

Article

Bridging Nanoscience and Chemistry as a Lever for Developing Higher-Order Questioning Skills Among High School Students

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Abstract

Developing higher-order thinking skills in general, and question-asking skills in particular, is considered a cornerstone for fostering critical and cognitive thinking skills. Question-asking is a key component in student engagement toward understanding complex scientific concepts. This study investigates two innovative dimensions in chemistry education: the integration of nanoscience and nanotechnology aspects into chemistry instruction, and its impact on development of question-asking skills among 11th-grade high school students. Using a quasi-experimental design, 120 students were divided equally into experimental and control groups. Both groups read a simplified scientific text on redox reactions; the control group's text addressed redox reactions only, while the experimental group's text had nanoscience aspects embedded within the same redox context. Students' questions were evaluated by five judges using a validated four-level questioning hierarchy, ranging from factual to complex integrative knowledge. Results revealed significant differences in both the number and cognitive level of questions generated by the two groups. Students exposed to the nano-integrated text demonstrated markedly higher question-asking skills. In conclusion, integrating nanoscience into chemistry instruction was shown to be a powerful gateway to developing higher-order thinking, enabling students to ask more cognitively advanced questions, deepen their scientific understanding, and engage more meaningfully with scientific content.

Keywords: critical thinking; quality of questions; question asking ability (QAA); nanoscience education; scientific text

1. Introduction

Higher-order thinking skills encompass questioning, problem solving, critical thinking, and decision-making competencies (Watted, 2023a). Many researchers believe that traditional science curricula do not lead to the development and acquisition of higher-order thinking skills (Zohar & Dori, 2003). These curricula are still based on learning scientific definitions and facts without the context of their application in real life and the development of higher-order thinking (Antonio & Prudente, 2024; Chan & Erduran, 2025; Li et al., 2023).

To ensure that learners attain higher-order thinking skills, science must be taught in ways that stimulate high-level cognitive skills (Miri et al., 2007; Zohar, 2004). This is best done by exposing students to interdisciplinary problems that integrate technological, environmental, and social aspects of scientific subjects as an integral part of the science

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teaching. When taught in this framework, students are given the opportunity to use systemic thinking, are required to ask questions, and, on their own, seek explanations and possible solutions to the problem or issue presented to them or raised by them (Bati, 2023; Slavinec et al., 2019; Zoller, 2015).

Student-generated questions (SGQ) is an active learning strategy that emphasizes empowering students to engage in knowledge construction (Watted, 2023b). Many researchers consider SGQ related to the classroom topic to be a meaningful and engaging activity that extends students' content learning and develops their higher-order thinking skills. SGQ is a way to encourage students to engage in analysis, problem-solving, and inquiry. Moreover, SGQ can be used to activate metacognitive processes that lead to more effective learning. The quality of students' questions also provides a measure of their understanding and is in line with constructivist teaching principles to promote students' autonomous learning skills and cognitive development (Aflalo, 2021; Herranen & Aksela, 2019; Yu, 2009).

Student questions play an important role in science learning and inquiry-based approaches. A systematic review of 30 articles, both research and descriptive report articles, highlights the importance of using student questions as a starting point for inquiry-based science education (Herranen & Aksela, 2019).

Questioning is a natural trait that everyone possesses. Learners can develop questioning skills, but cannot develop, on their own, the ability to generate important questions. Teachers must help students learn to ask thoughtful questions. The format of help should be designed in a way that makes it easy for active learners to ask significant questions that trigger a series of other valuable questions. The series of questions will encourage learners to think critically. Higher-order questions, such as those involving prediction, inference, and evaluation, are particularly effective in promoting critical thinking. These types of questions require students to go beyond mere memory and engage in complex cognitive processes, which include idea analysis, comparison and contrast, inference, prediction, evaluation, and justification (Causey & Spencer, 2024; Chin & Brown, 2002; Chin & Osborne, 2008; Herranen & Aksela, 2019).

Beyond these basic sources, more recent literature continues to deepen the connection between the categorization of students' questions and the level of thinking they reflect. Causey and Spencer (2024), in a mixed-methods pilot study involving 33 children in a summer preschool program, showed that explicit instruction in the Question Formulation Technique (QFT) resulted in a significant increase in the number of "wonderment" and high-level questions. Similarly, Maplethorpe et al. (2022), in a study of 89 fifth- and sixth-grade students, found that the quality of questions students formulated was predicted by reading comprehension ability, positive attitudes toward writing, and perceived level of understanding of the text, with effects varying by text genre. Odden and Russ (2019), in a qualitative analysis of parallel case studies of undergraduate students discussing introductory physics, showed that certain 'vexing' questions that students formulate both stimulate and sustain their scientific thinking processes (sense-making) over time.

This distinction between lower- and higher-order questions can be further formalized through structured hierarchies that classify questions according to their cognitive level. Taboada and Guthrie (2006) developed one such hierarchy and found that the level of a question a student formulates is directly related to the depth of conceptual understanding gained from the text: lower-level questions (requesting a single fact) were associated with superficial understanding, whereas higher-level questions (integrating conceptual knowledge and identifying relationships among ideas) were associated with deeper and more meaningful conceptual understanding. This finding provides the theoretical basis for the four-level hierarchy used in the present study—from factual knowledge (Level 1) to questions integrating analysis and integration of information

(Level 4)—and clarifies why the level of a question, not merely its quantity, was chosen as a central measure for assessing the development of higher-order thinking among students (see Section 2.4, Table 2).

Nanoscience and nanotechnology can be characterized as comprising a gateway to a new world (Jackman et al., 2016). Nanoscience is a multidisciplinary science that studies materials, structures, and systems at the nanometer scale (Jones et al., 2013).

Educational researchers have proposed updating science curricula in schools by integrating concepts related to nanotechnology into teaching materials. They argue that such a revision will ultimately allow for the building of an educated and skilled workforce, as well as a responsible generation that will make correct decisions of a scientific nature (Blonder, 2021; Jackman et al., 2016; Spyrtou et al., 2021).

In this context, the study by Sakhnini and Blonder (2015) that examined the application of nanoscience in chemistry teaching in Israel noted that today's high school chemistry curriculum is loaded with many important chemical concepts and it is very difficult to add modern content to the existing curriculum. Nevertheless, many studies emphasize the importance of integrating modern chemistry content such as nanotechnology into the high school curriculum (Much et al., 2022). For this purpose, Sakhnini and Blonder (2015) described the eight fundamental concepts of nanoscience and nanotechnology for high school students. These concepts—including size and scale, size-dependent properties, characterization methods, classification of nanomaterials, and fabrication approaches, among others—were identified through a three-round Delphi study involving both nanotechnology researchers and science teachers, reflecting expert consensus on which nanoscale concepts are essential for high-school-level instruction. When students are exposed to nanotechnology, they perceive chemistry as more relevant to their lives, and more modern than the typical chemistry presented in school, and as a result, their motivation to study chemistry and related subjects increases (Sakhnini & Blonder, 2015).

In addition to the importance of integrating aspects of nanoscience and nanotechnology into high school and academic curricula, studies have shown the importance of the subject in developing higher-order thinking skills. The study of nanoscience and nanotechnology demonstrates to students how the circle of knowledge expands as well as reveals to them the connection between different scientific fields (Dori et al., 2014; Park, 2019).

