak, but no color changes were detected. However, a few white spots appeared inside the soda can, likely caused by aluminum corrosion as a form of chemical degradation.[50,84]

Once the inquiry was completed, the students placed the following samples in the blue recycling bin: toilet paper, 80-gram sheet of paper, graph-paper notebook sheet, advertisement paper, shopping bag, packaging cardboard, notebook cover, and storage cardboard. In the yellow recycling bin, they placed white shopping bag, colored shopping bag, notebook cover, and soda can. The exterior of the Tetra Pak raised some

Table 9 Changes observed in paper samples after 100 days of exposure

Paper sample	At the beginning of the inquiry	At the end of the inquiry
Toilet paper	 Day 1	 Day 80
80-gram sheet of paper	 Day 1	 Day 58
Graph-paper notebook sheet	 Day 1	 Day 80
Advertisement paper	 Day 1	 Day 60
Shopping bag	 Day 1	 Day 100

doubts because although it is made of cardboard, it is part of a composite package. Therefore, they ultimately decided to place it in the yellow recycling bin also.

Phase 3. Interpretation of results and conclusion drawing (RQ2)

Students' interpretation of results. This section presents the consensus reached by the group to understand the molecular-level processes responsible for the macroscopic changes observed.

Paper and cardboard underwent physical degradation and photodegradation, leading to wrinkles, folds, material breakage, separation into parts or fibers, and fragment detachment.[40,82] Hydrolytic degradation also contributed to this process,[40] dissolving cellulose polymers and causing material swelling. The observed color changes could be attributed to the decomposition effects of microorganisms from the soil or air.[40]

Table 10 Changes observed in cardboard samples after 100 days of exposure

Cardboard sample	At the beginning of the inquiry (Day 1)	At the end of the inquiry (Day 100)
Packaging cardboard		
Notebook cover		
Storage cardboard		
Tetra Pak (exterior)		

Plastics experienced physical degradation,[81] which explains the formation of wrinkles. Folds and breakages were only observed in thinner plastics. Thermal degradation and photodegradation might have also contributed to these breakages,[40] as well as the appearance of stains and color changes. However, plastics did not undergo hydrolytic degradation given that plastic polymers do not form interactions with water molecules.[40,82] Additionally, plastics are not biodegradable by microorganisms, given that they are synthetic polymers.

Metal degradation was limited to chemical degradation (corrosion), which led to the appearance of mild rust stains.[50,81] Physical degradation also played a role in the formation of wrinkles in thin metal sheets.[42] Given that metals lack covalent bonds, they are barely affected by thermal degradation or photodegradation.[81]

Paints and color coatings experienced photodegradation and thermal degradation,[50] causing discoloration and cracking. They may have also undergone hydrolytic degradation due to water absorption. Additionally, physical degradation contributed to flaking.[40,82]

Students' conclusions. Based on the results obtained, the students formulated the following general conclusions:

(1) A period of 100 days is insufficient for the complete degradation of any material. The studied materials, except for paper and cardboard, remained practically unchanged during this time and would require a much longer period to undergo significant changes (hypothesis H1 is rejected).

(2) The main properties responsible for the changes in material decomposition are elasticity, hygroscopicity, the degradation of certain components, cohesion, and fragility.[82]

(3) The environmental conditions during the inquiry facilitated the photodegradation (solar radiation), thermal degradation (temperature fluctuations between day and night), hydrolytic degradation (variations in humidity, especially on rainy days), biodegradation (fungal growth), and chemical degradation or corrosion (metal deterioration). Among them, hydrolytic degradation caused the most significant changes in some materials.[40,82]

(4) Given the long degradation time of materials and the environmental consequences of improper disposal, raising social awareness is essential to promoting sustainable practices. Encouraging recycling and ensuring proper waste disposal are key to minimizing environmental impact.

Additionally, students formulated the following specific conclusions for each material type:

Paper and cardboard

(1) Paper decomposes the fastest due to its low cohesion and fragility, breaking into smaller pieces. Thickness is a key factor that slows down its decomposition (hypotheses H2 and H3 accepted).

Table 11 Changes observed in plastic samples after 100 days of exposure

Plastic sample	At the beginning of the inquiry (Day 1)	At the end of the inquiry (Day 100)
White shopping bag (thin)		
White shopping bag (thick)		
Colored shopping bag		
Notebook cover		

Table 12 Changes observed in metallic samples after 100 days of exposure

Plastic simple	At the beginning of the inquiry (Day 1)	At the end of the inquiry (Day 100)
Tetra Pak (interior)		
Soda can (exterior)		
Soda can (interior)		

(2) Rain accelerates the degradation of paper and cardboard by softening the material and causing it to separate into layers (H2 and H3 accepted).

(3) Tetra Pak, composed of both cardboard and aluminum, degrades much more slowly than regular cardboard (H4 accepted).

Plastics and metals

(1) The slow decomposition of plastic and metal materials results in their long persistence in the environment (H1 accepted).

(2) No signs of degradation were observed in plastics (H5 rejected).

(3) The initial stages of corrosion were observed in metals (H6 accepted).

Green chemistry principles in the inquiry (RQ3). Table 13 presents the evidence gathered during the inquiry process that allows the identification of the green chemistry principles[5] underlying the students' inquiry. In total, five principles were identified including waste prevention (principle 1), less hazardous chemical syntheses (principle 3), use of renewable feedstocks (principle 7), design for degradation (principle 10), and real-time pollution prevention (principle 11). Moreover, all stages of the inquiry contributed to the application of green chemistry principles, particularly the conclusion stage, where all five principles were observed, and the inquiry planning stages, which notably reflected principle 10.

