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Didactic Sequence for the Introduction of Infrared Absorption Spectrophotometry at the High School Level

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Abstract A didactic sequence is proposed using an infrared puzzle and a didactic questionnaire for the teaching-learning of infrared spectroscopy at the upper secondary level. The didactic sequence that was designed was implemented in person in the subject of Chemistry IV at the high school level, corresponding to the sixth semester of the curriculum of the National School of Sciences and Humanities (CCH), Vallejo Campus, of the National Autonomous University of Mexico. In the didactic sequence, students understand the importance of functional groups where they determine organic compounds, by identifying regularities, properties, and structure of alcohols, aldehydes, ketones, and carboxylic acids. After applying the didactic sequence, a post-test questionnaire was applied, and the results showed that the students significantly improved their knowledge of IR when using the puzzle that allowed them to correctly identify the bands that identify the carbonyl group.

Keywords: *Infrared spectroscopy, didactic sequence, Hake index, high school*

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1. Introduction

Infrared spectroscopy is an instrumental technique that allows the identification of the functional groups of a compound. This information is obtained from the vibrations of the bonds that occur after they have been subjected to infrared radiation, this information is presented in the form of a spectrum [1]. The result obtained from the infrared spectroscopy analysis is an infrared spectrum of the molecule being analyzed. An infrared is a sequence of absorption bands or bands in a frequency range within the range between 4000-400 cm^{-1}. Each band in the spectrum represents a type of specific vibration that occurred in an atomic bond, when the infrared beam interacted with that molecule. These vibrations come from specific atomic bonds that present the molecule of the molecule analyzed [2]. Infrared spectroscopy involves the understanding of physical principles, molecular interactions, and the analysis of complex spectra. Functional groups, such as carbonyl groups, are identified through specific patterns in the infrared spectrum.

At the high school level, at the College of Sciences and Humanities (CCH) of the UNAM (Mexico), in the subject of Chemistry II, students have as prior knowledge the identification of the carbonyl functional groups present in carboxylic acid, aldehyde, amides, ketone and ester, structures observed in macronutrients, and in the fifth semester in the subject of Chemistry IV they understand the different oxidation reactions of hydrocarbons aldehydes are obtained, ketones and carboxylic acids. However, the teaching of infrared spectroscopy is not considered as a formal subject, so it is necessary to look for alternatives to strengthen the teaching-learning process in this area of knowledge, exploring novel strategies through the generation of didactic materials that strengthen the learning of this analytical technique and its link to real problems [3]. The elaboration of a didactic sequence is an important task to organize learning situations that will be developed in the students' work. It is the teacher's responsibility to propose to students sequenced activities that are focused on learning. The sequences constitute an organization of the learning activities that will be carried out with the students and for the students to create situations that allow them to develop meaningful learning [4].

The structure of the sequence is integrated with two elements that are carried out in parallel: the sequence of learning activities and the assessment for learning inscribed in those same activities. Detecting a learning difficulty or possibility allows the progress of a sequence to be reorganized, while the results of a learning activity, the products, work, or tasks that the student performs constitute elements of evaluation [5]. In this sense, the sequence integrates learning principles with those of assessment, in its three dimensions: diagnostic, formative and summative. The line of didactic sequences is made up of three types of activities [6].

1. Openness: The opening activities are varied at first, they allow to open the learning climate, where the students will react by bringing to their thoughts various

information that they already have, either from their previous school training, or from their daily experience. Establishing opening activities in the topics is a challenge for the teacher because it is a question of working with a problem that constitutes an intellectual challenge for the students. The opening activity can be developed from a task that students are asked to do, such as: doing interviews, looking for information about an established problem, looking for information on YouTube or an APP that exists freely on the internet (Play Store or App Store).

2. Development: The purpose of development activities is for the student to interact his/her previous knowledge with new information. The source of information can be diverse, a teaching presentation, a discussion about a reading, a video of academic origin, the resources that the teacher can use are also very varied, he can use applications that his students can access, if the teacher uses a site to store information (Moodle, Google Drive, Box Chrome, Classroom, Quizizz, among others) can be supported by this. In these cases, it is advisable to support the students' discussion with certain guiding questions. During the content development activities, the teacher can make a presentation on the main concepts, theories, and skills. Two moments are relevant in development activities, the intellectual work with information and the use of that information in a problem situation. The problem can be real or formulated by the teacher, the problem can be part of a larger work project of the course it is important that, it is not limited to a school application of the information, to answering a questionnaire of questions about the text or to carrying out exercises from which 10 textbooks come, rather, it is desirable that this application of information be meaningful. Therefore, linking it to a case, problem or project may have more relevance for the student.

3. Closure: Closing activities are carried out with the aim of achieving an integration of the set of tasks carried out, allowing a synthesis of the process and the learning developed. Through them, the aim is for the student to rework the conceptual structure that they had at the beginning of the sequence, reorganizing their structure of thought based on the interactions they have generated with the new questions and the information they had access to. These synthesis activities can consist of reconstructing information from certain questions, performing exercises that involve using information in the resolution of specific situations (the more unprecedented and challenging the better). They can be carried out individually or in small groups, because the important thing is that students have a space for intellectual action and communication and dialogue among their peers. In the case of working on cases, projects or problems, it may be the progress of a previously planned stage. The closing activities provide an evaluation perspective for the teacher and the student, both in the formative and summative sense. In this way, the proposed activities can generate multiple information about both the learning process of the students and the obtaining of evidence of learning [7]. Underlying the formation of this proposal of activities is simultaneously a perspective of formative assessment, which allows feedback to the process through the observation of the progress, challenges, and difficulties that students present in their work, as well as summative assessment, which offers evidence of learning, on the same path of learning [8].