A common learning approach in chemistry is inquiry. The results of a literature survey on learning chemistry using an inquiry approach reveal that such a model has both potential and limitations (Jegstad, 2024). Inquiry learning activities reflect scientific epistemology that comprises proposing, explaining, evaluating, justifying, and constructing knowledge. These activities are components of critical thinking skills (NRC, 2000). In practice, however, it has been found that students have difficulty asking questions, and thus using inquiry in teaching, chemistry in this case, contributes to students' critical thinking skills (Jegstad, 2024; Orosz et al., 2023; Santoso et al., 2018).

One way to perhaps inspire learners to ask questions in chemistry is by introducing them to the world of nanomaterials. The unique properties of matter at the nanoscale, which differ fundamentally from those observed at the macroscale, present students with phenomena that challenge their existing knowledge frameworks (Sarwar et al., 2024). This cognitive gap between the familiar and the unfamiliar creates a natural opportunity for epistemic curiosity and higher-order questioning. Moreover, integrating nanoscience into chemistry curricula has been shown to foster scientific curiosity, critical thinking, and innovation among students (Tawiah et al., 2024), while its inherently interdisciplinary nature provides students with opportunities to build integrative understanding across scientific domains (Kähkönen et al., 2016). Together, these features position nanoscience as a powerful lever for developing higher-order questioning skills in science education.

While prior research has demonstrated the potential of nanoscience education to foster scientific curiosity and critical thinking (Tawiah et al., 2024), and while the importance of higher-order questioning skills in science learning has been well established (Zohar, 2004; Miri et al., 2007), the specific impact of integrating nanoscience content into chemistry instruction on students' question-asking skills and the cognitive level of their questions remains largely unexplored, particularly at the secondary school level. Therefore, the present study aims to address this gap.

In light of the above literature review, which emphasizes on the one hand the importance of integrating innovative and emerging scientific topics into the school curriculum, and in particular the integration of nanoscience and nanotechnology, and on the other hand, the importance of developing higher-order thinking skills and fostering critical thinking among students, the current study examines the impact of integrating concepts and aspects of nanoscience and nanotechnology in chemistry studies on question-asking skills and the cognitive level of the questions raised by students. In doing so, the study aims to shed light on the importance of integrating nanoscience as a modern science relevant to everyday life and as a pedagogical tool for fostering higher-order thinking skills in science teaching. To this end, the study focuses on the ability of secondary school students studying chemistry to ask questions in general and inquiry-type questions in particular, after critical reading of a scientific text about oxidation–reduction reactions (redox) based on Abu Much's research (Abu-Much, 2021) that incorporated concepts and aspects of nanoscience on the subject of redox reactions. The subject of redox reactions is considered a fundamental and central topic in the chemistry curriculum and, therefore, constitutes an appropriate basis for examining the impact of integrating nanoscience on questioning skills and their cognitive level.

In line with the objectives of the study, the following research questions are examined:

How does studying a scientific text on redox reactions that incorporates aspects of nanoscience and nanotechnology affect students' question-asking skills? Specifically:

- (a) Their overall question-asking skills;
- (b) The cognitive level of the questions they raise;
- (c) The cognitive level of the questions they raise for further investigation.

2. Materials and Methods

2.1. Research Population and Sample

The study involved ($N = 120$) 11th-grade students from four classes (aged 16–17 years) from secondary schools in the Arab community in southern Israel. Both the experimental group and the control group had the same number of participants ($N = 60$). Additional details about the distribution of participants are presented in Table 1.

Table 1. Distribution of research participants among the study groups.

	Experimental Group (%)	Control Group (%)
Number of Participants	60 (50%)	60 (50%)
Grade Level	11th Grade	11th Grade
Track	Advanced Chemistry	Advanced Chemistry

The four classes were studying chemistry at the most advanced level (basically, equivalent to the AP level in the US or A-levels in the UK). The topic of redox reactions is thus part of these students' chemistry curriculum. Each class was assigned to either the experimental group or the control group. The control group studied an original scientific text on the subject of redox reactions that did not incorporate aspects of nanoscience and

nanotechnology, and the experimental group studied an integrated scientific text that incorporated concepts and aspects of nanoscience on the subject of redox reactions. The assignment was made via a convenience sample based on the authors' personal acquaintances with the schools in the area. To verify the homogeneity of the groups before the intervention, a chi-square test for homogeneity was performed for categorical variables. The results of the test indicated that no statistically significant differences were found between the experimental group ($N = 60$) and the control group ($N = 60$) as regards gender: $\chi^2(1) = 0.52$, $p = 0.47$; socioeconomic background: $\chi^2(2) = 1.34$, $p = 0.51$; and learning achievement: $\chi^2(3) = 4.33$, $p = 0.23$. These findings indicate the homogeneity of the groups at the beginning of the study.

The topic of redox reactions is a mandatory component of the external matriculation examination in the advanced chemistry curriculum in Israeli secondary schools, taught in 11th grade as part of the compulsory national chemistry program (Israel Ministry of Education, 2025). After studying the topic of redox reactions in accordance with the curriculum, only students in the experimental group had two consecutive introductory lessons (each lesson lasting 45 min) where they were exposed to basic concepts and principles in nanoscience and nanotechnology, using demonstrations, videos, and examples from everyday life.

After this, both groups participated in two consecutive lessons (each lesson lasting 45 min), during which each group was given reading assignment of a scientific text derived from an article by Abu-Much (2021) and adapted to the students' level. The text distributed to the control group dealt with the topic of redox reactions (reduction of silver ions) and included a description of a laboratory experiment and a presentation of its results, without any reference to aspects of nanoscience and nanotechnology. In contrast, the experimental group received a scientific text that, while also dealing with the topic of redox reactions, further included two different experiments for the reduction of silver ions: the first experiment led to the formation of a precipitate of neutral silver and the second experiment led to the formation of a suspension of nanometric silver particles.

After reading the scientific text, students from both groups were asked to write down any questions that the assignment raised in their mind.

This research complied with the American Psychological Association Code of Ethics. This study was reviewed and approved by the college's Institutional Review Board (approval number: [AACE-CE1-10072025]). Informed consent was obtained from each trainee.

2.2. Methodology, Tools, and Data Analysis

The current study applied a quasi-experimental research method, comparing a control group with an experimental group (Campbell & Stanley, 2015; Gopalan et al., 2020). Students in the experimental group received a scientific text on redox reactions in the context of nanoscience and nanotechnology, while students in the control group received a scientific text on redox reactions without the context of nanoscience and nanotechnology. At the end of the scientific text, students were asked to answer one of two questionnaires, depending on which group they were in (Appendix A or Appendix B).

2.3. Research Variables

The independent variable is critical reading of a scientific text on redox reactions, which takes two values: studying a scientific text with aspects of nanoscience and nanotechnology, and critical reading of a scientific text on redox reactions without the context of nanoscience and nanotechnology. The dependent variables are students' ability to ask questions after reading a scientific text and the cognitive level of the questions raised by the students.

