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Laboratory experiment design: Integrating silica gel for hands-on learning in water treatment and environmental stewardship

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ABSTRACT

This study emphasizes the importance of laboratory work by using an unknown chemical in high school and university chemistry courses. It explores the use of silica gel in desiccant bags for water treatment as a cost-effective and educational tool, emphasizing environmental stewardship. The research targets high school and university students, demonstrating silica gel's effectiveness in removing dyes and heavy metal ions from water and its potential use in sustainable construction materials. Pedagogically, the study aims to enhance students' comprehension of environmental chemistry and sustainability through hands-on, problem-based learning. Safety considerations and innovative teaching methods are integral to the laboratory experience. The research illustrates the practical application of scientific knowledge in addressing real-world environmental challenges, promoting a circular economy, and inspiring sustainable practices in scientific education.

Keywords: silica gel, desiccant, water treatment, unknown chemical, sustainability education

INTRODUCTION

Laboratory work in high school and university chemistry is crucial for a deep understanding of the subject (Reid & Shah, 2007) It combines hands-on experience with problem-based learning (Albanese & Mitchell, 1993; Prince & Felder, 2006) to enhance students' grasp of chemical phenomena and theoretical concepts (Chen et al., 2016). This method develops critical thinking, problem-solving, and analytical skills, while fostering scientific inquiry and creativity (Gomez Gomez, 2024). It also encourages teamwork and effective communication, essential in scientific fields (Morgan, 2023). Overall, lab work significantly contributes to students' scientific literacy and practical skills, preparing them for future academic and professional endeavors in chemistry.

In general, effective chemistry lab work integrates clear goals, pre-lab preparation, and innovative teaching (Reid & Shah, 2007; Seery et al., 2019). It emphasizes critical thinking and practical application of theoretical concepts. Safety, hands-on experiments, real-world relevance, and regular assessments are essential. The use of modern equipment, guided inquiry, teamwork, and expert instruction enhances the learning environment. Continual updates and feedback ensure a dynamic and effective laboratory experience, fostering deep understanding and skills in chemistry. Another key in designing impactful chemistry experiments is choosing relevant content, such as water pollution studies using dyes (Luong et al., 2016) and heavy metals (Phuong et al., 2023) (Fe[III] ion). This approach offers globally applicable content and aligns with cost-effective laboratory practices. By integrating such content, we ensure educational inclusivity and practicality, catering to a diverse student body.

However, laboratory work in education faces criticism for limited educational value and inefficient use of time (Nakhleh et al., 2002). Simple experiments are viewed as unproductive, while more complex ones often demand more time and understanding than allowed by the course structure. Therefore, one approach to constructing effective laboratory work is to base it on previously published research, also known as research-based practice (Nakhleh et al., 2002). Specifically, research-based practices address common criticisms and challenges in laboratory work, such as unclear objectives, disconnection between lab activities and theoretical concepts, and the risk of trivial or unproductive experiments. On the other hand, the use of unknown chemicals in teaching organic chemistry can increase students' interest and enhance the educational value of preliminary laboratory work

Table 1. Abstract for student feedback

A hands-on approach to teaching water treatment and environmental stewardship
-Our study is set within an innovative educational framework at the high school and undergraduate levels. It focuses on the intersection of science and practical application, particularly in environmental chemistry and the use of porous materials like silica gel in desiccant bags. In contrast to costlier alternatives, our experiment introduces silica gel as a versatile and cost-effective material for removing dyes and heavy metals from water. -Through hands-on experimentation, students explored various adsorption techniques, including non-thermal stirring, thermal stirring, and column chromatography. They discovered the affordability and effectiveness of silica gel, with our findings indicating optimal conditions for the non-thermal approach: mass of silica gel, stirring time, the number of revolution stirring, and the number of treatment rounds. On the other hand, in terms of heavy metal removal, ionic silica gel demonstrated its efficiency as "a catalyst" in converting Fe (III) ions, with significant environmental safety and no waste production. -A notable aspect of our research was the exploration of silica gel's application beyond water treatment. We emphasized its potential as a substitute for natural sand, addressing the global shortage of construction materials. The innovative integration of used silica gel, particularly from desiccant bags, with cement for building materials, highlights a sustainable method in resource utilization. This approach not only offers an environmentally safe alternative but also underlines the importance of sustainable methods in environmental chemistry.