Learning gain is a term widely used to describe the tangible changes in learning that have been achieved after a specific intervention [9]. Individual differences in learning, i.e., how a learner obtains, understands, interprets, organizes, and processes information, have been related to learning gain [10]. Hake's normalized gain [11] is a parameter that accounts for the evolution of student learning and avoids the problem of comparing students who start a course better prepared than others do and allows us to determine whether a teaching methodology is efficient with respect to the student's initial knowledge. It is defined as the ratio of the increase of a preliminary test (pretest) and a final test (post-test) with respect to the maximum possible increase.

$$g = \frac{post-test(\%) - pretest(\%)}{100 - pretest(\%)}$$

The value obtained gives an idea of the level of gain in the learning of concepts, according to Hake [11], these levels are grouped into the following standard gain score (g)

Low gain ($g \leq 0.3$)

Medium gain ($0.3 < g \leq 0.7$)

High gain ($g > 0.7$)

A variety of approaches have been reported to improve the student's ability to learn the interpretation of infrared spectra such as question-based card game [12], physical models [13], comics [3], virtual reality [14], and machine learning algorithms [15]. The prominence of carbonyl stretch bands in IR spectra has made them attractive for studying molecular concepts. For example, students successfully predicted the relative stretching frequencies of carbonyl based on resonance, hydrogen bonding, and the inductive effect [16]. Inquiry-guided instruction also helped draw resonance structures and predict how resonance influence the strength of the carbonyl bond [17].

The puzzle, as a didactic strategy, is a versatile and effective pedagogical tool that has proven its effectiveness in teaching complex concepts. When applied to the teaching of infrared spectroscopy, this strategy becomes a valuable resource for learning a subject that can often be abstract and challenging for students. This pedagogical approach makes it possible to break down the topic into more manageable and relatable pieces. Each fragment of the puzzle represents a key component of the infrared spectrum, such as molecular vibrations, absorption intensities, and characteristic patterns of functional groups. Students, by working with these individual pieces, can gradually understand how they fit into the bigger picture of spectral analysis.

2. General Objective

Develop and implement a didactic strategy, so that the high school student can identify the carbonyl group present in an organic structure, based on infrared spectroscopy, using a puzzle as didactic material.

3. Methodology

Table 1. Didactic sequence. Identification of the carbonyl functional group with the infrared technique

<table>
<tr><td colspan="2">Didactic sequence. Identification of the carbonyl functional group with the infrared technique</td></tr>
<tr><td>THEME:
Identification of the carbonyl functional group with the Infrared technique</td><td>CLASS: 1</td></tr>
<tr><td colspan="2">OBJECTIVE OF THE TOPIC:
Define and analyze the electromagnetic spectrum for the introduction of infrared absorption spectroscopy.
Learn the identification of functional groups by means of a puzzle of 3 different spectra of aldehydes, ketones, and carboxylic acids</td></tr>
<tr><td>LESSONS TO BE LEARNED

The student:
You will know the origin of IR.
Understand what the electromagnetic spectrum is all about
The student understands that the functional group determines the properties of organic compounds by means of the IR spectrum, by identifying the wave numbers that characterize each type of functional group of carbonyls.</td><td>PRIOR KNOWLEDGE:
Electromagnetic systems
Electromagnetic spectrum
Dipole moment
Functional group concept.
Relationship, properties of organic compounds and their functional group</td></tr>
<tr><td colspan="2">ACTIVITIES</td></tr>
<tr><td colspan="2">OPENING PHASE</td></tr>
<tr><td>Prior to the class, they will be sent complementary information with the definition of the electromagnetic spectrum and spectroscopy for their study prior to the class.
SOCIALIZATION OF OBJECTIVES
TIME: 5 minutes
Present the objectives, the learning to be achieved and the agenda to the students</td><td>TECHNIQUE: Exhibition

MATERIAL: Power point presentation, projector</td></tr>
<tr><td>APPLICATION OF THE PRETEST QUESTIONNAIRE
TIME: 10 minutes
The class begins by applying a previous questionnaire, which will contain concepts that will be reviewed in class.
At the beginning of the class, the instructions for the resolution of the questionnaire will be given, which will be hosted on the Quizizz platform, and a time of 10 minutes will be given to solve it. (only for experimental group)
The average of the answers will be projected for everyone to know·
For the control group, the same printed questionnaire will be applied.

PURPOSE OF THE ACTIVITY: To assess the student's prior knowledge of the electromagnetic spectrum and infrared spectroscopy.</td><td>TECHNIQUE: Quizzes interactive questionnaire (This questionnaire will only be applied to the experimental group)

Traditional questionnaire will apply the same questions to the control group.

MATERIAL: Cell phone, questionnaire sheets</td></tr>
<tr><td colspan="2">DEVELOPMENT PHASE</td></tr>
<tr><td>SPECTROSCOPY
TIME: 10 minutes
It defines what spectroscopy is and how electromagnetic radiation interacts with matter at the atomic and molecular levels.
PHET SIMULATOR (EXPERIMENTAL GROUP ONLY))
TIME: 15 minutes
Subsequently, an exercise will be carried out with the simulator of "molecules and light" that will exemplify how the molecules found in the atmosphere interact with the different radiations
https://phet.colorado.edu/sims/html/molecules-and-light/latest/molecules-and-light_all.html?locale=es

THE INFRARED SPECTRUM
TIME: 20 minutes
Know the main concepts of infrared, how it interacts with matter, definition of dipole moment, resonance, the different types of vibrations in polyatomic molecules and the presentation for the understanding of interpretation of the infrared spectrum and the presentation of some examples of spectra where it will be solved in a group learning to use the tables of the infrared spectrum for the identification of the functional groups present in the spectrum
At the end of the topic for the control group, 3 infrared spectrum exercises will be applied where they indicate in writing which functional group corresponds to them by means of the infrared spectrum tables.</td><td>TECHNIQUE: Exhibition

MATERIAL: Power point presentation, projector, cell phone (for simulator use) Infrared spectrum tables</td></tr>
<tr><td>PUZZLE APPLICATION (experimental group only)
TIME: 20 minutes
At the end of the class theme, the didactic material of the puzzle of a spectrum will be used where the students can organize it and thus learn to locate the different tensions associated with the carbonyl group in the spectrum.
Subsequently, the results will be reviewed using an IR simulator and functional groups
https://applets.kcvs.ca/irSuite/IRSuite.html</td><td>TECHNIQUE: Simulator and puzzle exhibition