2.4. Research Tools

The research tools were two questionnaires that students filled out after critical reading of a scientific text (Appendices A and B). The scientific text was derived from and based on primary literature that had been simplified to suit the students' reading level and their chemical scientific background. Primary literature is the term used for scientific texts originally written by scientists, that is, a scientist's report of their research work published in a peer-reviewed professional journal (Yarden et al., 2001). Each text contained the scientific background needed on redox reactions, an explanation of analytical methods performed during the presented experiment, the experimental procedure, and the results, translated into Arabic. The text was simplified linguistically and conceptually, and supplemented with foundational background explanations (e.g., basic redox terminology, principles of spectrophotometric analysis, and the Tyndall effect) to bridge the gap between the primary literature's assumed background and the students' knowledge level. The complete texts administered to the control and experimental groups were provided in full as Appendix C and Appendix D, respectively.

Both texts were derived from an original scientific article written by Abu-Much (2021). The article was selected because it met several necessary criteria. First, it addresses redox reactions, a mandatory topic in the advanced chemistry curriculum in Israeli secondary schools. Second, it describes laboratory experiments employing analytical methods appropriate for the scientific level of the students. Third, the text integrates concepts from the field of nanoscience with the topic of redox reactions. This approach is supported by the findings of Sakhnini and Blonder (2015), who found that presenting chemical content through a modern, applied-science perspective increases students' perceived relevance of the material being taught. Specifically, the experimental text visually highlights for students the transition from macroscale to nanoscale, i.e., the change from the gray precipitate of silver to the colorful suspension of silver nanoparticles, as a concrete marker of a 'new' chemical outcome. The text received by the control group was derived from the article and included a description of a lab experiment in the reduction of silver ions, without reference to nanoscience, and its analysis, while the text received by the experimental group included reference to and demonstrations of lab experiments and analyses that combine the topic of redox reactions and nanoscience. The following are excerpts from the two texts—for the control group and the experimental group, respectively—taken from Abu Much's article (Abu-Much, 2021):

"Reduction of Silver Ions by Copper Disks—A solution of silver nitrate (1 M) was prepared by dissolving 42.5 g of silver nitrate (AgNO_3 , 99%, Sigma-Aldrich, St. Louis, MO, USA) in 250 mL of double-distilled water. Ten copper disks (each with a mass of 1.5 g) were then added to the solution. Gradually, a gray precipitate appeared, while the solution turned from transparent to blue. After 30 min, the blue solution was separated from the silver precipitate by filtration and was set aside. Based on the values of the standard reduction potentials (E°) of copper and silver ions, we could estimate that Cu(s) can spontaneously reduce silver ions in an aqueous solution. The blue colored solution obtained was analyzed by a UV-vis spectrophotometer, Ultraspec 2100 pro, Amersham Biosciences, Little Chalfont, Buckinghamshire, UK".

"Reduction of silver ions by trisodium citrate—An aqueous solution of silver nitrate (AgNO_3 , 99%, Sigma-Aldrich, St. Louis, MO, USA) was prepared by dissolving 0.0425 g of silver nitrate in 250 mL of double-distilled water. The solution was placed on a stirring hot plate and was heated to boiling. An aqueous solution of 1% *w/w* trisodium citrate dihydrate ($\text{HOC(COONa)(CH}_2\text{COONa)}_2\cdot 2\text{H}_2\text{O}$, Sigma-Aldrich, St. Louis, MO, USA) was

prepared by dissolving 0.2 g in 20 mL of double-distilled water. Next, 5 mL of the trisodium citrate solution was added drop by drop to the boiled solution of silver nitrate while stirring vigorously. The mixture gradually turned from transparent to yellow-green, no precipitate was formed. The yellow-green-colored solution obtained was analyzed by a UV-vis spectrophotometer, Ultraspec 2100 pro, Amersham Biosciences, Little Chalfont, Buckinghamshire, UK.”

Students were asked to read the scientific text and answer the attached questionnaire. Only the following two questions were selected for analysis:

1. List all the questions you would like to ask after reading the scientific text.
2. From the list of questions, select the most interesting question you would like to investigate.

Students’ questions were validated for content by five judges, three chemistry experts, and two schoolteachers, according to the taxonomy developed by Huang et al. (2017), based on the four types of Marbach-Ad and Sokolove (2000). Categorization of the students’ questions, as level 1, 2, 3, or 4, in line with Taboada and Guthrie’s (2006) question hierarchy, was based on their complexity, namely, factual knowledge, conceptual knowledge including analysis, integration, and question complexity (Table 2). Questions on which no consensus was reached among the judges were excluded from the final statistical analysis.

Table 2. Questioning types and hierarchies.

Hierarchies ¹	Type of Question ²	Question Score	Examples
Level 1	The question is logically or verbally incorrect or stems from a misunderstanding or misapprehension.	0	Why does silver disappear when silver nitrate is dissolved in water? What is the original color of the copper disks? Does the laser radiation heat the solution? What is the reaction that occurs between laser radiation and the solution?
Level 2	Questions about factual propositions or simple descriptions from the text or phenomena that are directly identified by key words such as “what, where, when,” for facts. The answers to these questions are found in the text itself.	1	What color did the solution turn after the copper disks were added? Which substance was reduced? What was the resulting precipitate? Copper or silver? What is the difference between an oxidizing agent and a reducing agent?
Level 3	Cognitive process questions reflect the student’s extended thinking, extended thought, and synthesis of prior knowledge (more than is available in the text). In this process, the question should reflect the relationships between pieces of information, often including sorting, comparing, contrasting, classifying, and summarizing using keywords such as “how, what more, what causes...”	2	How can the color change of the solution from transparent to blue be explained chemically and scientifically? In the second experiment, was the reduced silver obtained in the form of nanoparticles? Is the reaction an exothermic reaction or an endothermic reaction? What prevented the nanoparticles of silver from undergoing attraction? Is the shining line in the yellow-green solution an indication of the existence of reduced silver nanoparticles? Did the negative charge of the citrate ions stabilize the particles?
Level 4	Questions at this level primarily indicate evaluation, infer-	3	Would using a reducer without an electrical charge result in a precipitate rather than nanoparticles?

ence, induction, and innovation. They indicate the promotion of students' cognitive and metacognitive activities. The questions often integrate the information and contain the basis for a new research hypothesis.

What would happen with the reverse reaction, i.e., a solution of copper ions with solid silver?
If this chemical reaction had occurred with a basic solution (with hydroxide ions), would the experimental results be similar?
How can the color change of regular silver with nano-sized silver be explained? How does this manifest itself in terms of energy levels?

¹ Taboada and Guthrie (2006); ² Marbach-Ad and Sokolove (2000).

2.5. Research Process

The research program was as follows:

1. Teaching and transferring a unit on the subject of redox reactions to students during the second trimester of the school year, subject to the Ministry of Education's curriculum.
2. The chemistry teachers in the participating schools underwent an hour-and-a-half lecture on the subject of nanoscience and nanotechnology, which was delivered by the study's author.
3. The classes were divided into two groups, an experimental group and a control group.
4. Only the students in the experimental group had two consecutive lessons (each lesson lasting 45 min) where they were exposed to basic concepts and principles of nanoscience and nanotechnology, with an emphasis on redox reactions for preparing metal nanoparticles.
5. Two scientific texts were compiled based on an article by Abu-Much (2021). The first text dealt with the subject of redox reactions without reference to nanoscience and nanotechnology and was intended for the control group; the second text included examples and results of redox reactions related to nanoscience and nanotechnology and was intended for the experimental group.
6. Both groups participated in two consecutive lessons (each lesson lasting 45 min) during which each group received the scientific text appropriate to it. At the end of the critical reading, the students were asked to answer the attached questionnaires (Appendix A or Appendix B), and in particular to raise questions and choose the most interesting question for further investigation.
7. Data collection and analysis of results.

