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Research Paper

From Colors to Beer-Lambert Law: A Cognitive Learning Module

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ABSTRACT:
Background: A colored compound selectively absorbs certain wavelengths of visible light while transmitting others, as reflected in its UV-Vis spectrum. The spectrum manifests both the intensity and energy of light that a particular compound absorbs. Reading a spectrum involves understanding the factors that affect the intensity and energy of the absorbed light.
Purpose: Herein, a curriculum-based Problem-Based Learning (PBL) teaching module is developed for undergraduate students to rediscover the above concepts.
Method: Students revisited the concepts underlying the origin of color in inorganic complexes and built hypothetical demo spectra for a compound at different concentrations. Students acquired the UV-Vis spectra for $KMnO_4$ at different concentrations and plotted the graphs on the Excel platform. A quantitative estimate of the electronic transition energies was made for each observed peak.
Results: The hypothesis regarding spectral change with compound concentration was tested from the results, and the relation between concentration and absorbance was reestablished. Responses to post-lab questionnaires indicated that the module promoted enquiring aptitude among the students and enhanced their ability for spectral data interpretation.
Conclusion: The module may bridge the gap between theoretical knowledge and hands-on experience in the field of UV-Vis spectroscopy through active cognitive engagement.

Keywords: Analytical Chemistry, Inorganic Complex, UV-Visible Spectroscopy, Beer-Lambert Law, Undergraduate, Problem Based Learning, Group Discussion, Hands-On Learning, Questionnaire review

1. Introduction

1.1. Background of UV-Vis Spectroscopy and Beer-Lambert Law

Like the mesmerizing color of a substance fascinates the eyes of the beholder, the chemistry of origin of color captivates the minds of chemistry students [1]. The relation between visible light absorption and the manifestation of a particular color in a compound is best understood by UV-vis spectroscopy. The versatility of UV-vis spectroscopy is not restricted to academic research but is widely applicable to the numerous fields associated with our day-to-day life [2-6] such as in analytical, pharmaceutical, food and beverage industries, environmental science, biomedical, forensics, material science, verifying the efficiency of sunglass and sunscreens, etc. Further, this multifaceted spectroscopy technique is based on the overarching theme of Beer-Lambert law [7] which connects the amount of light absorbed with the solution concentration and pathlength light travels through solution by a simple equation given as, $A = \epsilon cl$, where, A is absorbance, ϵ is the molar absorptivity of the solute, l is the path length of the sample chamber, and c is the molar concentration of the sample solution.

1.2. Gaps in Traditional Teaching Approaches

Though a student gathers the theoretical concepts of electronic absorption and excitation along with the crystal field splitting and origin of color in transition

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metal complexes, they are introduced to the practical aspects of UV-vis spectroscopy only in the later under graduate (UG) stage. In the laboratory classes at this stage a student encounters an absorption vs. wavelength spectrum of a particular compound. The phenomena of light-mater interaction as dealt in the UG level concerns the two distinct features i.e. (i) the wavelength at which absorption occurs and (ii) the quantity of light absorbed. In the study of electronic transition, the students gained an understanding that an electron in a particular state absorbs light of fixed energy and gets promoted to a higher energy state. It translates an idea that if light of a broad energy (wavelength) range fall on a compound, a particular wavelength light is absorbed depending on the energy gap between the two energy states. On the other hand, the teaching of UV-vis spectroscopy begins with Beer-Lambert law.

In the traditional laboratory and side by side theory classes for UV-vis spectroscopy a gap appears in assimilation of both these features of light mater interaction through the observed spectra. The traditional chemistry laboratory experiments follow a recipe based or cook book model type learning methodology [8], which involves a previously verified and tried procedure. Each student follows the particular recipe meticulously to reach at a known identical result. Such method, although develops the technical and psychomotor skills, it does not create a scope for creative engagement of the students. The participants have limited scope to assimilate any active input into the learning process, such as building up hypothesis, experiment design to test the hypothesis, data analysis, and verification of hypothesis.

1.3. Rationale for Problem-Based Learning (PBL)

On the contrary to traditional lab methods, problem-based learning (PBL) method is based on the philosophy to guide the student on a path similar to that traversed by the scientists [9-13] in discovering the particular knowledge. In the learning process, students are exposed to the methodology of knowledge generation and thereby develop scientific thought process. It further helps the students to combine their theoretical understanding on the subject with hand on skill thereby developing a coherent knowledge base. To translate this philosophy into action, specific module needs to be developed for each experiment based on the level of understanding of the students, which also needs to be upgraded from time to time.

1.4. Objectives of the Study

- To foster cognitive engagement in the learning of UV-vis spectroscopy and the Beer-Lambert law through active inquiry.
- To develop students' ability to formulate and test hypotheses relating concentration changes to UV-Vis spectral variations.
- To enhance students' proficiency in using Microsoft Excel for graphical data analysis and interpretation.
- To sharpen students' observational skills for interpreting UV-vis spectra and deriving meaningful conclusions.
- To deepen students' macroscopic understanding of the principles underlying the Beer-Lambert law.
- To facilitate a conceptual and experiential rediscovery of the Beer-Lambert law in the context of light-matter interaction.

2. Literature Review

2.1. Problem-Based Learning in Science Education

Problem based learning has emerged as a transformative approach in science education emphasizing in critical thinking, deeper understanding and lifelong learning skills starting from medical education in 1960s [14]. PBL methodology places students in complex and real-world problems aiming at active exploration and solution development. In the scenario of science education, PBL conveys the focus from memorization by repetition to problem-solving and inquiry driven learning, where knowledge is actively assembled by students [15]. Research underlines that, PBL improves students' scientific thinking, problem-solving potential and learning motivation [16-17]. In addition, PBL

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circumstances have been corelated with metacognitive and self-directed learning skills [18]. In laboratory practices, PBL allows students to engage with scientific practices beyond traditional experimental procedures [19] which fosters authentic scientific practices. On the other hand, challenges such as increased workload required to complete the process and the need for essential facilitations skills among educators have also been reported [20].