MATERIAL:
Cell phone, cardboard, puzzle</td></tr>
<tr><td colspan="2">CLOSING PHASE</td></tr>
<tr><td>APPLICATION OF POST-TEST QUESTIONNAIRE (ASSESSMENT)
TIME: 10 minutes
Resolution of the questionnaire which will be hosted on the Quizizz platform and a time of 10 min will be given to solve it. (only for groups that will apply the didactic strategy)
The average of the answers will be projected for everyone to know·
For the control group, the same printed questionnaire will be applied.
RESOLUTION OF DOUBTS
TIME: 3 minutes</td><td>TECHNIQUE: Quizzes interactive questionnaire (This questionnaire will only be applied to the experimental group)
Traditional questionnaire will apply the same questions to the control group.

MATERIAL: cell phone, questionnaire sheets</td></tr>
</table>

The didactic strategy was applied to two groups (Group number 673 and 693) of students, in person, of the CCH Vallejo UNAM, in the sixth semester who are enrolled in the subject of Chemistry IV during the semester 2023-2. The first group 693 was integrated by 9 students, 8 women, 1 male, aged between 17 and 19 years as a control group, the second group 673 was integrated by 10 students, 8 women, 2 men aged between 16 and 20 years as an experimental group. A didactic sequence was designed (Table 1) that included the use of some simulators and the Quizizz application, which is easy to access and allows for an active class with the students.

4. Results and Analysis of Results

Diagnostic assessment

For the diagnostic assessment in the control group and the group, five questions were posed by means of a multiple-choice pretest questionnaire that referred to questions regarding the electromagnetic spectrum and what is the infrared spectrum.

Question 1. Relate the applications of the different types of radiation.

Question 2. It is the study of the interaction of electromagnetic radiation with a substance and is based on incoming and outgoing radiation, it is known as interaction or absorption energy.

Figure 2 presents the results of question 2, which consists of identifying the concept of the infrared spectrum. According to this, 30% of the control group responded by relating it to the electromagnetic spectrum, and 50% of the students associated this concept with the electromagnetic spectrum. It is worth mentioning that the correct answer in this questionnaire was the infrared spectrum. However, only 15% of the students in the control group answered accurately, identifying that the definition corresponds to the infrared spectrum, as did 30% of the experimental group. These results suggest that a significant percentage of learners do not have a clear understanding of the concept of the infrared spectrum.

Question 3. Requirements for a molecule to absorb infrared radiation.

Figure 3 presents the results of question 3, which consists of identifying the requirements for a molecule to absorb infrared radiation, 69% of the control group answered correctly and in the experimental group 80% answered correctly, which means that the students have an idea of how the molecule with having a dipole moment and resonance can absorb infrared radiation.

It is mainly used to transmit information such as AM and FM radios, cell phones, televisions, and many other media.	Infrared
It is used in antennas, radars, satellites for telecommunications and in more everyday use for cooking and heating food.	Ultraviolet
We commonly call it light; they are the waves that our eyes are sensitive to and as we see in a very small part of the electromagnetic spectrum.	Radio
Its application is in the medical field for disinfection and sterilization, also to reveal the hidden marks of banknotes, important documents, and forensic investigations.	Microwave
They are able to pass through opaque bodies and are used, for example, in medicine to obtain X-rays.	Visible
It allows us to know the main functional groups of the molecular structure of a compound. Another very common use is in remote controls and fiber optics	X-rays