2.6. Data Analysis

To test the research hypotheses, independent samples *t*-tests were conducted to examine the differences in the number and level of questions raised by the students in the two groups. A two-way ANOVA was also performed in each group. To compare frequencies (percentages) of questions between the two groups, a non-parametric χ^2 test was used. All analyses were performed in SPSS software, version 31.0.

3. Results

3.1. Dimension 1: Number of Questions Raised by Students

The first research question examined the differences in question-asking skills between students studying a scientific text on redox reactions that incorporates aspects of nanoscience and students studying a scientific text on redox reactions that does not incorporate these aspects. To this end, we examined the number of questions each student asked after reading the scientific text. The comparison between the control group and the

experimental group was made using an independent samples *t*-test. The findings are presented in Table 3.

Table 3. Comparison of the average number of questions asked by each student in the experimental and control groups.

	Control Group (N = 60)			Experimental Group (N = 60)			t(df = 118)	p-Value
	Range	Mean	S.D.	Range	Mean	S.D.		
Number of questions	3.0–7.0	5.17 ^a	0.91	5.0–10.0	7.17 ^b	1.30	−9.75	<0.001

Different superscript letters (^a, ^b) within a row indicate a statistically significant difference between the control and experimental groups ($p < 0.001$).

The findings presented in Table 3 indicated a statistically significant difference in the number of questions ($t = -9.75$, $p < 0.001$). It was found that the average number of questions asked by students in the experimental group (who studied a scientific text with a combination of aspects of nanoscience and nanotechnology— $M = 7.17$, $SD = 1.30$) is significantly higher than the average number of questions posed by students in the control group. Similarly, the range of the number of questions raised by students in the experimental group was between five and 10 questions per student, and among the control group, between three and seven questions per student.

Examining the distribution of the number of questions that each student presented, the findings show that in the experimental group, more than half of the students were able to formulate more than seven questions (14—seven questions, 16 students—8 questions, 9 students—9 questions). Among the control group, only four students presented seven questions, and all the rest presented a smaller number of questions. The distribution of the number of questions is depicted in Figure 1.

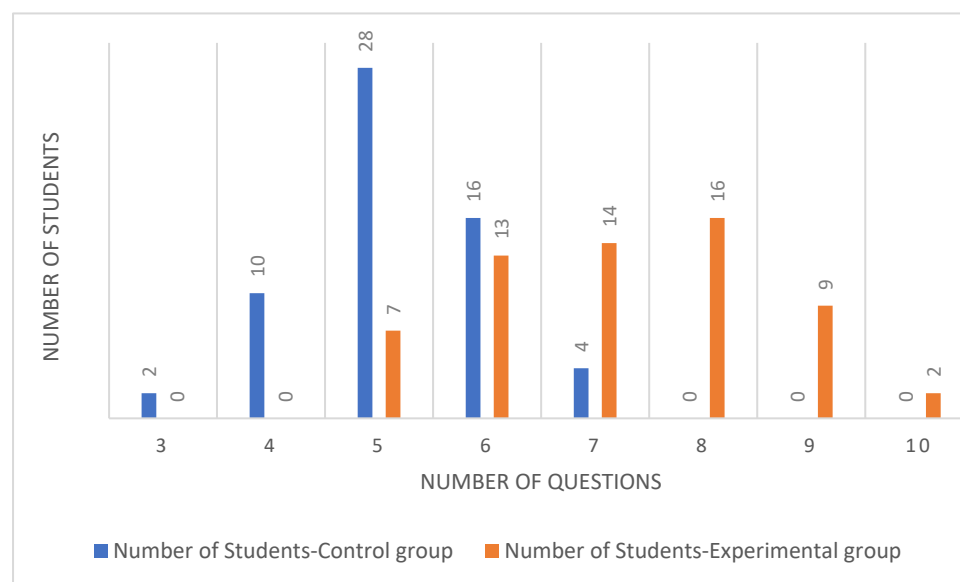


Figure 1. Distribution of the number of questions raised in the experimental and control groups.

3.2. Dimension 2: Cognitive Level of Questions

The second research question examined the differences in the cognitive level of the questions raised by students after reading a scientific text on redox reactions that incorporates aspects of nanoscience and nanotechnology, compared to students who read a scientific text on redox reactions that did not incorporate these aspects. To this end, a chi-square test was used to compare the distribution of questions according to the four cognitive levels between the two groups. The findings are presented in Table 4.

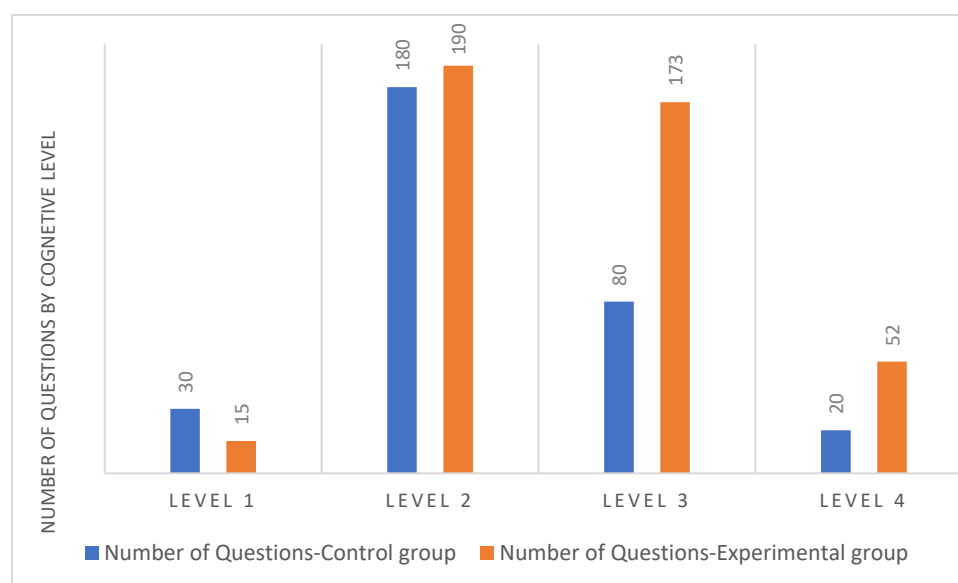
Table 4. Comparison of the cognitive level of the questions between the experimental and control groups.

	Control Group (<i>n</i> = 60)		Experimental Group (<i>n</i> = 60)		chi(3)	<i>p</i> -Value
	<i>n</i>	%	<i>n</i>	%		
Level 1	30 ^a	9.7	15 ^b	3.5	35.14	<0.001
Level 2	180 ^a	58.1	190 ^b	44.2		
Level 3	80 ^a	25.8	173 ^b	40.2		
Level 4	20 ^a	6.5	52 ^b	12.1		

Different superscript letters (^a, ^b) within a row indicate a difference between the control and experimental groups in the distribution across question levels, $\chi^2(3) = 35.14$, $p < 0.001$.