2.2. Conceptual Learning and Cognitive Engagement

The process of procuring comprehensive awareness of principles, equations and important relationships is crucial for effective science education. It opposes the learning type where students remember facts and formulas without understanding fundamental principles [21]. Cognitive engagement defined as the allocation of mental ability to understand complex problems, plays a crucial role in executing conceptual learning results [22]. Active learning strategies like PBL significantly enhance cognitive engagement of students by prompting them to connect fresh information with existing cognitive structure [23]. Additionally, scaffolds that promotes metacognition such as reflective questioning in prelab and post lab sessions, collaborative discussion further enhances students' cognitive engagement [24]. However, facilitating notable cognitive engagement needs instructional and high-quality scaffolding.

2.3. PBL in Spectroscopy and Analytical Chemistry Education

Application of PBL in the fields of spectroscopy and analytical chemistry highlights the demand for developing theoretical understanding, practical and analytical skills. Traditional methods usually fail to represent the complexity and multidisciplinary nature of analytical chemistry [8]. On the other hand, PBL allows students to address spectroscopy not just as a set of techniques but as a problem-solving toolbox fundamental to scientific inquiry. Researchers have demonstrated that incorporating PBL scaffolds into spectroscopy domains increases conceptual understanding of instrumental methods and data analysis [25]. Students engaged in PBL constructed spectroscopy activities showed enhanced ability to interlink spectral data to determination of molecular structure [26-27]. In addition, PBL promotes cooperative and group learning essential in science laboratories where team work reflects professional practices [28-31].

However, successful implementation of PBL in analytical chemistry needs thoughtfully stretch problems that are complex and originated with students' preknowledge [32-34]. Moreover, evaluation practices should develop to explore higher order thinking skills instead of simple recollection. In the undergraduate level teaching UV-Vis spectroscopy is employed as a tool to demonstrate different phenomena involving qualitative and quantitative analysis of analytes. The tetrahedral cobalt-isopropyl complex (blue) reacts with methanol to form octahedral coordination (pink) with visual color change. The UV-Vis spectroscopy is used to calculate the equilibrium constant of this reaction, thereby help in teaching the concept of Le Chatelier's principle and equilibrium constant [35]. Teaching chemistry has been made engaging by employing daily use materials such as coffee and olive oil. The UV-Vis spectroscopy is used to assess the quality of these materials [36-37]. The application of B-L law is at the center of all these studies. However, the focus of these interventions is to determine the concentration of an analyte rather than developing an understanding on UV-vis spectrum and B-L law. From the perspective of students understanding there are three specific aspects of this law- (i) interpretation of the UV-vis spectrum of a real compound, (ii) to extract data from the spectra to visualize the relation between concentration and absorbance, and (iii) the submicroscopic understanding of the relation. It may be further emphasized that the B-L law is not manifested in an individual spectrum of a compound taken at a specific concentration. The student only observes one or more than one peaks in a wavelength vs absorbance curve. Therefore, a systematic, step wise and ordered introduction of the above three aspects is essential to give a clear picture to the students about the B-L law. To meet these pedagogy challenges, we developed a PBL based method to introduce the UV-Vis spectroscopy and B-L law for transition metal complexes.

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3. Methodology of the study

3.1. Research Design

This study employed a concurrent embedded mixed-methods strategy within a design-based research framework. The quantitative strand, following a One-Group Pretest-Posttest Quasi-Experimental Design, assessed students' conceptual understanding and data analysis skills before and after the PBL module. Simultaneously, the qualitative strand, using a Qualitative Descriptive Design, explored students' inquiry behavior, reflective thinking, and experiential perceptions through group discussions, narrative responses, and observational notes. Quantitative data served as the primary focus, while qualitative insights were embedded to enrich the interpretation of learning outcomes. This integrated approach enabled a comprehensive evaluation of how the PBL intervention impacted both cognitive and affective aspects of students' understanding of the Beer-Lambert Law.

3.2. Participants and Setting

The participants of the study were third-year undergraduate Chemistry students from the Department of Chemistry, Ravenshaw University, Cuttack, enrolled in Core Paper-XI and Core Paper-XII Laboratory courses. A total of approximately 36 students took part in the module. Students worked collaboratively in small groups (5–6 members per group) during laboratory activities. The teaching-learning sessions were conducted in the university's analytical chemistry laboratory and the E-resource center equipped with UV-vis spectrometers and computer systems.

3.3. Development of the PBL Module

The PBL module was carefully designed to systematically guide students through the process of hypothesis building, experimental verification, data analysis, and conceptual understanding of UV-vis spectroscopy and the Beer-Lambert Law. The module was structured into four classes, each of two hours, (see table 1) distributed over pre-laboratory, laboratory, and post-laboratory activities.

3.3.1. Pre-Laboratory Activities

The pre-laboratory activities were intended to activate prior knowledge and prepare students for inquiry-based learning.

Pre-Lab Questionnaire: Students were given a questionnaire exploring the origin of color in transition metal complexes, prompting group discussions and individual reflections.

Conceptual Recapitulation: Key concepts such as electronic transitions, absorbance and wavelength maxima were revisited.

Hypothesis Development: Students were asked to draw hypothetical UV-vis spectra for solutions of varying concentrations to predict how concentration would influence absorbance without prior exposure to experimental data.

3.3.2. Laboratory Activities

The laboratory sessions engaged students in experimental verification of their hypotheses through hands-on experience:

Solution Preparation: Students prepared stock solutions of $KMnO_4$ and performed serial dilutions to obtain five different concentrations.