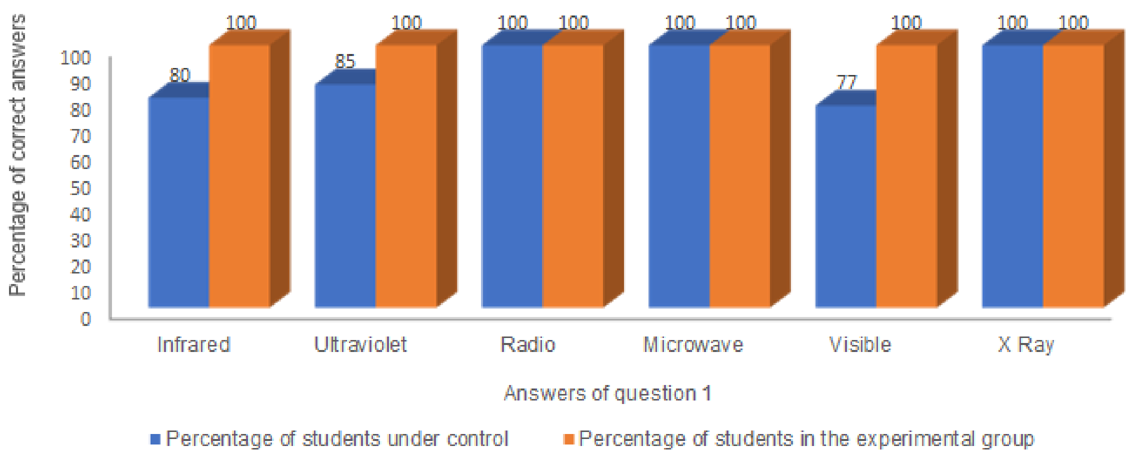


Figure 1. Percentage of answers obtained in the pretest of question 1

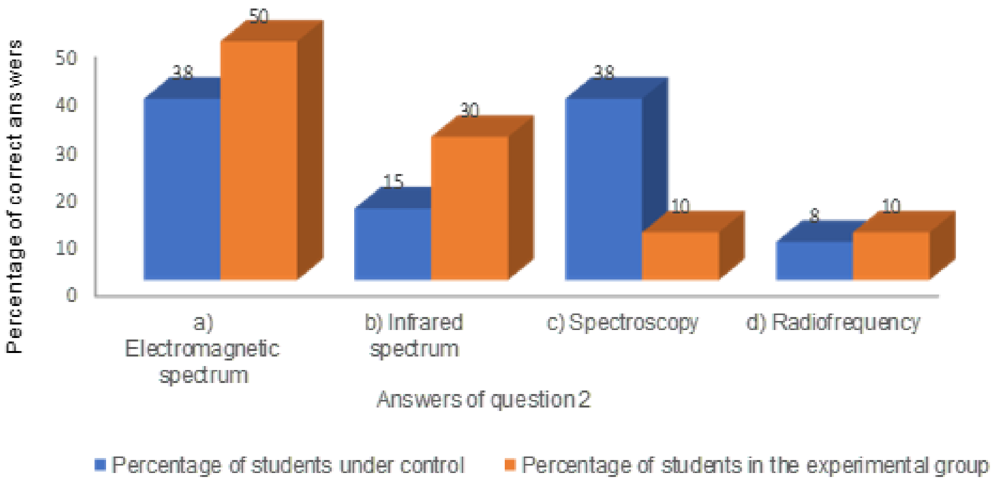


Figure 2. Percentage of answers obtained in the pretest of question 2

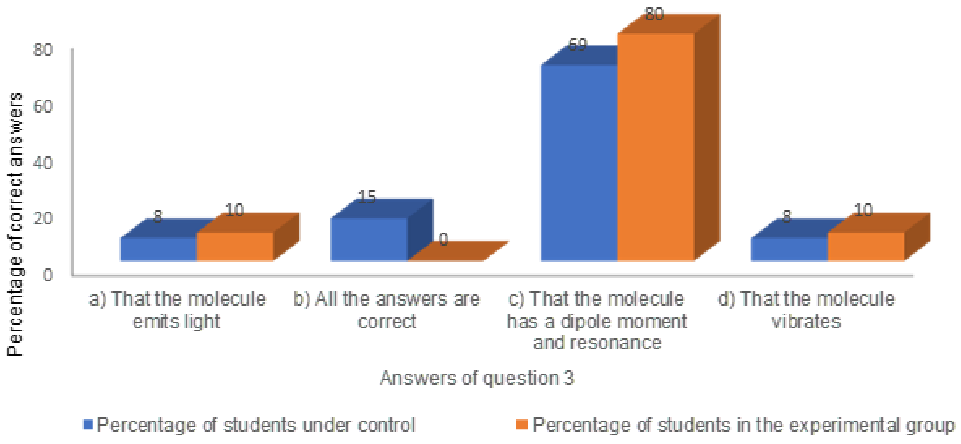


Figure 3. Percentage of answers obtained in the pretest of question 3

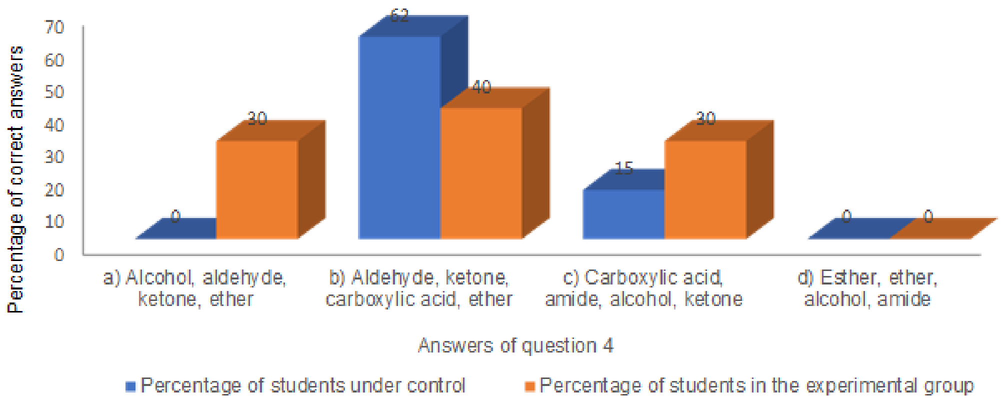


Figure 4. Percentage of answers obtained in the pretest of question 4

Question 4. These are the compounds that contain the carbonyl group.

Figure 4 presents the results of question 4, which consists of selecting the compounds that contain the carbonyl group, and it is evident that 62% of the students in the control group and 40% in the experimental group were able to identify functional groups that include the carbonyl group.

Question 5. What happens when infrared radiation interacts with the molecule?

Figure 5 presents the results of question 5, which consists of selecting the answer of what happens when infrared radiation interacts with the molecule. Where he demonstrates that students have an alternative conception of infrared radiation when it interacts with the molecule, movements of electrons are presented. Which indicates that they are not clear when infrared radiation can be absorbed, causing the bonds of molecules to be strained and not their electrons.