The findings presented in Table 4 indicate a statistically significant difference in the cognitive level of the questions between the experimental and control groups ($\chi(3) = 35.14$, $p < 0.001$). Most of the questions asked by the experimental group are at levels 2 and 3 (44.2% and 40.2%, respectively), compared to 58.1% and 25.8%, respectively, asked by the control group. Additionally, 12.1% of the questions raised by the experimental group were categorized as in the highest level, level 4, compared to only 6.5% of the questions from the control group.

This gap is more pronounced when looking at the absolute number of questions at each level. For example, students from the experimental group composed 173 questions at level 3 and another 52 questions at the highest level 4, compared to the control group who offered only 80 questions at level 3 and only 20 questions at level 4. A comparison of the distribution of the number of questions at each level appears in Figure 2.

**Figure 2.** Distribution of the number of questions by level of cognitive thinking in the experimental and control groups.

Every question presented by the students received a score (see Table 2). We can look, for example, at a student who offered five questions. Two questions were on level 2 and three were on level 3. This student's score is thus: 2 questions $\times$ 1 (level 2) + 3 questions $\times$ 2 (level 3) = 8 points. Table 5 presents a comparison of the scores, using a *t*-test for independent samples, between the experimental and control groups.

Table 5. Comparison of the average score for questions offered by the experimental and control groups.

	Control Group (<i>n</i> = 60)			Experimental Group (<i>n</i> = 60)			<i>t</i> (118)	<i>p</i> -Value
	Range	Mean	S.D.	Range	Mean	S.D.		
Score	2.0–10.0	6.67 ^a	1.69	7.0–18.0	11.53 ^b	2.52	−12.41	<0.001

Different superscript letters (^a, ^b) within a row indicate a statistically significant difference between the control and experimental groups ($p < 0.001$).

The findings presented in Table 5 indicate a statistically significant difference in the scores of the questions ($t = -12.41$, $p < 0.00$). It was found that the average question score among the experimental group ($M = 11.53$, $SD = 2.52$) is significantly higher than the average question score among the control group.

3.3. Dimension 3: Cognitive Level of the Follow-Up Question

The third research question focused on whether there would be a difference in the cognitive level of the question chosen for further investigation between students in the experimental group and students in the control group. Students were asked to choose one question from the questions they raised, for the purpose of further investigation or as the question that interests them the most. In the experimental group, all 60 students chose a follow-up question (100%), compared to the control group, where only 32 students out of 60 chose a follow-up question (53.3%). The selected questions were classified into four cognitive levels, with level 4 representing the highest level, and were given a score ranging from 0 to 3 points depending on their level. The comparison between the levels and question scores between the two groups was made using the chi-square test. The findings are presented in Table 6.

Table 6. Comparison of the level of the question selected for further research or of interest to students between the experimental and control groups.

		Control Group (<i>n</i> = 60)		Experimental Group (<i>n</i> = 60)		chi(3)	<i>p</i> -Value
		<i>n</i>	%	<i>n</i>	%		
Level	Level 1	21 ^a	35.0%	3 ^b	5	74.17	<0.001
	Level 2	5 ^a	8.3%	17 ^b	28.3		
	Level 3	2 ^a	3.3%	26 ^b	43.3		
	Level 4	4 ^a	6.7%	14 ^b	23.3		

Different superscript letters (^a, ^b) within a row indicate a difference between the control and experimental groups in the distribution across question levels, $\chi^2(3) = 74.17$, $p < 0.001$.

The findings presented in Table 6 indicate a statistically significant difference in the level of the questions selected for follow-up research or the most interesting question. In the control group, 46.7% of the students decided not to ask a question or did not find a point in the text that interested them enough that they wanted to investigate further whereas the entire experimental group chose to ask a question. The level of questions in the experimental group is statistically significantly higher than in the control group ($\chi(3) = 74.17$, $p < 0.00$). For example, 23.3% of the students in the experimental group chose a level 4 question (the highest) compared to 6.7% among students in the control group. Dropping a level, among the experimental group, 43.3% of the experimental group asked a level 3 question compared to only 3.3% of students in the control group. A comparison of the distribution of question levels between the experimental and control groups is shown in Figure 3.

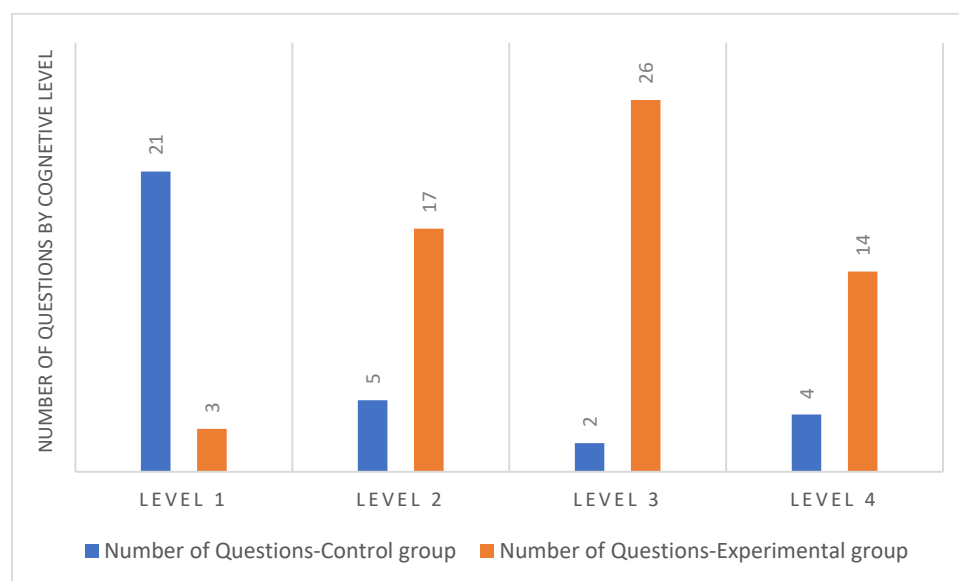


Figure 3. Comparison of the level of the questions selected for further research or of interest to students between the experimental and control groups.

4. Discussion

The present study aimed to examine the potential of integrating aspects of nanoscience and nanotechnology in chemistry teaching as a means of developing questioning skills among students. This goal is consistent with a growing trend in the research literature calling for a shift from traditional science teaching methods toward innovative and interdisciplinary approaches that foster higher-order thinking and critical thinking (Rajan & Watted, 2024; Watted & Barak, 2024). The field of nanoscience and nanotechnology, being a multidisciplinary scientific field by its very nature, is seen as offering a unique opportunity to students to experience the integration of different fields of knowledge, and to develop deep insights into the big ideas of science (Spyrtou et al., 2021). Furthermore, nanoscience like any other content area, can be taught either through the transfer of knowledge at a superficial level, or in a way that encourages deep engagement with complex ideas, depending on the pedagogical approach used. The findings of the current study indicate that when nanoscience is integrated into an accessible and pedagogically structured context, as was done in the experimental text used in the current study, it can support the development of higher-order thinking and engagement with complex ideas.