UV-Vis Spectroscopy: Students recorded absorbance spectra for each concentration using Agilent Cary $100 UV/Vis$ spectrometer.

Data Recording: Absorbance data were collected and saved digitally for further analysis.

Data Analysis: Students plotted Absorbance vs. Wavelength graphs using Microsoft Excel, calculated energy gaps (ΔE) for absorption peaks, and constructed calibration curves plotting absorbance versus concentration at λ_{max} values.

3.3.3. Post-Laboratory Activities

Post-laboratory sessions focused on reflective analysis and conceptual synthesis:

Hypothesis Testing: Students compared their experimental results with their initial hypotheses to validate or refine their conceptual understanding.

Graphical Interpretation: Students critically interpreted the plots to establish the linear relationship between absorbance and concentration, reaffirming the Beer-Lambert Law.

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Table 1: The structured module into four classes.

Class	Activity Focus	Duration in hours
Class I	**Pre-lab discussion:** Prior knowledge activation, discussion on color and UV-Vis spectrum. **Hypothesis building:** Predicting changes in spectra with concentration variation.	2hrs
Class II	**Laboratory work:** Solution preparation, dilution, UV-Vis spectra recording.	2hrs
Class III	**Data processing:** Plotting absorbance vs. wavelength graphs using Microsoft Excel.	2hrs
Class IV	**Post-lab questionnaire:** Observations, hypothesis validation. **Data analysis:** Calibration curve plotting and interpretation.	2hrs
Final Evaluation Class	**Final assessment:** Conceptual reflection and extended questions.	45min

Extended Inquiry: Students were prompted to explore the effect of path length on absorbance theoretically, enhancing their submicroscopic understanding.

3.4. Data Collection Tools

Data collection for evaluating the effectiveness of the PBL module included both quantitative and qualitative methods:

3.4.1. Questionnaires

Pre-lab questionnaires assessed students' prior conceptual understanding and their initial hypotheses about UV-Vis spectra and concentration changes. Post-lab questionnaires captured students' reflections on their experimental findings, understanding of the Beer-Lambert law, and their feedback on the PBL approach.

3.4.2. Observation and Feedback Analysis

Throughout the sessions, systematic observations were made regarding students' group interactions, inquiry behavior, graph plotting skills, and conceptual discussions. Student feedback forms were administered at the end of the module to gather perceptions on cognitive engagement, scientific thinking development, and the overall learning experience. Both quantitative feedback (through Likert scale ratings) and qualitative feedback (open-ended comments) were analyzed to triangulate findings and validate the effectiveness of the intervention.

4. Results and Discussion

4.1. Students' Hypothesis Formulation and Testing

In the first laboratory class, solutions of $CuSO_4.5H_2O$, $KMnO_4$ and $K_2Cr_2O_7$, and were taken in three different beakers bearing purple, orange and light blue colors respectively (see Figure 1.a). The beakers were placed in the front table and a demo UV-Vis plot of Absorbance vs. Wavelength (λ) was drawn on the teaching board (see Figure 1.b). It was explained that the colored compounds show similar kind of spectrum in the visible region of the spectrum. Looking at these different colored solutions and a demo spectrum the questions that evolve spontaneously to any observer are compiled as follows:

i. Why these solutions are colored?

ii. Why different compounds show different colors?

iii. What information does it give?

iv. What does λ_{max} and intensity or Absorbance in the graph signify?

The students were divided into 6 groups with 6 students in each group. The students wrote the answers to the above questions individually after an intragroup discussion. On analyzing the answers given by each student at the first glance, it was observed that members of the same group have given different answers to the same question. It shows that although they discussed together but they answered the questions as per their individual perspective. They did not try to build a

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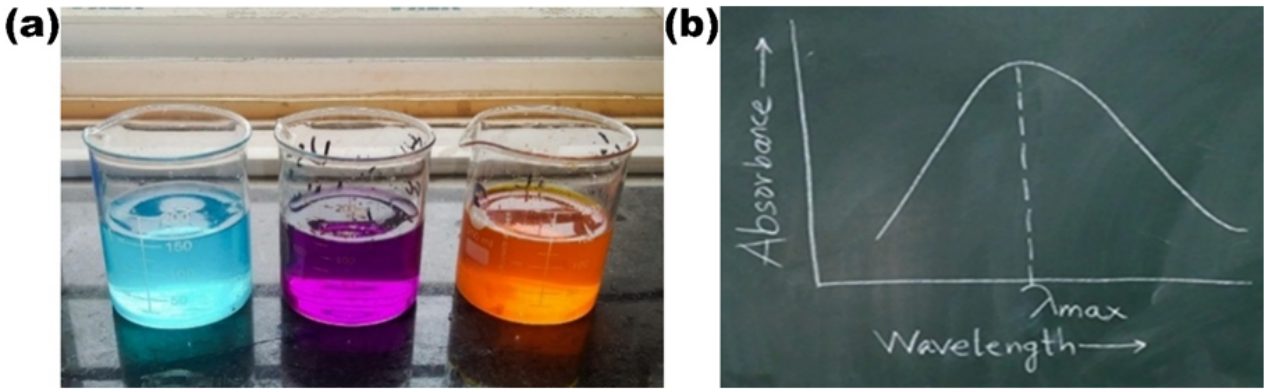


Figure 1: Figure 1- a)Solutions of $CuSO_4.5H_2O$, $KMnO_4$ and $K_2Cr_2O_7$ in distilled water in three different beakers kept on the Teacher's table. (b)Absorbance vs. Wavelength graph of a demo compound drawn on the black board.