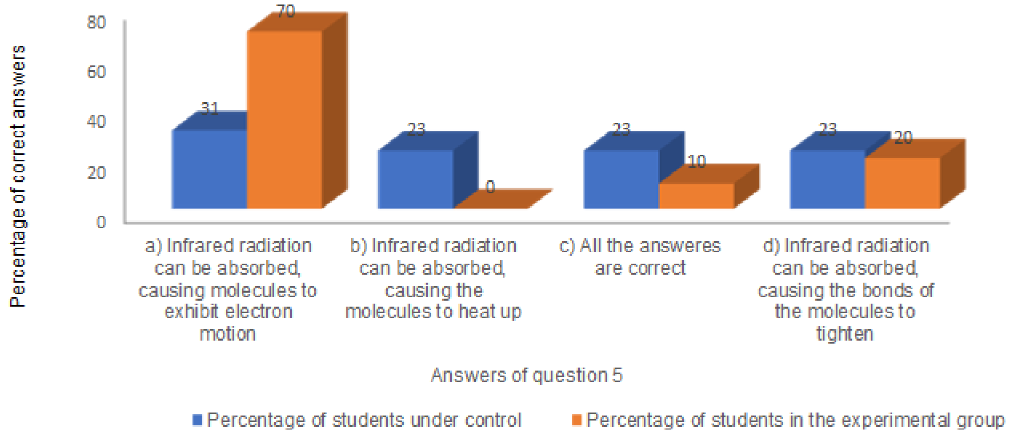


Figure 5. Percentage of answers obtained in the pretest of question 5

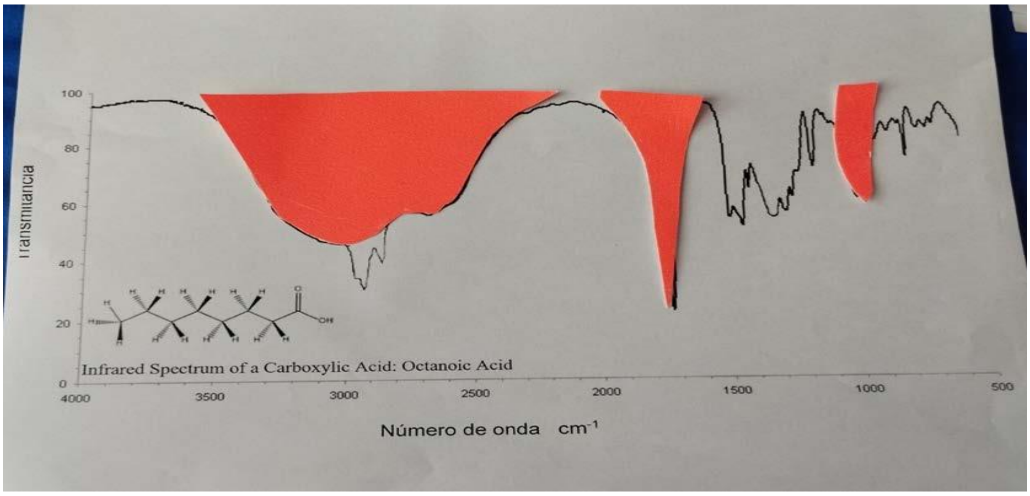


Figure 6. Puzzle "carboxylic acid" (https:// applets.kcvs.ca/ irSuite/exampleFiles/ octanoicacid/octanoicacid.html=)

Formative Assessment

For the formative assessment, an activity was carried out with the didactic material with the infrared spectra that were used for the experimental group and the same spectra of the puzzles (Figure 6) were applied in the traditional way for the control group, where they were instructed to color.

Summative Assessment

For the summative assessment, a five-question questionnaire (posttest) was applied to the same groups of students who received the pretest.

Question 1. Sort the following groups from highest to lowest frequency, placing the item corresponding to the functional group in the box.

Figure 7 presents the results of question 1 of the posttest, which consists of ordering in the boxes the items corresponding to the functional groups from highest to lowest frequency within the infrared spectrum, where it is shown that the students who answered in the experimental group had more correct answers in the order of frequency of the functional groups than those of the control group.

Question 2. From the following spectrum, which carbonyl functional group does it correspond to?

Moving the letters are far away from the structures and are confused, which are in the pictures.

Figure 8 presents the results of question 2 of the posttest, which consists of identifying the infrared spectrum to which carbonyl functional group it corresponds, as this question was from the same exercise that the students did both in the control group and in the experimental group, 69% of the control group correctly answered that the spectrum corresponds to a ketone while in the experimental group it was 67%.

Question 3. Which of these regions does not belong to the region of an IR spectrum?

a) Fingerprint region.
b) C-H Strain region
c) Radio frequency region
d) OH Region

Question 3 of the posttest asks the identification of a region that does not belong to the IR spectrum among several options. Figure 8 shows the results of this question. 54% of students selected the "Fingerprint Region" as the region that does not belong, while 38% chose the correct answer. On the other hand, in the experimental group, 58% of the students answered correctly.

These results (Figure 9) indicate that students in the experimental group demonstrated a better understanding of regions of the IR spectrum compared to the control group. Importantly, the "Radio Frequency Region" was correctly identified as the region that does not belong to the IR spectrum, as this is part of the electromagnetic spectrum.