To answer the study's questions, the students' ability to ask questions after critical reading of a scientific text on the topic of redox reactions was examined. The text was derived from primary literature and simplified to match the students' level, in line with the pedagogical approach of using adapted science literature (APL) as a bridge between the science of scientists and school science (Yarden, 2009), an approach that has been found to improve critical thinking and scientific skills (Goudsouzian & Hsu, 2023). The study focused on three dimensions: the number of questions raised by students, the questions' cognitive level, and the level of questions chosen for further investigation. The findings showed that students in the experimental group, who were exposed to a text that combined aspects of nanoscience with a redox topic, raised a greater number of questions at a higher cognitive level compared to students in the control group who read a text without a nano context.

The finding indicates that the text that combined aspects of nanoscience aroused higher cognitive involvement among the students and a greater desire to investigate and understand. Student questions play an important role in meaningful learning and scientific inquiry, and they are a potentially valuable resource for both teaching and learning

(Chin & Osborne, 2008). Moreover, higher-level “wonderment” questions such as comprehension, prediction, and anomaly identification questions indicate a deep learning approach and drive cognitive processes of hypotheses, predictions, and explanations, in contrast to basic factual questions that generate less productive discussion (Chin & Brown, 2002).

The cognitive level of the questions was significantly higher in the experimental group, while in the control group, the vast majority of the questions were low-level questions. This high cognitive level among the students in the experimental group was also reflected in the type of questions they asked. For example, a student asked: “Do the results obtained from the passage of laser radiation indicate the existence of larger particles? Given that no precipitate was produced in the second reaction, does this mean that the reduced silver is in the nanometer size?” These questions indicate high-level integrative thinking, connecting optical phenomena to redox processes and the unique properties of nanoparticles. Another student asked: “What is the difference between solid copper and sodium citrate, since both are strong reducers of silver ions,” a question that indicates the ability to compare and analyze chemical processes at an in-depth level. In contrast, students in the control group asked mainly factual questions such as “What does the blue solution contain?” and “Why did the solution turn from clear to blue?”—questions whose answers are derived directly from the scientific text and do not indicate thinking beyond the material being read.

As an additional illustration, the two high-level questions presented above may also be discussed in relation to the Theory of the Five Pillars of the Mind (Tokuhamma-Espinosa, 2019; Demkanin et al., 2025): the first appears to involve “Relationships” between concepts, and the second appears to involve “Categories.” This offers one possible way, among others, of further illustrating the complexity already captured by the classification of student questions.

In reference to the questions raised for further investigation, a particularly striking difference was observed in the choice of a follow-up-for-investigation question. All the students in the experimental group chose a follow-up question. This finding is perhaps the most significant, as it indicates not only the ability to ask questions, but also a meta-cognitive ability, the ability to identify and choose the best question for further investigation. Student questions help to stimulate knowledge construction, encourage further investigation in inquiry-based science teaching, and nurture the cultivation of higher-order thinking skills (Herranen & Aksela, 2019). The fact that all students in the experimental group were able to select a follow-up question, while almost half of the students in the control group did not, indicates that exposure to the topic of nanoscience created real engagement and interest that motivated students to want to explore further.

These findings can be attributed to two central and complementary characteristics of nanoscience and nanotechnology as an educational subject, its innovation on the one hand, and its interdisciplinary nature, on the other. First, within the standard chemistry curriculum followed by the participants, nanoscience is a new and largely unfamiliar topic. However, nanotechnology concepts have been successfully introduced at earlier educational stages, including primary and early-childhood education, in other contexts (Spyrtou et al., 2021; Dorouka & Kalogiannakis, 2024), suggesting that the novelty of the topic is context-dependent rather than inherent to the field. Phenomena such as the synthesis of silver nanoparticles using sodium citrate, the color change of colloidal solutions depending on the size of the particles, and the unique properties of materials at the nanoscale create a cognitive gap between students’ existing knowledge and the new information to which they are exposed. This gap arouses epistemic curiosity, that is, an internal desire to fill the existing knowledge gap, and motivates students to ask deeper questions. When a student encounters information that surprises them or contradicts their expecta-

tions, such as the discovery that nanometer-sized silver particles scatter light differently from regular silver, they are naturally stimulated to ask deeper questions and seek explanations. Students' questions can be triggered by unfamiliar words or inconsistencies between existing knowledge and new information, which give rise to cognitive disequilibrium or epistemic curiosity (Chin & Osborne, 2008).

On the other hand, the interdisciplinary nature of nanoscience, which combines chemistry, physics, biology, materials science, and engineering (Bryan & Giordano, 2015; Demkanin & Bartošovič, 2025), prompts students to connect different fields of knowledge previously studied and build a more complex and integrative understanding. The students in the experimental group were not only required to understand the topic of redox reactions, but also to connect it with nanometric phenomena, with optical properties of colloidal particles, and with modern technological applications. This connection between different fields led to questions at a higher cognitive level, questions that combine knowledge from multiple fields, and to the selection of more sophisticated and intriguing research questions. The interdisciplinary nature of nanoscience provides a unique opportunity for students to experience collaboration between different scientific fields and develop deep insights into the big ideas of science (Vrtič & Lindell, 2025).

The findings of the current study are consistent with many previous studies in the field and strengthen and expand existing knowledge regarding the contribution of nanoscience to the development of higher-order thinking among students. First, the connection between integrating nanoscience into a curriculum and the development of critical thinking and integrative learning is also found in the study by Park (2019), who developed a nanotechnology course and showed that presenting chemistry concepts through the lens of nanotechnology applications, in the fields of electronics, medicine, sports, and the environment, promotes critical thinking and the ability to connect different areas of knowledge. This finding is consistent with what was observed in the experimental group in the current study, in which students were able to connect redox processes to nanometric phenomena and ask connecting and integrating questions.

Second, the findings of the current study are consistent with the claim of Tawiah et al. (2024), according to which the integration of nanotechnology education into the teaching curriculum fosters scientific curiosity, critical thinking and innovation among students, while emphasizing practical experiments and interdisciplinary collaboration. Indeed, the current study found that students in the experimental group, who were exposed to the scientific text that integrates nanoscience aspects on the topic of redox, raised a greater number of questions at a higher cognitive level compared to students in the control group, a finding that supports the assertion that the nanometric topic aroused scientific curiosity and led to deeper cognitive engagement.

Third, Spyrtou et al. (2019) show that a teaching module in nanoscience and nanotechnology promotes students' analytical, explanatory and interpretative skills, as well as dispositions such as self-confidence and curiosity. The findings of the current study are consistent with this finding. Students in the experimental group asked questions at levels 3 and 4 at a significantly higher rate than the control group, which strengthens the claim that exposure to nanoscience content develops higher-order thinking skills.

Fourth, in their research, Kähkönen et al. (2016) and Vrtič and Lindell (2025) emphasize the interdisciplinary nature of nanoscience as a factor that allows students to build a comprehensive understanding of scientific principles and experience collaboration between different scientific disciplines. The findings of the current study are consistent with this view. The level 3 and 4 questions raised by students in the experimental group show that they combined knowledge from multiple fields and indicate integrative and complex thinking. This finding suggests that the interdisciplinary nature of nanoscience, along with the novelty of the topic, contributed to the increase in the level of questions in the

experimental group. Finally, Spyrtou et al. (2021) found that students exposed to nanoscience content recognize its importance and relevance to everyday life, which explains why all the students in the experimental group, in contrast to almost half of the students in the control group, made the effort to choose a follow-up question for investigation. It was the sense of relevance and interest created by the nanometric topic that motivated the students not only to ask questions, but also to want to continue exploring them.