The IBL carried out can be considered successful in its indirect contributions to green chemistry principles, supported by the findings of Duangpummet *et al.*,[68] which indicate that IBL is effective for learning green chemistry principles if it addresses at least four of them. Similarly, it encourages students to explore their knowledge and discover for themselves how to apply green chemistry principles in real-life situations.[9] These findings are consistent with previous research, including the study by Lee,[70] who argued that students' reports indicate they are considering green chemistry principles even in experiments where they are not explicitly asked to address them.

Student evaluations of the experience (RQ4)

Overall, the experience was well received by students ($\bar{x} = 8.08/10$, $\sigma^2 = 2.15$) (question "a" from the survey). Regarding their perception of acquired learning (question "b"), students

Table 13 Green chemistry principles underlying the inquiry designed and implemented by students

Inquiry phases	Related green chemistry principle	Evidence
Phase 1. Inquiry planning and designing		
Problem formulation	Principle 1. Waste prevention	Students identify a real-world problem—the accumulation of waste in their environment—and decide to investigate what happens to materials over time, reflecting the need to prevent waste generation
	Principle 10. Design for degradation	Students investigate what happens to materials exposed to the environment for extended periods and whether they degrade naturally or persist. This prompts reflection on the design and composition of materials
Students' theoretical background	Principle 10. Design for degradation	Students search for information about the properties of materials and their relationship with degradation
Hypotheses	Principle 10. Design for degradation	Students formulate hypotheses about the degradation of materials based on their chemical composition and properties
Selection of samples and study variables	Principle 10. Design for degradation	Students select materials and the most suitable variables to study degradation over time. This encourages reflection on whether the final design persists in the environment or degrades into harmless products
Phase 2. Inquiry implementation		
Implementation and collected data	Principle 11. Real-time analysis for pollution prevention	Students propose observing and recording different degradation mechanisms over a 100-day period. During this time, they track when the material breaks down or disappears and observe changes in color, shape, or texture, allowing them to reflect on how environmental factors affect material properties
Phase 3. Interpretation of results and conclusion drawing		
Students' interpretation of results	Principle 10. Design for degradation	Students interpret the results by relating external factors to the properties of materials, reflecting on material design
Students' conclusions	Principle 1. Waste prevention	Students identify that promoting recycling and ensuring proper waste disposal are key to minimizing environmental impact
	Principle 3. Less hazardous chemical syntheses	Students understand that materials with long degradation periods have greater environmental impact and should be designed to produce substances with little or no toxicity
	Principle 7. Use of renewable feedstocks	The promotion of recycling and proper waste disposal suggests an interest in reducing dependence on non-renewable resources, aligning with the use of more sustainable materials
	Principle 10. Design for degradation	The students' conclusion that 100 days is not enough for complete degradation highlights the need to design products that can break down into non-harmful substances
	Principle 11. Real-time analysis for pollution prevention	Observing various degradation mechanisms (photodegradation, biodegradation, corrosion, *etc.*) helps students understand how materials break down in the environment

Table 14 Categorization of responses to the question "I have learned…"

Category	Description	Percentage (%)	Example
Material characteristics	Knowledge about materials and their degradation	40.0	I have learned that each material has very different characteristics and compositions, which make some take much longer to degrade
Degradation	Changes in materials over time	32.0	Not all materials degrade in the same way due to their chemical composition and structure Plastics in nature may undergo slight changes due to weather conditions. Their condition over time is predictable since they undergo minimal change
Environmental impact	Consequences of material degradation on the environment	20.0	Plastics take the longest to degrade, which is why they remain in streets and oceans for much longer
Other	Skepticism and unclear answers	8.0	I already knew all the information I learned

highlighted their increased knowledge of materials, degradation processes, and environmental implications (Table 14). Additionally, participants reported a perceived improvement in their knowledge before and after the inquiry (before: 5.36/10, $\sigma^2 = 4.79$; after: 7.64/10, $\sigma^2 = 3.03$) (question "c").

Students observed how the degradation of different materials impacts the environment, fostering a critical understanding of sustainability. Learning chemistry in environmental contexts through scientific inquiry provides students with a unique opportunity to use their research findings to understand real-world environmental issues, enhancing their environmental sensitivity in alignment with the principles of green chemistry.[37,85] Advancing the transition toward a greener world requires integrating education with supportive policies for ecological transition. Eco-innovation projects such as this represent valuable educational strategies to promote this shift.[51]

Student engagement in the inquiry (question "d") was notably high, with 72% reporting significant involvement, 24% very high involvement, and only 4% indicating no engagement. These findings align with Davis *et al.*,[86] who also observed a significant increase in student participation in IBL.

Table 15 presents the response categories regarding the collaborative learning methodology used in the inquiry (question "e").

As observed (Table 15), 44.8% of students viewed inquiry as an innovative methodology that fosters collaborative group work. This dimension encompasses both a positive attitude toward teamwork and the ability to critically reflect on the results obtained, while respecting and valuing peers' ideas and making decisions collectively.[72] Group collaboration was key to the success of the inquiry, enabling students to actively participate in its different stages, an aspect recognized by 10.5% of participants. Through hypothesis formulation, experimental design, data collection, and analysis, students developed cooperation and communication skills, allowing them to compare results and gain a more comprehensive understanding of degradation processes. Regarding the proposed designs, 15.8% of students highlighted that inquiry enhanced their motivation and creativity. Additionally, 28.9% of students perceived that group collaboration also contributed to meaningful learning acquisition.