consensus over any answer. It has been observed that the students have the idea that the color of these inorganic complexes is due to either d-d transition or ligand-metal charge transfer. However, there is considerable confusion over the particular nature of transition in each of the individual compound. Only 28 % of the students could distinguish the particular kind of transition taking place in each of the three compounds. It may be noted that only 20% of the students also could correlate that different colors are due to the absorption at different wavelengths. As all the students had limited expose to the graph of a UV-vis spectrum at this stage, it was difficult for them to correlate the wavelength and intensity with energy difference and the amount of the material respectively. It may be noted that although students had a prior knowledge of mathematical relation between the energy gap and the corresponding wavelength of absorbed radiation, but in this initial stage of the class, they could not correlate it with the provided demo graph. A noticeable observation was that, 8 number of students (who belonged to different groups) carried the common perception that, the color of a compound depends upon its molecular mass and size. In a previous work Haiyan Al Fulaiti, et al. interviewed some undergraduate students regarding UV-Vis spectra of two molecules and a qualitative categorization of the statements have been made. The answers referred in level 2 in the order of their sophistication matches with the present answer to the questionnaire [38].

In the subsequent portion of the class, B-L law which has already been taught in their theory classes (as it is the part of their theory syllabus in 5th semester), was recapitulated along with the mathematical expression, $A = \varepsilon cl$ which shows that the concentration variation leads to Absorbance variation and the students were asked to draw the Absorbance vs. Wavelength plot for solutions of a hypothetical molecule in three different concentrations c_1, c_2, and c_3 such that $c_1 > c_2 > c_3$. to build up their own hypothesis that if the concentration of a particular compound changes, then how their UV-Vis spectrum would change. It is worth mentioning that the students were already introduced a demo Absorbance vs. Wavelength graph of a hypothetical compound at particular concentration in the first class and the aim behind the second class was to make the students able to translate the mathematical knowledge into graphical presentation.

As shown in the graph in Figure 2, only 16% of the students showed that with increase in concentration the absorbance increases without any change of the peak position, 28 % students showed that the peak position moves to higher energy site with gradual decrease in intensity and other 20% of the students showed that with increase in concentration the peak position moves to higher energy site without any change in absorbance. This observed different graphical representation by different students may have arisen as because in the B-L law the effect of concentration on the absorption energy has not been explicitly spelled out. As because it is dealing with the different concentrations of the same

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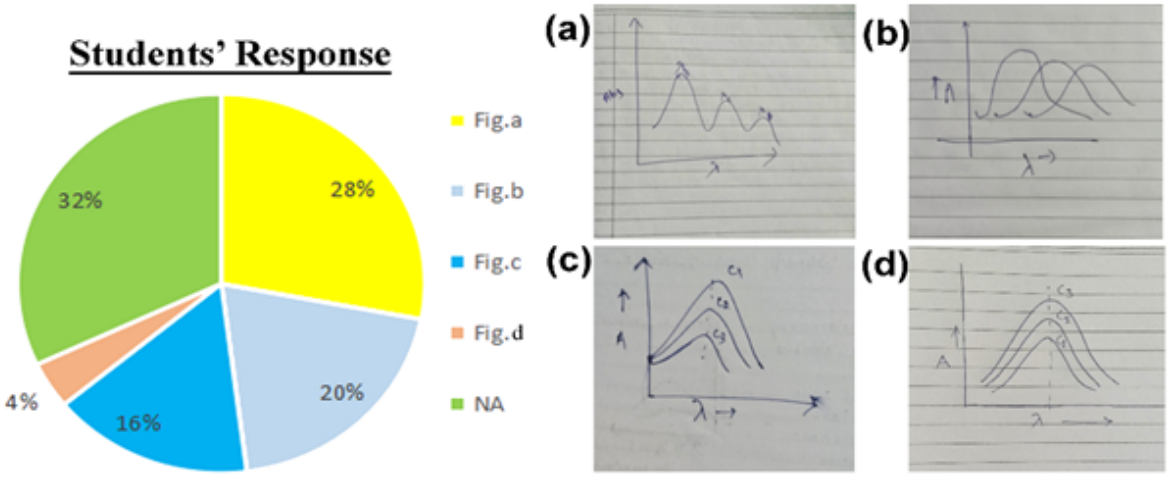


Figure 2: Students' response against the question to draw the Absorbance vs. Wavelength plot for solutions of a hypothetical molecule in three different concentrations c_1, c_2, and c_3 such that $c_1 > c_2 > c_3$ in the prelab. (NA- not answered)

substance, the energy gap and hence the absorption energy of the spectrum is expected to remain constant. The origin of this observed difference in opinion might have come from the above-mentioned aspect B-L law which is not dealt with its due importance in the theory class.

4.2. Experimental Observations and Analysis

In second class, our objective was not only to make the students able to test their own hypothesis but also to develop their experimental skills in different activities like weighing in the digital balance, preparing the stock solution, and diluting the stock solution to get definite concentrations. The students were introduced to the UV-VIS instrument (Agilent Cary 100 UV/Vis having Tungsten Halogen as the light source and wavelength range from 190nm to 900nm.), its operation with Cary WinUV software, and its ray diagram. The use of quartz cuvettes for putting the reference solution and the solution under study in line with the incident ray has been demonstrated to the students.

The students performed the lab works in small groups consisting of 5-6 members in each group. The students prepared $KMnO_4$ stock solution of 10-3 M concentration and further diluted it to 5 different concentrations, i.e., c_1, c_2, c_3, c_4, and c_5 as given in table 2. Each group separately took the UV-Vis spectra of the solutions at different concentrations and collected the data in ASCII format by a pen drive for further processing.