In conclusion, the findings of the current study, together with the existing literature, strengthen the claim that integrating a new and interdisciplinary scientific topic such as nanoscience and nanotechnology into chemistry teaching, and specifically the subject of redox reactions, constitutes an effective pedagogical tool for developing high-cognitive questioning skills among secondary school students. This integration operates through two complementary mechanisms: it arouses epistemic curiosity due to the novelty of the topic, and it enables interdisciplinary connection due to its integrative nature.

In this study, the students in the experimental group asked 430 questions, compared to 310 questions asked by the students in the control group. The greater number of questions asked by the experimental group signifies the importance of the topic to those students. The questions proposed by students provide diagnostic information about their thinking processes and help educators assess their self-understanding and higher-order thinking skills (Chin & Brown, 2002), important questioning skills for critical thinking and decision-making.

When students ask questions, their motivation and interest in the topic of nanoscience increase, knowledge construction is stimulated, and a desire for further investigation is created (Herranen & Aksela, 2019). Requiring students to ask additional questions can be constructive by motivating students to integrate prior and new knowledge, make connections between different pieces of information, and clarify what they know (Chin & Brown, 2002). Thus, the results of the current study demonstrate that integrating different aspects of nanoscience allows students to connect different scientific theories and is in line with studies showing that exposure to nanoscience content increases students' curiosity and motivation (Spyrtou et al., 2021).

Recommendations for Further Research

The research underscores the need for further research about the importance of nanoscience teaching in the chemistry curriculum and its impact on students' attitudes regarding the subject and their achievements in it. Future research should use samples that are representative of students of different ages from assorted areas of the country and not limit itself to 11th-grade students in the south, as was done here. A broader research sample would represent the general population (high school students).

Given that the present study focused on a specific topic, "integration of nanotechnology when learning about the reduction of silver ions", it is suggested that future research should examine the influence of an intervention program on students' attitudes and academic achievements in other scientific subjects such as biology, physics, and other areas of chemistry, and over a longer timeframe than this study.

Moreover, it is recommended that modern science topics such as nanotechnology be integrated into the science curricula in schools with science, engineering and mathematics programs.

5. Conclusions

Nanoscience and nanotechnology are of great importance in the twenty-first century. Together they comprise an interdisciplinary field that can be included in chemistry, physics, biology, environmental sciences and engineering. In recent years, nanomaterials have entered our daily lives through innumerable consumer products. Therefore, it is important to carry out activities to introduce these new subjects into the chemistry curriculum in secondary schools. The findings of this study demonstrate that the introduction of nanoscience into the chemistry curriculum makes it more attractive than the traditional chemistry curriculum, thereby increasing students' motivation to study chemistry and related subjects.

Research on student questions has shown the potential they have to support students' thinking skills at different levels, helping them formulate explanations on their own, process ideas, understand concepts and identify key concepts. By asking the correct type of questions, students show that they understand, remember, and can apply what they have learned. Teacher support in this process, however, may be needed (Herranen & Aksela, 2019).

Three main conclusions can be drawn from the study findings. First, studying scientific texts on nanoscience and combining them with the topic of redox reactions motivated students to ask many and varied questions compared to students who studied a scientific text on redox without the context of nanoscience and nanotechnology. This suggests that integrating a nanoscience curriculum and motivating students to ask their own questions will provide students with a realistic view of what modern chemistry actually is, and can help students monitor their learning, investigate and support their ideas, nurture direct thinking in certain directions, and improve their understanding of scientific concepts and phenomena.

Secondly, differences in the knowledge acquired by the two groups were reflected in the types of questions they generated. The experimental group, which engaged with silver ion reduction in a nanoscience context, demonstrated a greater capacity for higher-order questioning compared to the control group, who studied the same reaction through a conventional text.

Thirdly, we observed differences between the students in the experimental group and the students in the control group in the levels of the questions chosen by them as their question for further research or as the most interesting question. The level of the questions chosen by the students in the experimental group was much higher than the level of the questions chosen by the students in the control group. The introduction of modern, widely applicable knowledge was shown to be responsible for these differences. Accordingly, we can say that introducing a modern learning strategy such as nanotechnology into the curricula of secondary schools motivates students to study chemistry. When students are exposed to nanotechnology, they see chemistry as more relevant to their lives and more modern than the chemistry they typically learn in school, thereby increasing their ongoing motivation to study chemistry. Teaching high school students nano-context questioning skills led them to ask more and better research questions. This impact can be extrapolated to additional areas of science, with the obvious conclusion that curricula should move in this direction so that student questions can also be used as stepping stones for additional, more complex learning through class discussions, debates, investigations, problem-based learning, and project work.

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view and editing, R.A.M. and A.D.; visualization, R.A.M.; supervision, R.A.M.; project administration, R.A.M. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki, and approved by The Institutional Ethics Committee of the Arab Academic College of Education in Israel (protocol code AACE-CE1-11052026 and date of approval 10 July 2025).

Informed Consent Statement: Informed Consent was obtained from all participants involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. The Questionnaire Completed by the Control Group Students

Describe, based on the description in the scientific article, the following concepts:

- Reduction
- Oxidation
- Standard reduction potentials (E°)

Did a chemical reaction occur? If so, describe the reactants.

Why is spectrophotometric analysis used?

How do you explain the resulting color changes?

What was the purpose of passing a laser beam across the solutions?

List all the questions you would like to ask after reading the scientific text.

Write down the scientific concepts or phenomena that were not clear to you.

From the list of questions, select the most interesting question you would like to investigate.

Appendix B. The Questionnaire Completed by the Experimental Group Students

Describe, based on the description in the scientific article, the following concepts:

- Reduction
- Oxidation
- Standard reduction potentials (E°)

Did a chemical reaction occur? If so, describe the reactants.

Why is spectrophotometric analysis used?

How do you explain the resulting green-yellow solution?

Why is spectrophotometric analysis used?

What was the purpose of passing a laser beam across the solutions?

List all the questions you would like to ask after reading the scientific text.

Write down the scientific concepts or phenomena that were not clear to you.

From the list of questions, select the most interesting question you would like to investigate.

Appendix C. Scientific Text for the Control Group

Dear student,

The following is a scientific text derived from an article published in a peer-reviewed international scientific journal. The text has been translated into Arabic for your convenience.

Please read the text below and answer the questions that follow.

This text is for research purposes only and does not affect your grade.

Thank you very much for your cooperation.

This scientific text is based mainly on a scientific article published in a peer-reviewed scientific journal in 2021.

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Redox Reactions—A Chemical Reaction Between Silver Ions and Solid Copper

Introduction—Redox Reactions

Redox reaction is a reaction in which electrons are transferred from a reducing agent to an oxidizing agent. This reaction is manifested in many chemical processes in everyday life, such as the formation of rust. As a result of a redox reaction, the oxidation state of the substances participating in the reaction changes. Oxidation and reduction are complementary chemical reactions, and neither can occur without the other. Reduction is a reaction in which electrons are transferred from a molecule, atom, or ion with low electronegativity to particles with higher electronegativity. Oxidation is the reverse reaction, namely, the release of electrons.