This social construction of learning is also influenced by the emotions that emerge during inquiry. Fig. 2 presents the emotions reported in response to question "f".

It can be stated that positive emotions predominated during the inquiry, given that more than half of the students reported feeling "very" or "quite" in several emotional categories. Specifically, students felt enthusiastic (72%), comfortable (72%), calm (64%), happy (64%), secure (60%), and confident (56%). These results suggest that inquiry not only enhances knowledge acquisition but also involves a broad range of emotions essential for learning.[70,73–75]

However, 36% of students reported feeling quite (20%) or very dissatisfied (16%) with the inquiry process. This dissatisfaction

Table 15 Categorization of responses to the question "Would you like the subject to always be taught through collaborative inquiries like the one we conducted?"

Category	Percentage (%)	Examples
Inquiry as an innovative methodology	44.8	Yes, because it's a different way of learning, not the usual approach
Meaningful learning	28.9	I'd like to keep working this way because if you study for an exam, you forget it in a week, but with inquiry, you learn more
Motivation and creativity	15.8	Yes. Inquiry captures our attention more because it's a fun and creative way to work where we have to think carefully about the steps we take
Active learning	10.5	I'd like to keep doing inquiries because it makes me feel more engaged in my learning

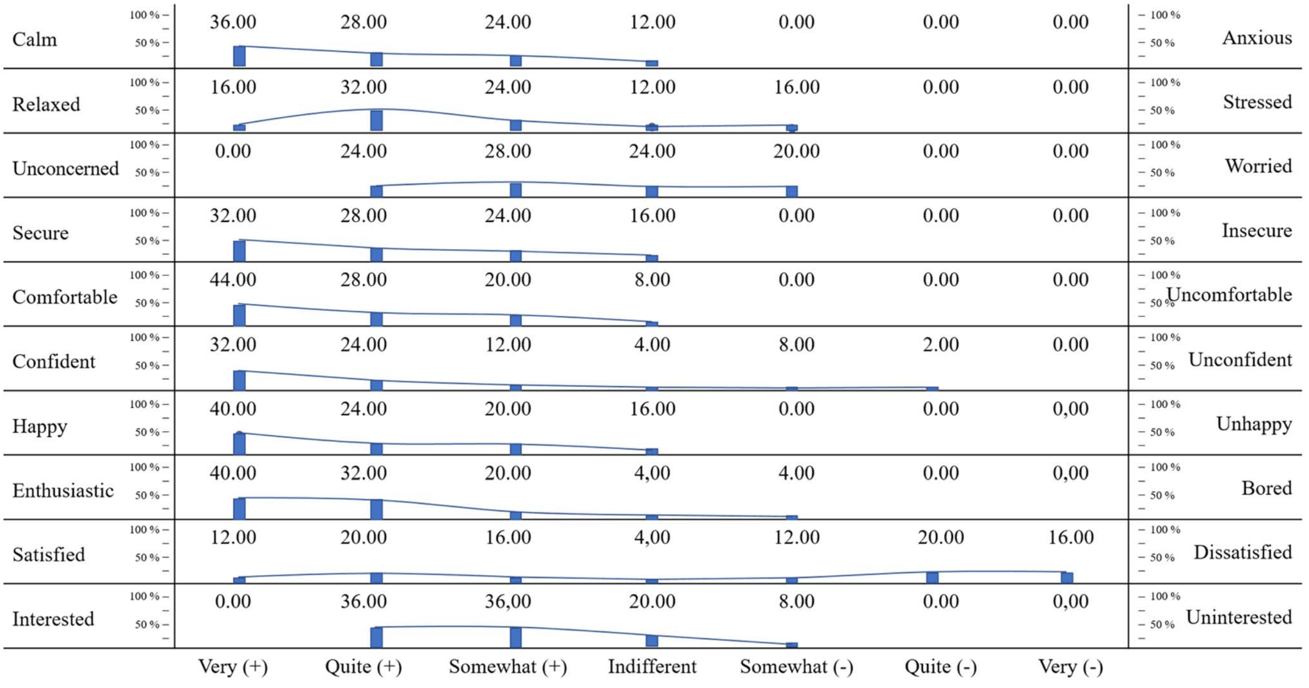


Fig. 2 Emotions experienced during inquiry.

could stem from several factors, such as the lack of familiarity with this approach, challenges in collaborating with peers, or misaligned expectations, whether they anticipated a more guided approach or expected more immediate, visible findings.

Conclusions

This study has presented the results of IBL on material degradation, conducted collaboratively with secondary school students in a real-world context during 100 days.

Regarding RQ1, the design and implementation of the inquiry carried out by the students is considered adequate and effective in achieving the proposed objectives. Students selected various discarded materials from their surroundings including paper, cardboard, plastic, and metal, each exhibiting different degrees of deterioration. This selection allowed them to observe real-life examples of degradation, facilitating the formulation of hypotheses on the environmental factors that may have contributed to the observed deterioration. Their hypotheses focused on the effects of environmental variables such as sun exposure, rain or humidity, and temperature fluctuations. Additionally, they established a systematic data collection protocol, regularly recording both environmental conditions and the degree of degradation of each material. The prolonged observation of degradation processes over the course of a trimester provided a deeper learning experience, allowing students to analyze changes in the materials in a progressive and evidence-based manner. A key aspect of the process was the collaborative work involved in designing and making decisions across the different stages of the inquiry. This collaboration was particularly crucial in data interpretation, enabling students to connect empirical observations to environmental factors, identify degradation patterns, and propose evidence-based explanations.[60,66] Furthermore, this process encouraged reflection on the need to adopt sustainable practices[7] to mitigate the environmental impact of waste, fostering awareness of reduction, reuse, and recycling as fundamental strategies to minimize pollution.