4.3. Spectral Interpretation and Conceptual Understanding

The third class was taken in the E-resource center of the Ravenshaw University, where students were demonstrated to import the ASCII data to the Microsoft Excel platform and draw the absorbance vs. wavelength curves for 5 different concentrations of $KMnO_4$ and merge them in a single graph. Each student was assigned a separate desktop for the said work and they individually drew the plot. Different colors were assigned to different concentration curves in the UV-Vis plot. They took the print out of their plot and pasted in their laboratory note book. The absorbance vs wavelength plot obtained by one of the students is given in figure 3. The students were instructed to revisit their hypothetical UV-Vis plot (drawn by them in class 2) and compare it with the experimental spectra. Also, after getting the Absorption peaks, they are asked to calculate the ΔE (eV) for the λ_{max} corresponding to each peak observed in the UV-Vis spectrum. The students realized that even in a single molecule a set of different electronic transitions may occur each associated with definite energy gap. In the visible region students identified two absorption peaks centering around 524 and 545 nm.

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Table 2: The amount of stock solution and distilled water taken to prepare different concentrations of $KMnO_4$ solution.

Solution	Stock Solution (in ml)	Distilled Water (in ml)	Molar Concentration
C_1	3.0	8.0	0.00027
C_2	2.5	8.5	0.00022
C_3	2.0	9.0	0.00018
C_4	1.5	9.5	0.00013
C_5	1.0	10.0	0.00009

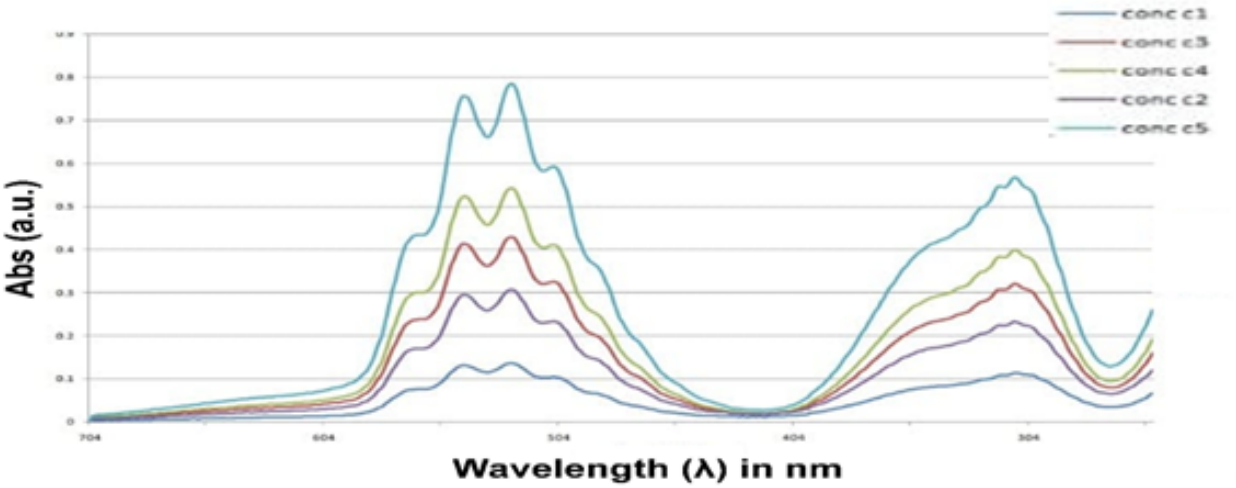


Figure 3: UV-Vis Spectra of $KMnO_4$ Solutions in Different Concentrations plotted in Microsoft Excel by a student

It was observed that all the students could individually plot the absorbance vs. wavelength graph for all the 5 prepared solutions in Excel with a little personal guidance. The students calculated correctly the ΔE (eV) corresponding to each λ_{max} in the spectrum.

In the Class IV, the students were instructed to observe the graphs carefully. The following questions have been formulated to assist the students.

i. What is the wavelength region for the observed violet color of $KMnO_4$?

ii. Do you observe any absorbance in this region?

iii. What changes do you observe in the spectra of $KMnO_4$ by decreasing the concentration?

iv. Do you observe any change in the λ_{max} position on decreasing the concentration?

All the students observed the spectra correctly and identified that there is no absorbance in the violet region of the spectrum. The students also reported that λ_{max} remained unchanged with change in concentration and the absorbance of each peak decreases with decrease in concentration. The hypothesis formulated by the students in the second class was examined and confirmed by observing the absorbance vs. wavelength graph of $KMnO_4$ at different concentrations.

4.4. Data Handling and Graphical Skills Using Excel

Though qualitatively it was observed that absorbance decreases with dilution, to find out the mathematical relation between them, in the 2nd computer lab class (in the latter half of the Class IV) students were asked to record the absorption of the peaks at 545nm and 524nm at the five different concentrations. These two particular peaks were chosen as these lie in the visible region. The students drew the graph between absorbance and concentration in Microsoft Excell platform. The points were fitted to a straight line proving that absorbance is directly proportional to concentration (see Figure 4- a and b).

It may be noted that in the present module no experiment was conducted to relate the path length with absorbance, however as the students had already gone through the experimental module, it is assumed

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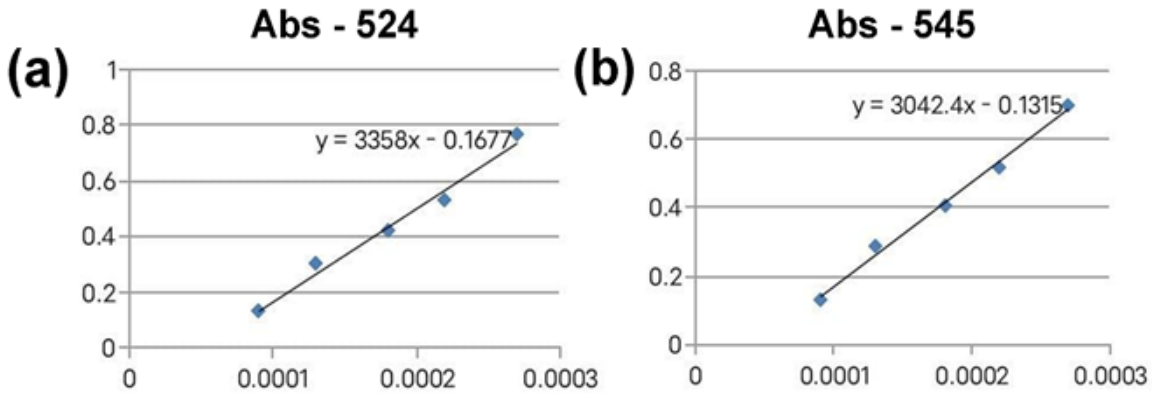