The substance that receives the electrons undergoes reduction (its oxidation state decreases) and is called the oxidizing agent, whereas the substance that releases the electrons undergoes oxidation (its oxidation state increases) and is called the reducing agent.

The uniqueness of transition metals lies in the fact that their active valence subshell is the d subshell (the third subshell after s and p). This subshell can hold up to 10 electrons, depending on the type of metal, and it can also both release and accept electrons in reactions with other metals and substances. Therefore, transition metals are highly active in oxidation and reduction processes.

Spectrophotometric Measurements in Colored Solutions

Chemical systems and colored solutions have a selective capacity to absorb light in the visible range. This capacity depends on the concentration of the component. The purpose of the measurement is to determine this concentration quantitatively, particularly at very low concentrations.

Such measurements are called colorimetric analysis or spectrophotometric analysis. This type of analysis can determine concentrations down to a few parts per million (ppm) or even less.

ppm = parts per million. 1 ppm = 1 g dissolved in one million grams of solution.

The main steps in a spectrophotometric determination are:

Preparing a suitable colored solution.

Measuring the light-absorbing capacity of the solution or comparing it with a solution of the same substance at a known concentration (standard).

For an accurate determination, a stable color with sufficient light-absorbing capacity is required. Some substances are naturally colored, such as permanganate ions (MnO_4^-). For colorless substances or those with weak color, a chromogenic agent (color-forming substance) must be added to obtain a colored system suitable for determination. For example, in determining iron ions, which are weakly colored, SCN^- or orthophenanthroline ions must be added (both form red compounds with trivalent and divalent iron ions, respectively). The chromogenic agent must react quantitatively with the substance being tested.

The Tyndall Effect

This is a physical phenomenon that explains the scattering of light when a light beam passes through a medium composed of particles large enough to cause the scattering of the light passing through them. These particles are “large enough” to scatter light, yet are not visible to the naked eye.

The Tyndall effect is generally used to distinguish between solutions that differ in the size of the dissolved or dispersed particles they contain. A regular solution of dissolved ions, such as a table salt solution, or dissolved molecules, such as a sugar solution, does not cause scattering of the light passing through it—that is, the solute particles are not large enough to cause scattering. In contrast, larger particles of a dissolved or dispersed substance cause scattering of the light beam upon collision, which is manifested as the appearance of a glowing line within the solution.

Redox Reaction Between Silver and Copper

In one of the chemistry experiments conducted with students studying chemistry at the academy for teacher training, an experiment was performed on the redox reaction between solid copper and a silver nitrate solution, $\text{AgNO}_3(\text{aq})$. First, an aqueous solution of silver nitrate (AgNO_3) was prepared in double-distilled water. Ten solid copper disks were then added to the solution. Gradually, a gray precipitate began to appear, while the color of the solution changed from clear to blue. After 30 min, the blue solution was separated from the gray precipitate by filtration.

The detailed procedure of the experiment is as follows:

A solution of AgNO_3 (250 mL) at a concentration of 1M was prepared by dissolving 42.5 g of silver nitrate in double-distilled water.

Ten solid copper disks (weighing 1.5 g each) were added to the solution.

Gradually, a gray precipitate began to appear, and the color of the solution changed from clear to blue.

After 30 min, the blue solution was separated from the gray precipitate by filtration. Based on the values of the standard reduction potentials (E°) of copper and silver ions, we could estimate that $\text{Cu}(\text{s})$ can spontaneously reduce silver ions in an aqueous solution. The blue colored solution obtained was analyzed by a UV-vis spectrophotometer, with maximum absorbance occurring at a wavelength of 630 nm. By calculating the absorbance at this wavelength, the ion concentrations were determined using the Beer–Lambert equation.

In addition, the passage of a laser beam through the blue solution (after filtration) was examined. As a result, the students were unable to detect anything within the solution.

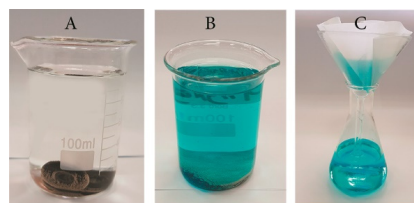


Figure A1. (A) Silver nitrate solution with the copper disks in the beaker, (B) after 30 min, (C) after filtration and separation of the gray precipitate from the blue solution.

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Questions

Please write down all the questions that come to mind after reading the text.

Please choose one question from among the questions you raised, the one that interests you the most.

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Redox Reactions—A Chemical Reaction Between Silver Ions and Tri-sodium Citrate

In one of the chemistry experiments conducted with students studying chemistry at the academy for teacher training, two different experiments were performed, whose purpose was to reduce silver ions in a silver nitrate solution, $\text{AgNO}_3(\text{aq})$.

In the first experiment, the silver ions were reduced using solid copper, whereas in the second experiment, reduction was carried out using the reducing agent trisodium citrate.

Procedure of the Experiment:

Reduction of Silver Ions by Solid Copper

First, an aqueous solution of silver nitrate (AgNO_3), of a concentration of 1 M was prepared by dissolving 42.5 g of silver nitrate in 250 mL of double-distilled water. Ten solid copper disks (weighing 1.5 g each) were then added to the solution. Gradually, a gray precipitate began to appear, and the color of the solution gradually changed from clear to blue. After 30 min, the blue solution was separated from the gray precipitate by filtration.

Reduction of Silver Ions by Trisodium Citrate

An aqueous solution of silver nitrate was prepared by dissolving 0.0425 g of silver nitrate in 250 mL of double-distilled water. The solution was placed on a stirring hot plate and was heated to boiling. An aqueous solution of 1% *w/w* trisodium citrate dihydrate ($\text{HOC}(\text{COONa})(\text{CH}_2\text{COONa})_2 \cdot 2\text{H}_2\text{O}$) was prepared by dissolving 0.2 g in 20 mL of double-distilled water. Next, 5 mL of the trisodium citrate solution was added drop by drop to the boiled solution of silver nitrate while stirring vigorously. The mixture gradually turned from transparent to yellow-green no precipitate was formed.



Figure A2. Yellow-green colored solution obtained from the reduction of silver ions by trisodium citrate. Reprinted (adapted) with permission from Abu-Much (2021). Copyright 2021 American Chemical Society.

To determine the concentration of the blue solution, spectrophotometric analysis was used, with maximum absorbance occurring at a wavelength of 630 nm. By calculating the absorbance at this wavelength, the ion concentrations were determined using the Beer–Lambert equation.

In addition, the passage of a laser beam through the blue solution (after filtration) was examined. As a result, the students were unable to detect anything within the solution.

To distinguish between the two different solutions obtained as a result of the reduction of silver ions, the passage of a laser beam through the two solutions was examined. As a result, the passage of the laser beam through the blue solution showed nothing, whereas when the laser beam passed through the yellow-green solution, the students observed a line of light within the solution.

Questions

Please write down all the questions that come to mind after reading the text.

Please choose one question from among the questions you raised, the one that interests you the most.

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