Regarding RQ2, the explanatory models used by students to understand material degradation and its environmental effects integrated multiple key factors. These included solar radiation, which accelerates the degradation of certain plastics by breaking down their polymers; temperature, which influences how quickly the chemical bonds of materials deteriorate; humidity, which can facilitate hydrolysis processes and increase the susceptibility of materials to wear; and microorganisms, which contribute to the biodegradation of certain materials by breaking them down into simpler compounds.

Students also linked these degradation processes to negative environmental impacts, such as the accumulation of materials (especially plastics) in the ecosystem, the release of toxic substances, and ecosystem disruption. Integrating these models not only allowed students to understand material degradation scientifically, but also analyze its environmental implications, extending the learning experience beyond the classroom context. In this regard, the inquiry encouraged reflection on the importance of responsible consumption habits and the need to transition toward more sustainable production models that minimize waste and promote the circular economy, reinforcing the relevance of green chemistry in everyday life.

In relation to RQ3, the IBL approach indirectly revealed five underlying principles of green chemistry, as following:[5] waste prevention (principle 1), less hazardous chemical synthesis (principle 3), use of renewable feedstocks (principle 7), design for degradation (principle 10), and real-time analysis for pollution prevention (principle 11), particularly during the planning and conclusion phases of the inquiry, consistent with the findings of Duangpummet *et al.*[68] However, other principles, such as atom economy (principle 2), designing safer chemicals (principle 4), safer solvents and auxiliaries (principle 5), design for energy efficiency (principle 6), reduction of derivatives (principle 8), catalysis (principle 9), and safer chemistry for accident prevention (principle 12), were not addressed. This highlights the need to promote educational proposals that bring green chemistry principles, typically associated with industrial contexts, closer to students' realities.[9,70] This study underscores that bringing green chemistry into the classroom offers unique opportunities for students to not only learn responsible scientific concepts and practices but also develop critical awareness of their role in planetary sustainability.[7,9,10,55] Green chemistry can promote health and safety by reducing waste and fostering students' sense of ownership and belonging.[9]

Regarding RQ4, students' perceptions suggest that IBL is a well-received approach, with high student engagement, fostering learning about key chemistry topics such as material properties, degradation processes, and environmental impact. Although students often struggle to integrate scientific knowledge into their daily lives,[87] this study demonstrates that scientific inquiry is an effective strategy to promote this integration.[38] Ultimately, the experience not only deepened students' understanding of material degradation but also raised awareness of the importance of addressing environmental issues caused by improperly discarded waste. The implementation of long-term collaborative proposals within IBL represents a rare methodological innovation in chemistry education, where investigations are typically short-term and individually conducted. This study shows that this key aspect is well received by students,[70] given that it enhances motivation and creativity. When situated in a collaborative context, it fosters meaningful learning, encourages active student engagement, and promotes positive emotions, helping to overcome common challenges in inquiry-based processes.[17] Moreover, this study advances previous research by integrating the analysis of students' emotions throughout the inquiry process, providing a more holistic perspective on learning and demonstrating the predominance of positive emotions during the innovative proposal, which in turn boosts motivation and creativity.

Educational implications, limitations, and future directions

The first educational implication highlights the importance of an extended duration of at least 100 days for the proposed inquiry. This period is essential for students to identify and understand the initial stages of material degradation, as well as to recognize the difficulty of plastic and metal decomposition in the environment. For a more comprehensive assessment, an even longer period would be recommended.

Another educational implication stems from the outdoor nature of this inquiry, where samples may be affected by various environmental factors, despite each student using three replicates per experiment. Ultimately, at the individual level, identical reproducibility across experiments is not guaranteed, even for the same student. This requires students to collaborate, share, and compare data, leading to a joint analysis that helps identify general trends. This process fosters teamwork, scientific communication, and collective data analysis.

As a limitation of this study, it is important to note that while each student selected samples that met the agreed-upon criteria, slight variations may have existed in thickness or printed design among samples from different students. Additionally, small differences in the exposure location of the materials were possible, although all students placed their samples outdoors. However, these minor discrepancies do not affect the validity of the experiment or compromise the reliability of the results.

In addition, although the evidence shows that aspects related to five of the green chemistry principles were addressed during the stages of the IBL, a limitation is that the experience does not allow for the exploration of all twelve principles. Consequently, a final session is proposed as a closing IBL, in which all the principles of green chemistry can be explicitly addressed.

Regarding future research directions, these preliminary findings will be integrated into educational game-based mobile applications currently being developed as part of a research project on ecological and digital transition to enhance science education.

Data availability

Data collected for this study have not been made publicly available owing to ethical considerations. Our research participants have consented to share their data only with the researchers directly involved in this project.

Author contributions

The authors of this work have been equally involved in all stages of the research, from conceptualization and methodological design to classroom implementation. Furthermore, they have equally contributed to data collection and analysis as well as to the writing and revision of the manuscript.

Conflicts of interest

There are no conflicts to declare.