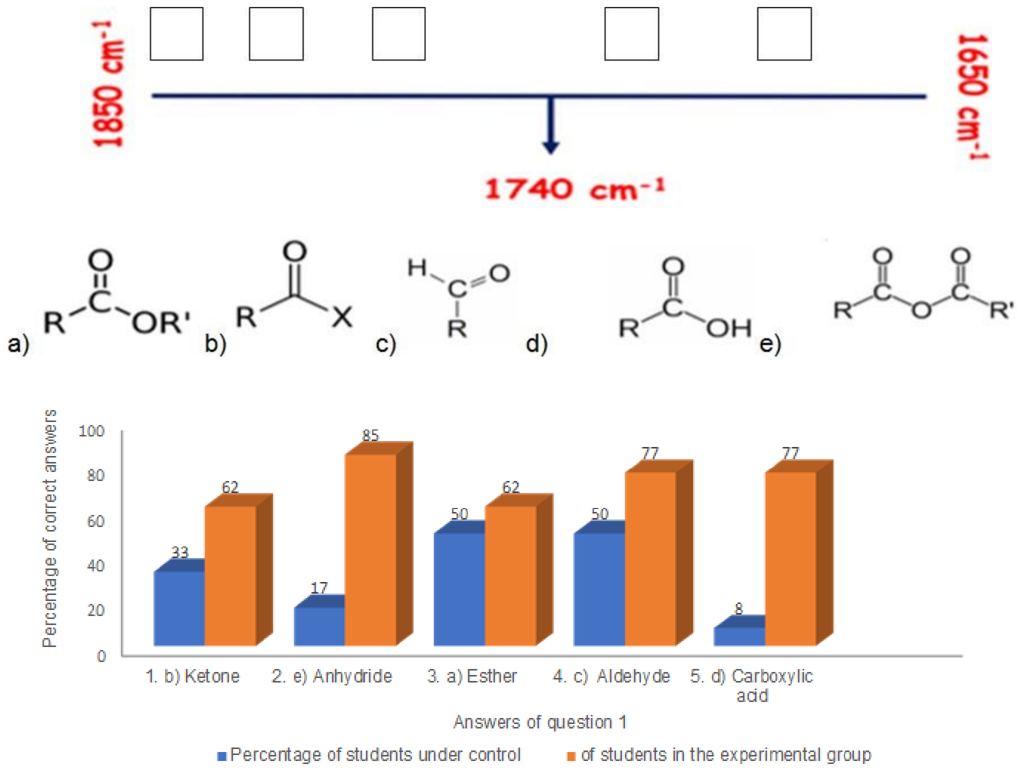
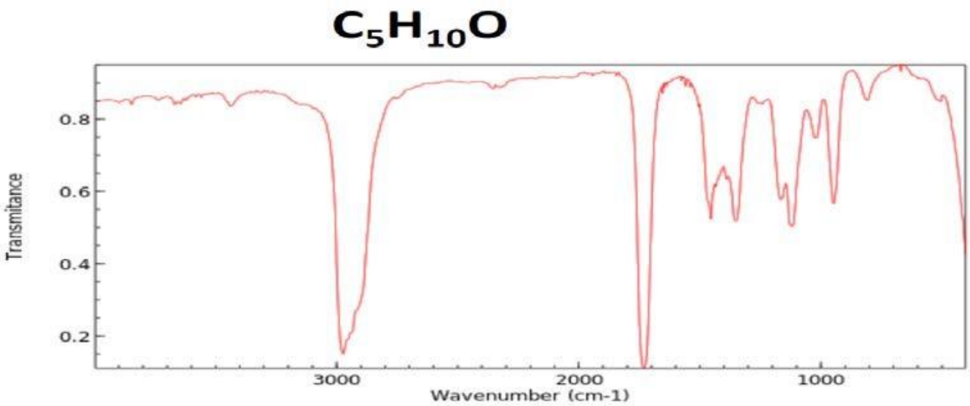


Figure 7. Percentage of answers obtained in the post-test of question 1



NIST Chemistry Web Book, SRD 69 (https://webbook.nist.gov/ cgi/cbook.cgi?ID=C107879&Type=IR-SPEC&Index=2s)