Table 2. Evaluation of student reactions to the experiment based on their review of the provided abstract

Statement	Response by category (N = 22)				
	SD	D	NE	A	SA
Before this experiment, I hadn't realized how a simple desiccant could play such a crucial role in environmental chemistry.	0.0%	0.0%	27.3%	63.6%	9.1%
I think the procedure for finding optimal adsorption conditions is quite challenging, so it needs to be carefully followed .	0.0%	0.0%	27.3%	68.2%	4.5%
Using silica gel in water treatment and construction exemplifies a circular economy by repurposing a material effectively, minimizing environmental footprint.	0.0%	9.1%	9.1%	54.5%	27.3%
This experiment has broadened my perspective on how chemistry can be directly applied to solve environmental issues.	0.0%	0.0%	13.6%	36.4%	50.0%

Note. SD: Strongly disagree; D: Disagree; NE: Neutral; A: Agree; & SA: Strongly agree

(Oyster, 1932). In particular, by identifying unknowns through their melting points or boiling points, students can engage in qualitative analysis of organic compounds. This method aims to break the monotony of routine laboratory exercises and provides a practical, hands-on approach to learning, which helps students better understand and apply fundamental concepts in organic chemistry.

Based on our research exploring the use of silica gel in desiccant bags for water treatment, we build a laboratory work as a research-based practice as well as an economical educational tool, blending chemistry with environmental stewardship (Ballantyne & Packer, 1996; Basheer et al., 2023; Damoah et al., 2024; Haack & Hutchison, 2016). This study goes further, delving into sustainability by investigating sustainable disposal methods for silica gel, thus fostering a comprehensive understanding of material lifecycles and reinforcing the significance of environmental responsibility (Cheng, 2019). Consequently, students can apply the skills acquired from similar experiments to solve real-world problems.

OVERVIEW OF LABORATORY EXPERIMENT

Our study focuses on high school students, particularly those enrolled in honor courses, as well as university students. However, the conditions under which we conducted our research ensured that the information provided from the experiments would yield significant educational value, laying the groundwork for the development of more appropriate experiments based on this concept. For high school students, we selected two teams; each team consisting of two second-year high school students who were trained as honor courses. Each team conducted experiments, one on Fe (III) ions and the other on dye substances, and both groups achieved bronze medals at the genius olympiad science competition held in 2022 and 2023, respectively. This indicates that the environmental and scientific educational aspects of our study are entirely suitable for high school students. Regarding university students, we conducted a survey among 22 second-year and higher students about their interest in these experiments, through provided abstract, as shown in **Table 1**. As can be seen from **Table 2** and **Figure 1**, the majority (72.7%) agree that they had not recognized how simple the experiment revealed the crucial role of silica gel from desiccants in environmental chemistry. In addition, a significant proportion (68.2%) find the measurement for optimal adsorption to be challenging, indicating a need for careful procedure following. A majority (81.8%) agree that using silica gel in water treatment and construction demonstrates a circular economy, with some disagreement (9.1%) and 9.1% of neutrality. Half of the respondents (50%) strongly agree that the experiment broadened their perspective on applying chemistry to environmental issues, with 36.4% agreeing and a smaller proportion being neutral.

PEDAGOGICAL GOALS

The pedagogical objectives of this program are crafted to provide a thorough, interactive, and advantageous educational journey for students. These goals aim not just at academic enrichment but also at nurturing a profound appreciation and dedication to environmental sustainability. Additionally, the material from this laboratory work is meticulously prepared, serving