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References

1 M. Duran and I. Dökme, The effect of the inquiry-based learning approach on student's critical-thinking skills, *Eurasia J. Math. Sci. Technol. Educ.*, 2016, **12**(12), 2887–2908, DOI: 10.12973/eurasia.2016.02311a.
2 European Commission, *Science Education for Responsible Citizenship*, Publications Office of the European Union, Luxembourg, 2015.
3 L. Magnussen, D. Ishida and J. Itano, The impact of the use of inquiry-based learning as a teaching methodology on the development of critical thinking, *J. Nurs. Educ.*, 2000, **39**, 360–364, DOI: 10.3928/0148-4834-20001101-07.
4 S. Prayogi and L. Yuanita, Critical Inquiry Based Learning: A Model of Learning to Promote Critical Thinking among Prospective Teachers of Physic, *J. Turk. Sci. Educ.*, 2018, **15**, 43–56, DOI: 10.1088/1742-6596/1317/1/012193.
5 P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, New York, 1998, p. 30.
6 R. A. Sheldon, Metrics of green chemistry and sustainability: past, present, and future, *ACS Sustainable Chem. Eng.*, 2018, **6**, 32–48, DOI: 10.1021/acssuschemeng.7b03505.
7 L. B. Armstrong, L. M. Irie, K. Chou, M. Rivas, M. C. Douskey and A. M. Baranger, What's in a word? Student beliefs and understanding about green chemistry, *Chem. Educ. Res. Pract.*, 2024, **25**, 115–132, DOI: 10.1039/D2RP00270A.
8 A. S. Cannon, A. E. Keirstead, R. Hudson, I. J. Levy, J. MacKellar, M. Enright and E. M. Howson, Safe and sustainable chemistry activities: fostering a culture of safety in K–12 and community outreach programs, *J. Chem. Educ.*, 2020, **98**(1), 71–77, DOI: 10.1021/acs.jchemed.0c00128.
9 P. Nahlik, L. Kempf, J. Giese, E. Kojak and P. L. Daubenmire, Developing green chemistry educational principles by exploring the pedagogical content knowledge of secondary and pre-secondary school teachers, *Chem. Educ. Res. Pract.*, 2023, **24**, 283–298, DOI: 10.1039/D2RP00229A.
10 V. G. Zuin, I. Eilks, M. Elschami and K. Kümmerer, Education in green chemistry and in sustainable chemistry: perspectives towards sustainability, *Green Chem.*, 2021, **23**, 1594–1608, DOI: 10.1039/D0GC03313H.
11 E. Hines, M. L. Jaubet, G. V. Cuello, R. Elías and G. V. Garaffo, Macro-, meso- and microplastic abundance in sandy beaches and factors influencing their distribution in a SW Atlantic resort, *Mar. Environ. Res.*, 2023, **190**, 106104, DOI: 10.1016/j.marenvres.2023.106104.
12 D. Darwis, I. F. Rachmat and A. Karim, The effectiveness of green chemistry practicum training based on experimental inquiry to improve teachers' science process skills, *Ilk. Online*, 2021, **20**(4), 540–549, DOI: 10.17051/ilkonline.2021.04.58.
13 A. J. Franco-Mariscal, Competencias científicas en la enseñanza y el aprendizaje por investigación. Un estudio de caso sobre corrosión de metales en secundaria [Scientific competences in teaching and learning through research. A case study about the corrosion of metals in secondary education], *Enseñanza las Ciencias*, 2015, **33**(2), 231–252, DOI: 10.5565/rev/ensciencias.1645.
14 N. Garner, A. Siol and I. Eilks, The potential of non-formal laboratory environments for innovating the chemistry curriculum and promoting secondary school level students education for sustainability, *Sustainability*, 2015, **7**, 1798–1818, DOI: 10.3390/su7021798.
15 D. Mandler, R. Blonder, M. Yayon, R. Mamlok-Naaman and A. Hofstein, Developing and implementing inquiry-based, water quality laboratory experiments for high school students to explore real environmental issues using analytical chemistry, *J. Chem. Educ.*, 2014, **91**(4), 492–496, DOI: 10.1021/ed200586r.
16 I. S. Putra, E. Susilaningsih and S. Wardani, Development of inquiry-based chemistry laboratory sheet oriented to green chemistry for improving the science process skills, *J. Innov. Sci. Educ.*, 2018, **7**, 87–94.
17 T. Wang, W. Wang and J. Wei, Challenges Encountered by Student Teachers in an Inquiry-Based Laboratory Process, *J. Chem. Educ.*, 2022, **99**(12), 3954–3963, DOI: 10.1021/acs.jchemed.2c00334.
18 G. Ceballos, P. R. Ehrlich, A. D. Barnosky, A. García, R. M. Pringle and T. M. Palmer, Accelerated modern human–induced species losses: Entering the sixth mass extinction, *Sci. Adv.*, 2015, **1**(5), e1400253, DOI: 10.1126/sciadv.1400253.
19 A. Lusher, P. Hollman and J. Mendoza-Hill, *Microplastics in Fisheries and Aquaculture: Status of Knowledge on Their Occurrence and Implications for Aquatic Organisms and Food Safety*, FAO, Rome, 2017.
20 K. M. Van Heuvelen, G. W. Daub, L. N. Hawkins, A. R. Johnson, H. Van Ryswyk and D. A. Vosburg, How do I design a chemical reaction to do useful work? Reinvigorating general chemistry by connecting chemistry and society, *J. Chem. Educ.*, 2020, **97**(4), 925–933, DOI: 10.1021/acs.jchemed.9b00281.
21 M. Donoso, La lucha contra los plásticos: una estrategia para el cambio en los patrones de producción y consumo [The fight against plastics: a strategy for change in production and consumption patterns], *Unisanta Biosci.*, 2018, **7**(6), 156–165.
22 M. Smith, D. C. Love, C. M. Rochman and R. A. Neff, Microplastics in seafood & the implications for human health, *Curr. Environ. Health Rep.*, 2018, **5**, 375–386, DOI: 10.1007/s40572-018-0206-z.
23 A. Iles, Greening chemistry: emerging epistemic political tensions in California and the United States, *Public Underst. Sci.*, 2011, **22**(4), 460–478, DOI: 10.1177/0963662511404306.
24 M. Epicoco, V. Oltra and M. Saint Jean, Knowledge dynamics and sources of eco-innovation: Mapping the Green Chemistry community, *Technol. Forecast. Soc. Change*, 2014, **81**, 388–402, DOI: 10.1016/j.techfore.2013.03.006.
25 E. J. Woodhouse and S. Breyman, Green Chemistry as Social Movement?, *Sci. Technol. Hum. Values*, 2005, **30**, 199–222, DOI: 10.1177/0162243904271726.