a) Ketone b) Anhydride c) Ester d) Aldehyde e) Carboxylic acid

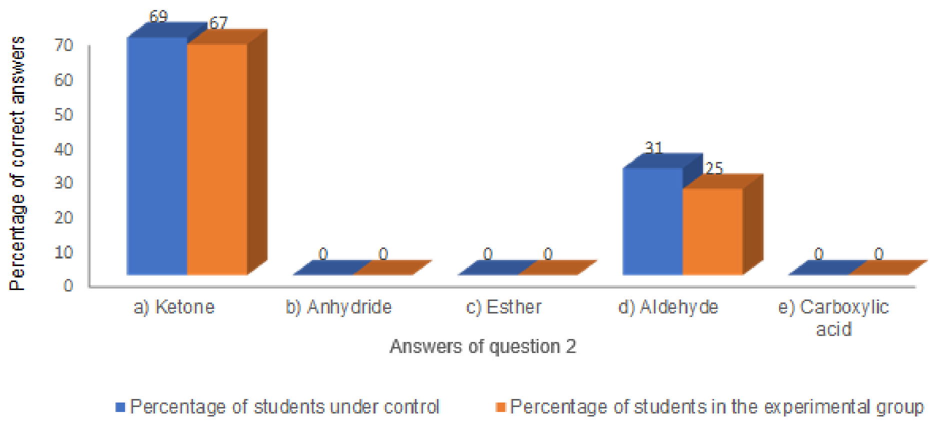


Figure 8. Percentage of answers obtained in the post-test of question 2

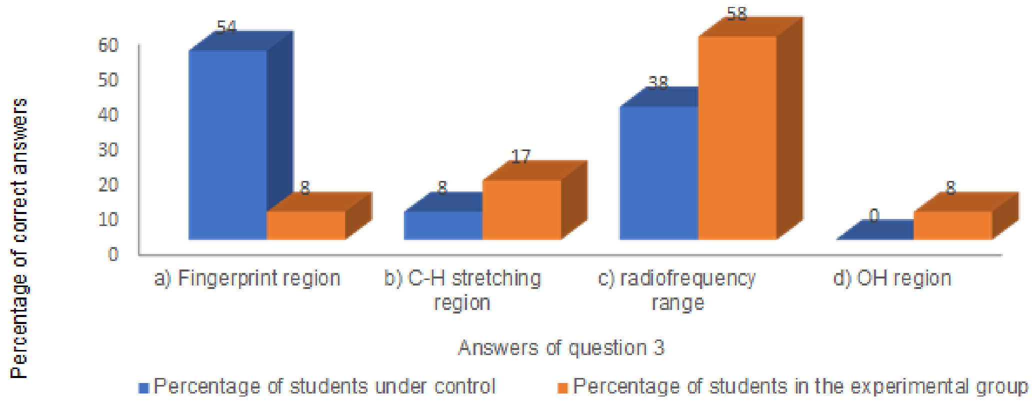


Figure 9. Percentage of answers obtained in the post-test of question 3

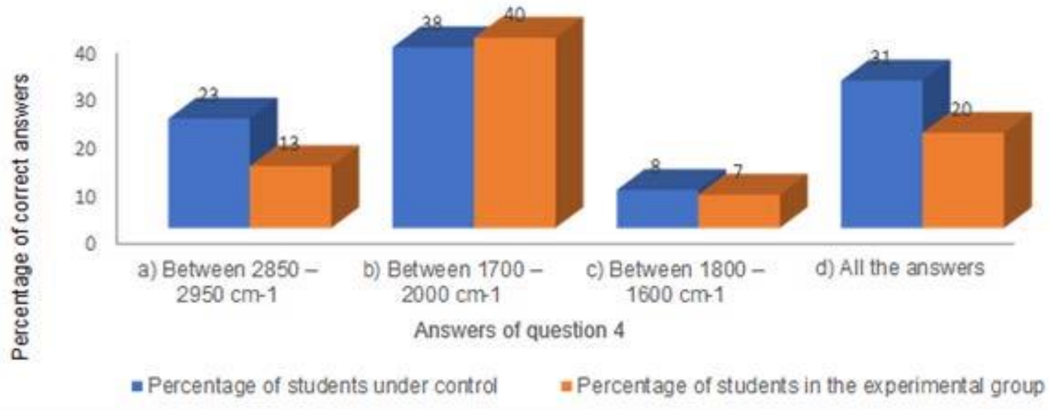
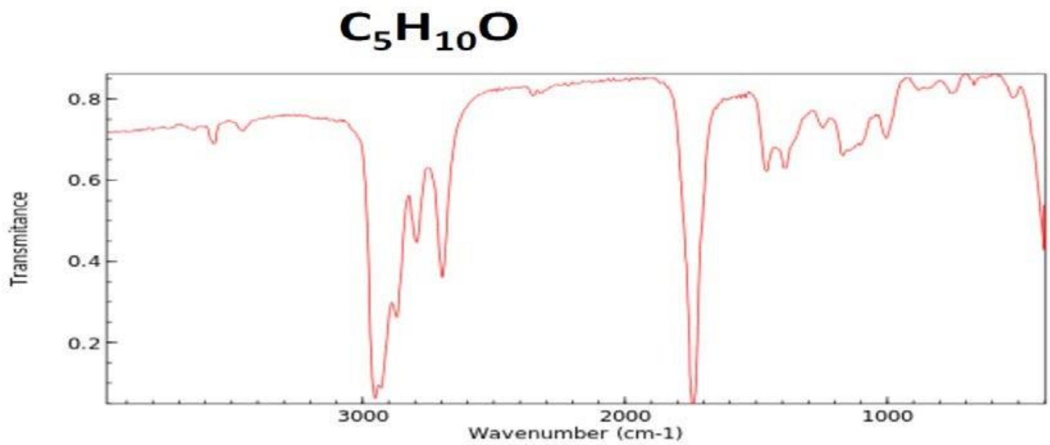


Figure 10. Answers obtained in the post-test of question 4



Web book Chemistry NIST, SRD 69 (https:// webbook.nist.gov/cgi/ cbook.cgi?ID=C110623&Type=IR-SPEC&Index=1)

a) Ketone b) Anhydride c) Ester d) Aldehyde e) Carboxylic acid

Question 4. In which region of the IR spectrum is the presence of the carbonyl group band observed?

a) Between 2850 – 2950 cm^{-1}

b) Between 1700 – 2000 cm^{-1}

c) Between 1800 – 1600 cm^{-1}

d) All answers are correct.

Figure 10 shows the answers to question 4, which consists of selecting the answer that indicates in which region of the IR spectrum the presence of the carbonyl group band is observed, 40% of the students in the experimental group and 38% of the control group who answered managed to understand that the presence of the carbonyl group band is observed in the RI region between 1700-2000 cm^{-1}.

Question 5. From the following spectrum, which carbonyl functional group does it correspond to?

Figure 11 presents the results of question 5 of the posttest, which consists of identifying the infrared spectrum to which carbonyl functional group it corresponds, as this question was from the same exercise that the students did both in the control group and in the experimental group, 40% of the control group correctly answered that the spectrum corresponds to an aldehyde, while in the experimental group it was 69%.

Assessment of learning gain

The instrument selected for the assessment was a multiple-choice questionnaire. The results are depicted in Table 2 and Table 3.

Figure 12 shows the grades obtained by each student who obtained the pretest and posttest of the control group.

Figure 13 shows the grades obtained by each of the students in the experimental group of the pretest and posttest questionnaires.

Table 2. Results of the control group

	Marks				
	Pretest (%)	**Posttest (%)**	**Average learning**	**Age**	**Gender**
Student 1	20	60	0.5	17	Female
Student 2	50	80	0.6	17	Female
Student 3	50	60	0.2	18	Female
Student 4	40	40	0	17	Female
Student 5	100	60	0	17	Female
Student 6	60	60	0	18	Female
Student 7	100	100	0	16	Female
Student 8	40	100	0	16	Female
Student 9	10	20	0.1	17	Male

Table 3. Results of the group of students who applied the didactic sequence

	Marks				
	Pretest (%)	**Posttest (%)**	**Average learning**	**Age**	**Gender**
Student 1	30	50	0.3	17	Female
Student 2	40	60	0.3	17	Male
Student 3	40	90	0.8	20	Female
Student 4	70	80	0.3	16	Female
Student 5	30	90	0.9	18	Female
Student 6	50	80	0.4	17	Male
Student 7	30	70	0.6	17	Female
Student 8	80	100	1	16	Female
Student 9	60	80	0.5	17	Female
Student 10	30	80	0.7	17	Female

The average learning gain of the course of the control group and the experimental group

$$g = \frac{post-test\ (\%) - pretest\ (\%)}{100 - pretest(\%)}$$

Low ($g \leq 0.3$)

Medium ($0.3 < g \leq 0.7$)

High ($g > 0.7$)

Group	Control group (673)	Experimental group (693)
Students	Average g	Average g
Course Average	0.15	0.6