Figure 4: (a) & (b): Conc. vs. Absorbance plot of $KMnO_4$ at λ= 545nm and 524nm respectively, drawn by a student in Microsoft Excel.

that they have developed a microscopic understanding of the UV-Vis spectrum. Therefore, to trigger higher level of abstract thinking among the students a question relating absorbance to the path length is asked and instructed to draw a suitable diagram to elaborate it.

In answers we found that 74% of students gave a graphical representation displaying a linear relation between absorbance and path length (see Figure 5-a). Four students wrote in their answers that with increasing path length number of absorbing molecules increases resulting in increase in absorption. Another two students diagrammatically represented that, but wrote that 'increasing the path length the volume of solution increases causing increasing absorbance' (see Figure 5-b). Interestingly one of the answers says "with greater pathlength, solution get enough time to absorb the incident radiation. Hence, the absorption increases." (see Figure 5-c). These answers signify that this module has triggered independent and creative thinking among the students.

4.5. Hazards and Safety

$KMnO_4$ used in the experiments may cause burning sensation, cough, sore throat or shortness of breathing upon inhalation. When exposed to skin may cause burning, irritation or redness. Also causes redness and burning of eyes. If ingested causes abdominal burning sensation and pain, diarrhea, nausea or vomiting.

Breathing protection should be used to avoid the inhalation of fine particles. Protective gloves and protective clothing must be used. For eye protection, safety glass must be used. Eating and drinking should be avoided during work [39].

4.6. Students, feedback on Learning Experience

After the completion of the teaching module, a feedback form was handed out to the students to express their opinion. The feedback response is summarized through a bar graph in Fig.6. The students gave overall affirmative response to the teaching methodology. The majority of the students said that the group discussion stimulated interest in them and their problem-solving skill. Their creativity got enhanced. The class improved their computer skill. The student felt more comfortable in the classes.

The qualitative feedback collected from students highlighted the effectiveness of the PBL module in transforming their learning experience. Students consistently expressed that the module promoted active engagement, conceptual clarity and critical thinking beyond rote memorization. Many students appreciated the opportunity for hypothesis-driven experimentation, noting that it fostered a deeper understanding of the Beer-Lambert Law through self-discovery rather than traditional didactic instruction. They emphasized improvements in communication skills, teamwork and scientific inquiry, attributing these gains to collaborative discussions and independent data analysis tasks. Notably, several students recognized the enhancement of their digital competencies, particularly in using Microsoft Excel for spectral data handling which they

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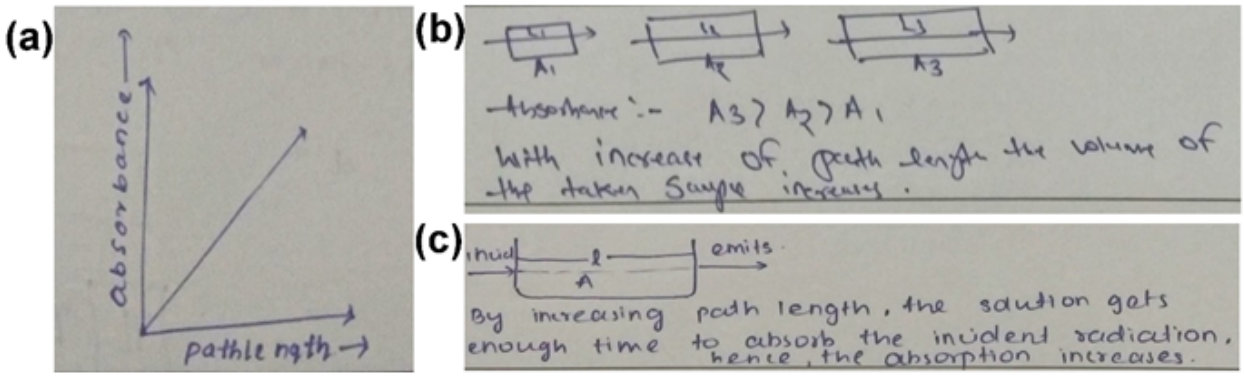


Figure 5: (a), (b), (c): Some of the students' response showing graphical representation of absorbance and pathlength.

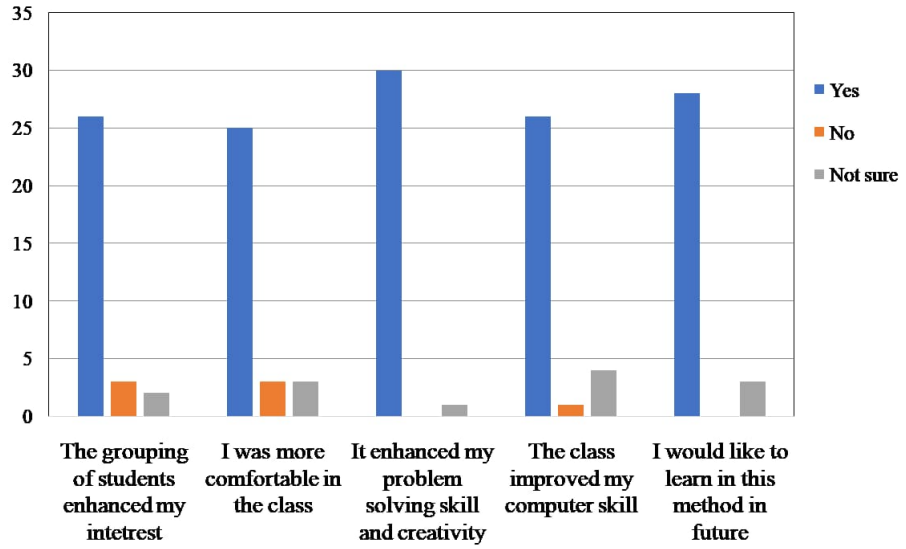


Figure 6: Students' response about the Teaching Module.