26 T. R. Karl and K. E. Trenberth, Modern global climate change, *Science*, 2003, **302**, 1719–1723, DOI: 10.1126/science.1090228.
27 W. Thuiller, Climate change and the ecologist, *Nature*, 2007, **448**, 550–552, DOI: 10.1038/448550a.
28 K. Abbass, M. Z. Qasim, H. Song, M. Murshed, H. Mahmood and I. Younis, A review of the global climate change impacts, adaptation, and sustainable mitigation measures, *Environ. Sci. Pollut. Res.*, 2022, **29**, 42539–42559, DOI: 10.1007/s11356-022-19718-6.
29 C. M. Malanoski, A. Farnsworth, D. J. Lunt, P. J. Valdes and E. E. Saupe, Climate change is an important predictor of extinction risk on macroevolutionary timescales, *Science*, 2024, **383**, 1130–1134, DOI: 10.1126/science.adj5763.
30 P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. Van Diemen, D. McCollum *et al.*, *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, WMO and UNEP, Geneva, 2022.
31 A. Bronstert, Floods and climate change: interactions and impacts, *Risk Anal.*, 2003, **23**(3), 545–557, DOI: 10.1111/1539-6924.00335.
32 S. Jiang, L. Tarasova, G. Yu and J. Zscheischler, Compounding effects in flood drivers challenge estimates of extreme river floods, *Sci. Adv.*, 2024, **10**, eadl4005, DOI: 10.1126/sciadv.adl4005.
33 H. Wang, J. Liu, M. Klaar, A. Chen, L. Gudmundsson and J. Holden, Anthropogenic climate change has influenced global river flow seasonality, *Science*, 2024, **383**, 1009–1014, DOI: 10.1126/science.adi9501.
34 A. Zargar, R. Sadiq, B. Naser and F. I. Khan, A review of drought indices, *Environ. Rev.*, 2011, **19**, 333–349.
35 A. Ramos and A. Torralba, Uso y potencial del Programa LIFE para la Educación Ambiental en educación formal, no-formal e informal, y especialmente en Educación Primaria [Use and potential of the LIFE Programme for Environmental Education in formal, not formal andinformal education, and especially in Primary Education], *Rev. Eureka Enseñ. Divulg. Cienc.*, 2020, **17**(3), 3501, DOI: 10.25267/Rev_Eureka_ensen_divulg_cienc.2020.v17.i3.3501.
36 United Nations, *Transforming Our World: the 2030 Agenda for Sustainable Development (No. A/RES/70/1)*, United Nations, 2015, https://t.ly/yfJ7.
37 G. M. Bodner, Understanding the Change Toward a Greener Chemistry by Those Who Do Chemistry and Those Who Teach Chemistry, in *Relevant Chemistry Education: from Theory to Practice*, ed. I. Eilks and A. Hofstein, Springer, Dordrecht, 2015, pp. 263–284, DOI: 10.1007/978-94-6300-175-5_14.
38 E. F. de Waard, G. T. Prins and W. R. van Joolingen, Pre-university students' perceptions about the life cycle of bioplastics and fossil-based plastics, *Chem. Educ. Res. Pract.*, 2020, **21**(3), 908–921, DOI: 10.1039/C9RP00293F.
39 M. Burmeister, F. Rauch and I. Eilks, Education for Sustainable Development (ESD) and chemistry education, *Chem. Educ. Res. Pract.*, 2012, **13**(2), 59–68, DOI: 10.1039/C1RP90060A.
40 B. Posada, La degradación de los plásticos [The degradation of plastics], *Rev. Univ. EAFIT*, 1994, **30**, 67–86.
41 C. Vasile, Degradation and decomposition, in *Handbook of Polyolefins*, ed. C. Vasile, Routledge, London, 2000, pp. 413–476.
42 M. Kurtz, *Handbook of Environmental Degradation of Materials*, Elsevier, 2012.
43 S. Lambert, C. Sinclair and A. Boxall, Occurrence, degradation, and effect of polymer-based materials in the environment, *Rev. Environ. Contam. Toxicol.*, 2013, **227**, 1–53, DOI: 10.1007/978-3-319-01327-5_1.
44 S. Zehra, M. Mobin and J. Aslam, An overview of the corrosion chemistry, in *Environmentally Sustainable Corrosion Inhibitors*, Elsevier, 2022, pp. 3–23, DOI: 10.1016/B978-0-323-85405-4.00012-4.
45 K. Sevim and J. Pan, Un modelo para la degradación hidrolítica y la erosión de polímeros biodegradables, *Acta Biomater.*, 2018, **66**, 192–199, DOI: 10.1016/j.actbio.2017.11.023.
46 C. V. Stephenson, B. C. Moses and W. S. Wilcox, Ultraviolet irradiation of plastics. I. Degradation of physical properties, *J. Polym. Sci.*, 1961, **55**, 451–464, DOI: 10.1002/pol.1961.1205516204.
47 K. Pielichowski, J. Njuguna and T. M. Majka, *Thermal Degradation of Polymeric Materials*, Elsevier, 2022.
48 M. Villetti, J. Crespo, M. Soldi, A. Pires, R. Borsali and V. Soldi, Thermal degradation of natural polymers, *J. Therm. Anal. Calorim.*, 2002, **67**, 295–303, DOI: 10.1023/A:1013902510952.
49 K. Mohan, Microbial deterioration and degradation of polymeric materials, *J. Biochem. Technol.*, 2011, **2**, 210–215.
50 W. D. Callister and D. G. Rethwisch, *Fundamentals of Materials Science and Engineering: an Integrated Approach*, John Wiley & Sons, Hoboken, 2020.
51 X. Li, L. Ma, S. Khan and X. Zhao, The Role of Education and Green Innovation in Green Transition: Advancing the United Nations Agenda on Sustainable Development, *Sustainability*, 2023, **15**, 12410, DOI: 10.3390/su151612410.
52 L. C. Voumik and M. Ridwan, Impact of FDI, industrialization, and education on the environment in Argentina: ARDL approach, *Heliyon*, 2023, **9**, e12872, DOI: 10.1016/j.heliyon.2023.e12872.
53 L. Ke, T. D. Sadler, L. Zangori and P. J. Friedrichsen, Developing and using multiple models to promote scientific literacy in the context of socio-scientific issues, *Sci. Educ.*, 2021, **30**, 589–607, DOI: 10.1007/s11191-021-00206-1.
54 S. Rahayu, Socio-scientific Issues (SSI) in Chemistry Education: Enhancing Both Students' Chemical Literacy and Transferable Skills, *J. Phys.: Conf. Ser.*, 2019, **1227**, 012008, DOI: 10.1088/1742-6596/1227/1/012008.
55 J. J. A. Idul, Q. M. I. Jaculbe, N. S. Lucine, M. D. Canama, M. D. Galve, C. L. Sayson and A. M. P. Walag, Green Modules: Integrating Green and Sustainable Chemistry Principles to Secondary Chemistry Modules through