Control group g = Low =0.15

Experimental group g = Medium = 0.6

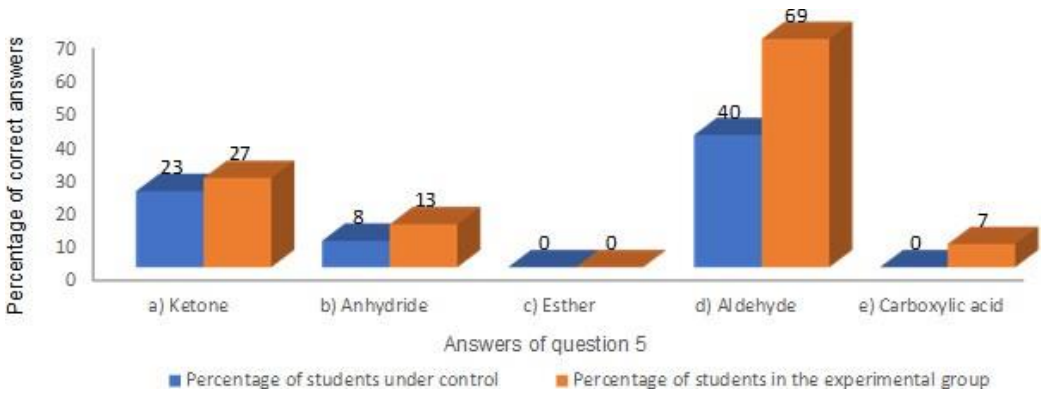


Figure 11. Answers obtained in the posttest of question 5

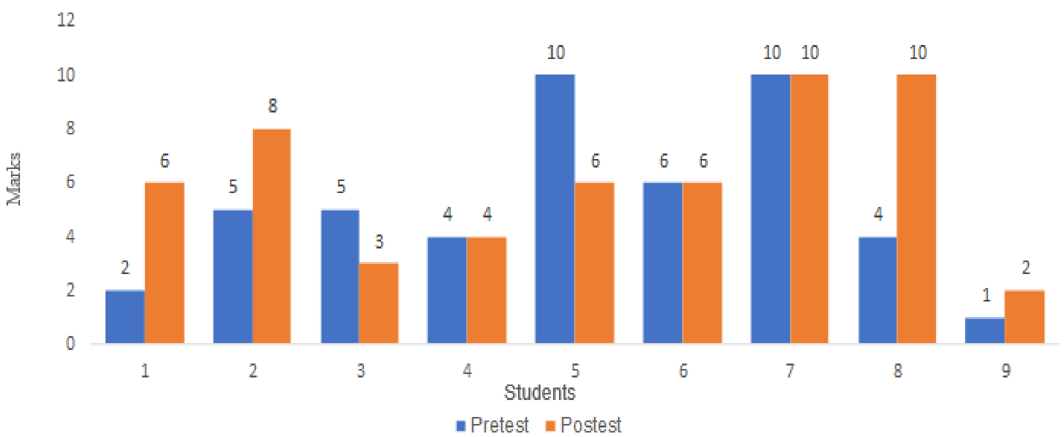


Figure 12. Control Group Learning Gain

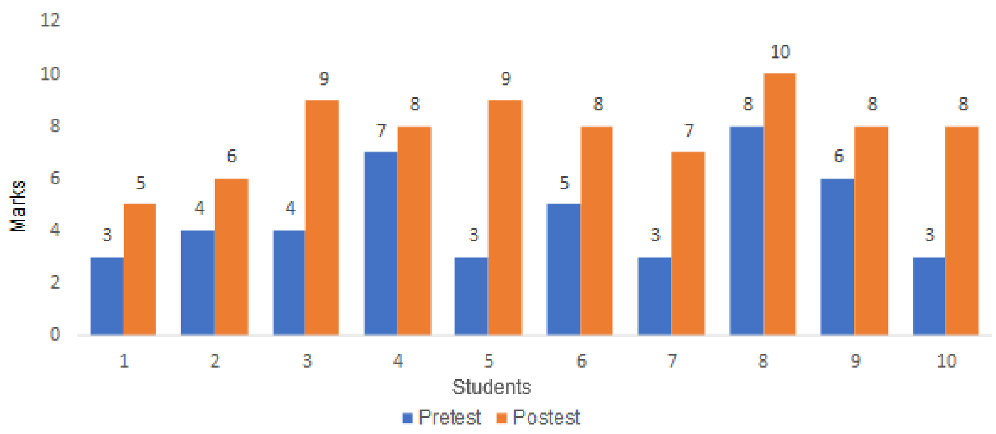


Figure 13. Learning gain of the group of students who applied the didactic strategy

5. Conclusions

Introduction of infrared absorption spectrophotometry at the upper secondary level had a considerable improvement in the degree of learning and can be fundamental to improve the teaching and learning process in the field of spectroscopy, specifically in the identification of the carbonyl group. This strategy was based on the use of a jigsaw puzzle as a teaching material, designed for high school students. The learning gain was at an intermediate level in the group that participated in the implementation of the didactic strategy developed. This result resulted in a positive impact on the students' interest, as it could be observed that they enjoyed the activity and found it entertaining, especially in the phase of assembling the puzzle pieces. In addition, in terms of its ability to identify carbonyl groups in organic compounds, a marked improvement was evidenced. In addition, it is important to note that this didactic strategy was designed to help high school students understand and assimilate the process of identifying the carbonyl functional group by infrared spectroscopy. Comparison between the experimental group that received the strategy and the control group that did not revealed that the students' participation in the experimental group was markedly more active. These findings support the idea that the use of innovative teaching materials, such as the puzzle used in this study, can be an effective tool for improving the understanding and retention of complex chemical concepts. In addition, student participation in the learning process is essential to achieve greater academic success and a greater understanding of topics related to organic chemistry.

The improvement in the identification of the carbonyl group and the increase in interest on the part of students are indicative that this strategy may be valuable in improving the quality of education in this field.

Limitations and scope

One of the main limitations that was manifested was the time constraint when addressing the questionnaires. This problem was since some participants chose to use their cell phones to solve the questionnaires through the Quizizz platform. Unfortunately, this choice proved problematic, as the platform imposed a time limit for completing each questionnaire. Consequently, participants were under pressure to respond quickly. In contrast, the control group, which opted for the traditional approach to addressing the questionnaires, was able to do so more calmly and reflectively. This methodology allowed them to obtain more robust and accurate results.

INFORMED CONSENT STATEMENT Informed consent was obtained from all subjects involved in the study.

CONFLICTS OF INTEREST The authors declare no conflicts of interest.

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