viewed as valuable for future research activities. Overall, the students' narratives reinforced that the PBL approach successfully bridged the gap between theoretical concepts and experimental practice, cultivating a more curious, confident and autonomous learner mindset in the chemistry laboratory environment.

5. Conclusion

This PBL based teaching module commendably fostered a scientific thinking among students allowing them from passive learners to active participants in the pathway of knowledge building. Through critical analysis of UV-Vis spectra students obtained more refined understanding about light-matter interaction and the foundation of the B-L law. The module not only nourished their grasp of theoretical conception but also sharpened their experimental and analytical skill. Further, this module provided necessary path to rediscover the variation in UV-Vis spectrum with the change in concentration of a compound. The students calculated the energy gaps between various electronic transitions involved in MnO_4- solution and correlated the absorbance profile with the observed color. It clarified the mathematical extraction of B-L law with actual data and observable phenomena. In conclusion, through this PBL based teaching module a macroscopic understanding developed among the students which connected the theoretical aspects of UV-Vis spectroscopy with real-life spectrum of a compound. The students' feedback highlighted the fruitfulness of this approach in amplifying comprehension, engagement and eagerness for the subject. This teaching methodology presents a replica for integrating

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fundamental concepts with active learning covering the Chemistry curriculum.

6. Pedagogical Implications

The execution of the curriculum based PBL module showed a notable shift from traditional recipe-based hands-on experience to an inquiry driven cognitively engaging instructional approach. It strengthened students' conceptual understanding in UV-vis spectroscopy and B-L law by involving them in the full process from hypothesis formulation to experimental verification. Group discussion, data interpretation and visualization through Excel not only enhanced their scientific thinking but also cultured communication and computer skill. This PBL teaching module authenticates the effectiveness of learner-centered approaches in encouraging deeper learning and analytical thinking in undergraduate science education.

7. Recommendations for Future Research

Future study should intend to validate the usefulness of this model across various educational settings and larger student populations. Relative involving control groups taught through traditional methods would help assess the relative advantages of the PBL method. In addition, expanding the range of the module to include more spectroscopic methods could reinforce students' understanding and relevance of scientific principles.

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Similarity Index: The authors hereby state that there is no similarity index in the abstract and conclusion, while overall similarity is less than 10%, with individual source contribution is 2% or less.

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Annexure

A-Laboratory Session

Third and fourth classes

UV-Vis ray diagram was taught to the students, a cuvette was shown to them and they were explained how the UV light from the source is passing through the cuvette.

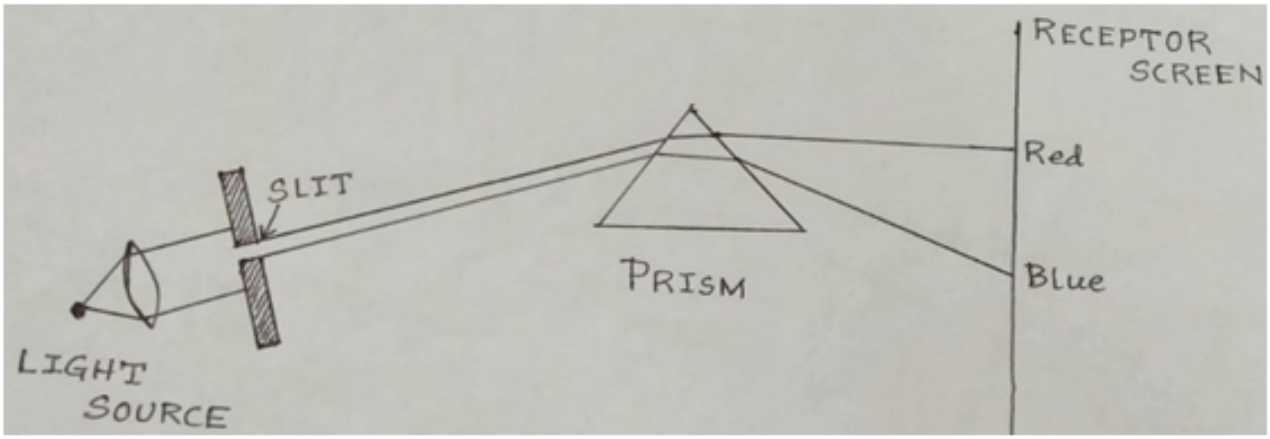


Fig S1: Dispersion of polychromatic light into its components by a prism.