Process-Oriented Guided Inquiry Learning, *J. Chem. Educ.*, 2025, **102**(3), 1104–1116, DOI: 10.1021/acs.jchemed.4c01360.

56 M. M. López-Fernández, F. González-García and A. J. Franco-Mariscal, Should we ban single-use plastics? A role-playing game to argue and make decisions in a grade-8 school chemistry class, *J. Chem. Educ.*, 2021, **98**(12), 3947–3956, DOI: 10.1021/acs.jchemed.1c00580.

57 S. Jiusto, S. McCauley and J. C. Stephens, Integrating shared action learning into higher education for sustainability, *J. Sustainability Educ.*, 2013, **5**, 1–22.

58 D. Rowe, Environmental Literacy and Sustainability as Core Requirements: Success Stories and Model, in *Teaching Sustainability at Universities*, ed. W. L. Filho, Peter Lang, Frankfurt, 2002, pp. 79–103.

59 D. Selby, As the heating happens: Education for sustainable development or education for sustainable contraction?, *Int. J. Innov. Sustain. Dev.*, 2007, **2**, 249–267, DOI: 10.1504/IJISD.2007.017938.

60 A. M. Asiri, Scientific inquiry-based teaching practices as perceived by science teachers, *Am. J. Educ. Res.*, 2018, **6**(4), 297–307, DOI: 10.12691/education-6-4-2.

61 B. K. Younis, The effects of scientific inquiry simulations on students' higher order thinking skills of chemical reaction and attitude towards chemistry, *Am. J. Educ. Res.*, 2017, **5**, 1158–1161, DOI: 10.12691/education-5-11-7.

62 D. M. Ferreira, F. C. Sentanin, K. N. Parra, V. M. N. Bonini, M. de Castro and A. C. Kasseboehmer, Implementation of inquiry-based science in the classroom and its repercussion on the motivation to learn chemistry, *J. Chem. Educ.*, 2021, **99**(2), 578–591, DOI: 10.1021/acs.jchemed.1c00287.

63 N. M. Goodey and C. P. Talgar, Guided inquiry in a biochemistry laboratory course improves experimental design ability, *Chem. Educ. Res. Pract.*, 2016, **17**, 1127–1144, DOI: 10.1039/C6RP00142D.

64 B. Tafa, The types and inquiry level of chemistry laboratory courses in Ethiopia higher education institutes: the case of practical organic chemistry I, *World J. Chem. Educ.*, 2014, **2**, 48–53, DOI: 10.12691/WJCE-2-4-1.

65 S. Gencer and F. Ekici, Preservice chemistry teachers' understanding of surface tension through guided-inquiry, *J. Chem. Educ.*, 2022, **99**(12), 3946–3953, DOI: 10.1021/acs.jchemed.2c00330.

66 S. Bevins and G. Price, Reconceptualising inquiry in science education, *Int. J. Sci. Educ.*, 2016, **38**(1), 17–29, DOI: 10.1080/09500693.2015.1124300.

67 National Research Council (NRC), *National Science Education Standards*, National Academy Press, Washington, DC, 1996.

68 P. Duangpummet, P. Chaiyen and P. Chenprakhon, Lipase-catalyzed esterification: An inquiry-based laboratory activity to promote high school students' understanding and positive perceptions of green chemistry, *J. Chem. Educ.*, 2019, **96**(6), 1205–1211, DOI: 10.1021/acs.jchemed.8b00855.

69 K. L. Cacciatore and H. Sevian, Teaching lab report writing through inquiry: A green chemistry stoichiometry experiment for general chemistry, *J. Chem. Educ.*, 2006, **83**(7), 1039, DOI: 10.1021/ed083p1039.

70 D. B. Lee, Re-casting traditional organic experiments into green guided-inquiry based experiments: student perceptions, *Green Chem. Lett. Rev.*, 2019, **12**, 107–116, DOI: 10.1080/17518253.2019.1609598.

71 M. Karpudewan, Z. Ismail and W.-M. Roth, Ensuring sustainability of tomorrow through green chemistry integrated with sustainable development concepts (SDCs), *Chem. Educ. Res. Pract.*, 2012, **13**, 120–127, DOI: 10.1039/C1RP90066H.

72 Y. Huang, Effectiveness of inquiry-based science laboratories for improving teamwork and problem-solving skills and attitudes, *J. Res. Sci. Teach.*, 2022, **59**(3), 329–357, DOI: 10.1002/tea.21729.

73 A. Bellocchi and A. Amat, Emotion and Science Teacher Education, in *Handbook of Research on Science Teacher Education*, ed. J. Luft and G. Jones, Routledge, New York, 2022, pp. 426–438.

74 G. L. Sinatra, S. H. Broughton and D. Lombardi, Emotions in science education, in *International Handbook of Emotions in Education*, ed. R. Pekrun and L. Linnenbrink-Garcia, Routledge, New York, 2014, pp. 415–437.

75 M. M. Alarcón-Orozco, A. J. Franco-Mariscal, J. M. Oliva and A. Blanco-López, Emotions Experienced by Preservice Early Childhood Teachers During a Training Program in Inquiry-Based Science Education, *J. Res. Sci. Teach.*, 2025, 1–23, DOI: 10.1002/tea.70007.

76 M. M. López-Fernández, El desarrollo de habilidades de pensamiento crítico mediante el diseño, implementación y evaluación de una secuencia de enseñanza-aprendizaje para la educación secundaria obligatoria sobre la contaminación medioambiental por plásticos [The development of critical thinking skills through the design, implementation and evaluation of a teaching-learning sequence for compulsory secondary education on environmental pollution by plastics], Doctoral thesis, University of Granada, Spain, 2022, https://hdl.handle.net/10481/79640.

77 A. J. Franco-Mariscal, R. Franco-Mariscal and G. Salas-García, El tren orbital: un juego educativo basado en una analogía para aprender la configuración electrónica en secundaria [The orbital train: an educational game based on an analogy for learning the electronic configuration in secondary school], *Rev. Eletrôn. Ludus Sci.*, 2017, **1**, 1–13, DOI: 10.30691/relus.v1i2.978.

78 A. Blanco-López and T. Lupión-Cobos, *La competencia científica en las aulas. Nueve propuestas didácticas [Scientific competence in the classroom. Nine didactic proposals]*, Andavira Editora, Santiago de Compostela, Spain, 2015.

79 P. Gil and M. Martínez, Emociones auto-percibidas en las clases de educación física en primaria, *Univ. Psychol.*, 2015, **14**, 923–936.

80 R. Méndez, *Materiales Al Descubierto. La Guía Esencial*, Autoedición, 2023.

81 S. Barroso and J. Ibáñez, *Introducción al conocimiento de materiales*, UNED, Madrid, 2014.

82 W. D. Callister and D. G. Rethwisch, *Material Science and Engineering*, Wiley, Hoboken, 2018.
83 A. J. Franco-Mariscal, Una práctica de laboratorio sobre corrosión de metales para secundaria [A laboratory practice on corrosion of metals for secondary school students], *Alamb., Did. Cienc. Exp.*, 2012, **70**, 98–108.
84 M. J. Cano-Iglesias and A. J. Franco-Mariscal, Una indagación sobre la corrosión de los metales y sus formas de protección [An inquiry about the corrosion of metals and their protection], *Alamb., Did. Cienc. Exp.*, 2024, **115**, 25–33.
85 P. T. Anastas, Twenty Years of Green Chemistry, *Chem. Eng. News*, 2011, **89**(26), 62–65.
86 A. N. Davis, S. G. Michaelov, C. J. Rogers, L. R. Weber, B. M. Boardman and G. M. Peters, Transforming a classic polymer demonstration into a flexible, inquiry-based laboratory experience for lower and upper division laboratories, *J. Chem. Educ.*, 2022, **99**(12), 3993–4000, DOI: 10.1021/acs.jchemed.2c00361.
87 T. D. Sadler and D. L. Zeidler, Patterns of informal reasoning in the context of socioscientific decision making, *J. Res. Sci. Teach.*, 2005, **42**(1), 112–138, DOI: 10.1002/tea.20042.