In the practical part, students were asked to prepare 10^{-3} M/L solution of $KMnO_4$ in distilled water (the stock solution) and to dilute it to 5 different concentrations, i.e., c_1, c_2, c_3, c_4, and c_5. The students were then asked to calculate the concentration of each diluted solution. They were then demonstrated and allowed to take the UV-Vis data of the above 5 solutions along with the stock solution. (The spectrophotometer used by us was Agilent Cary 100 UV/Vis having Tungsten Halogen as the light source and wavelength range from 190 to 900 nm)

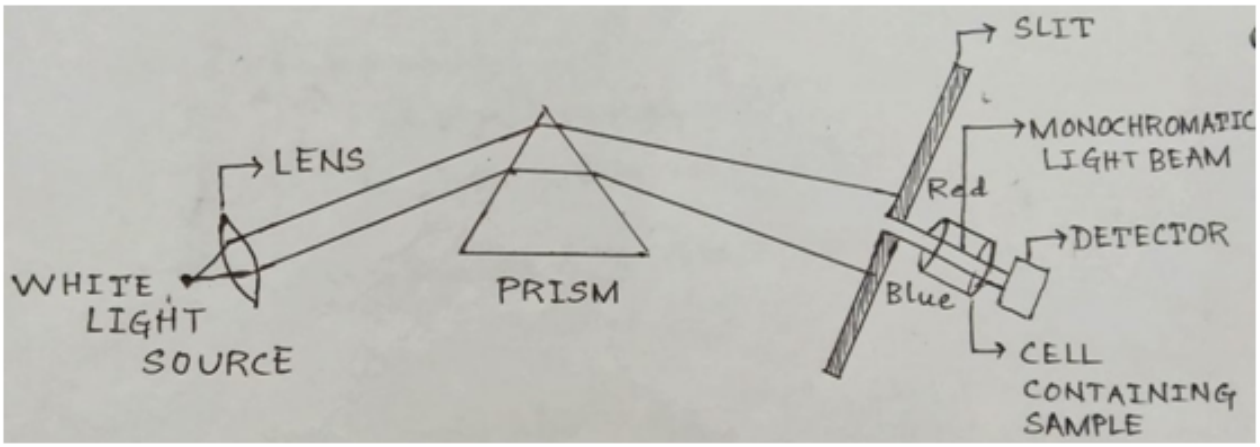


Fig S2: Schematic diagram for measurement of absorbed light by a sample solution.

B-Solution Preparation

Apparatus required:

100 ml Volumetric flask, burettes, spatula and test tubes

Chemicals required:

$KMnO_4$, distilled water

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Procedure:

- Dissolve 0.016 g of $KMnO_4$ in distilled water in a clean and dry 100 ml volumetric flask to get 10^{-3}M stock solution.
- Dilute the stock solution in the following ratios as given in Table 1. to get solutions of 5 different concentrations by the help of two burettes one containing stock solution and the other containing distilled water.
- Calculate the concentration of the diluted solution by using the law of Equivalence, i.e, $N_1V_1 = N_2V_2$

Table 3: The amount of stock solution and distilled water taken to prepare different concentrations of $KMnO_4$ solution along with their concentrations calculated by students against their respective Absorbance at λ_{max} = 524 nm

Solution	**Total Volume of Solution (in ml)**	**Stock solution (in ml)**	**Distilled Water (in ml)**	**Molar Concentration**	**Absorbance (in au) at λ_{max} = 524 nm**
C_1	11	3.0	8.0	0.00027	0.77938
C_2	11	2.5	8.5	0.00022	0.53826
C_3	11	2.0	9.0	0.00018	0.42531
C_4	11	1.5	9.5	0.00013	0.30712
C_5	11	1.0	10.0	0.00009	0.13587

C-Final Questionnaire after the Completion of the Teaching Module

i. Draw the UV-Vis spectrum of a compound with $\lambda_{\max}$ = 400 nm.

ii. Write down the mathematical equation for Beer-Lambert law.
Ans:

iii. The UV-Vis spectra of compound A has $\lambda_{\max}$ = 250 nm and that of compound B has $\lambda_{\max}$ = 420 nm. What conclusion do you draw?
Ans:

iv. How the absorbance of a particular sample solution can be decreased?
Ans:

v. Whether we have to take a constant volume of sample solution each time in the cuvette to get its UV-Vis spectra? Justify your answer.
Ans:

vi. Why absorbance increases with path length? Draw suitable diagram to explain it.

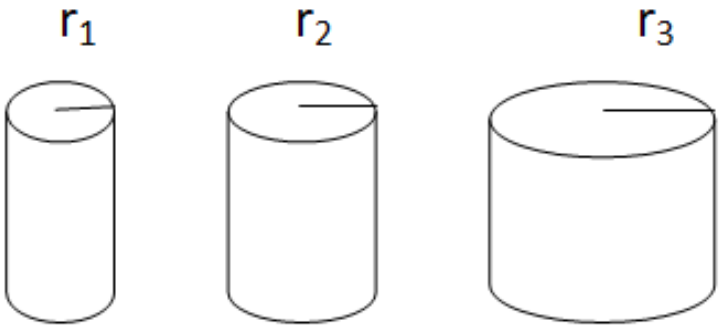
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vii. What happens to the energy gap between HOMO and LUMO when concentration of the sample is changed?
Ans:

viii. By using the following data for three different compounds A, B and C, give the increasing order of their energy gap between their respective HOMO and LUMO:

Compound	Colour	Energy Gap Between HOMO and LUMO
A	Violet	E_1
B	Orange	E_2
C	Red	E_3

ix. A sample solution of same substance in same concentration is taken in three different cylindrical cuvettes having surface radii r_1, r_2 and r_3 such that $r_3 < r_3 < r_3$. Draw the absorbance vs. λ_{max} graph for each cuvette.



x. Explain the origin of UV-Vis spectrum of $K_4[Fe(CN)_6]$ with the help of suitable diagram.

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D-Quantitative Feedback Questionnaire for the Students

Choose option A/B/C for the following statements.

A. Yes

B. No

C. Not sure

i. The grouping of students enhanced my interest.

ii. It was easier for me to solve the problem after the group discussion.

iii. I learned from the other students of my group.

iv. I was more comfortable in the class.

v. It enhanced my problem-solving skill and creativity.

vi. The class improved my computer skill especially in plotting graph in Microsoft Excel and analysing it.

vii. I would like to learn in this method in future.

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