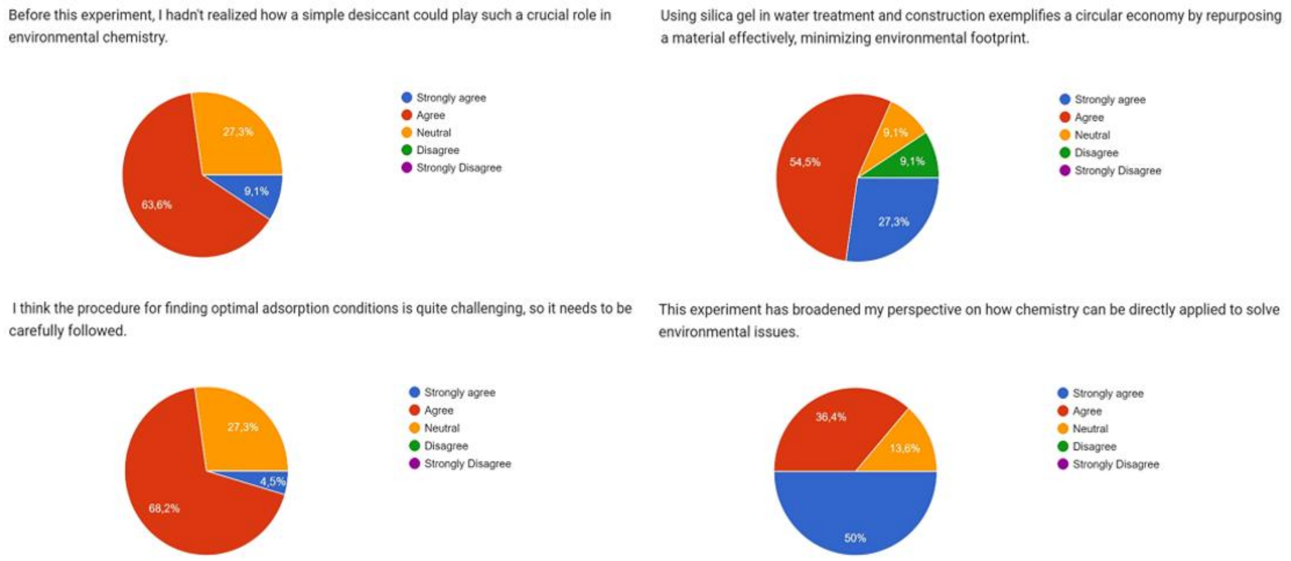

Figure 1. Student feedback analysis on experiment based on abstract review, number of student reviews is twenty two (Source: Authors' own elaboration)

as a resource for remote learning scenarios, particularly during extraordinary circumstances like the COVID-19 pandemic (Díez-Pascual & Jurado-Sánchez, 2022).

For academic purposes:

- To explain the formation of color in transparent solutions.
- To develop skills in predicting functional groups of organic dyes through infrared (IR) and nuclear magnetic resonance (NMR) spectroscopy.
- To propose reasons how dye and Fe^{3+} ion in wastewater can harm plants.
- To differentiate between physical and chemical adsorptions.
- To suggest methods to demonstrate the type of adsorption between dyes and silica gel.
- To explain the chemical catalysis occurring between silica gel and Fe^{3+} ions.
- To predict the surface modification of silica gel particles.
- To explain why unprocessed silica gel has become a challenging substitute for sand in construction materials.

For educational objectives:

- To engage students in dynamic, hands-on problem-solving experiences through the application of silica gel, fostering critical thinking and problem-solving skills
- To deepen students' understanding of key concepts in environmental chemistry and sustainability, promoting environmental stewardship among students.
- To explore the potential of silica gel in practical applications beyond water treatment, such as its use in the construction industry, aligning with principles of sustainable waste management and the circular economy.
- To equip students with the knowledge and skills to address current and future environmental issues.

HAZARDS

General Laboratory Safety

- Wear appropriate protective gear: Always use lab coats, safety goggles, and gloves.
- Understand emergency procedures: Know the location of safety equipment like fire extinguishers, eye wash stations, and first aid kits.

Specific Hazards and Precautions in Experiments

- Handling of chemicals: Be cautious when handling chemicals like dye solutions and silica gel. Avoid direct contact with skin and inhalation.
- Use of silica gel:
    - *General guidelines for silica gel*: Silica gel should be handled in a well-ventilated area to prevent inhalation of fine particles. Remind students that no laboratory materials, including silica gel, should be ingested or come into contact with eyes and mouth. Ensure silica gel is kept away from food and drinks.

  - *Specifics for larger granules (2-4 mm)*: The larger size of the silica gel granules used in experiments reduces risks such as inhalation. Despite their size, students should be careful not to scatter silica gel granules to prevent slipping hazards or accidental mixing with other substances.
- Preparation of phenol solution: Given its toxicity, the preparation of phenol solutions should be undertaken by educators or under direct supervision.
- Thermal stirring method: Be mindful of the heat source in the thermal stirring method to prevent burns.
- Disposal of materials: Ensure proper disposal of used silica gel and other chemical wastes as per environmental safety guidelines.

ANALYSIS OF EXPERIMENT OUTLINE

This analysis aims to clarify the pedagogical intent behind the content in the provided *Student Handout*. Given the adaptable nature of laboratory work design, the study presumes that a range of questions could be devised to align with varied teaching scenarios.

Pre-Lab Activity

Question 1. What is silica gel?

Question 2. Into what category of material is silica gel classified?

Understanding material properties (question 1 & question 2)

Studying silica gel's classification and properties enhances students' comprehension of material applications in chemistry, particularly its use as a desiccant and structural engineering for specific purposes. This understanding is crucial for material science and industrial applications.

Question 3. Why is silica gel used in desiccant bags?

Question 4. What is typically noted on desiccant bags?

Application in real-world scenarios (question 3 & question 4)

Exploring silica gel in desiccant bags and their safety warnings connects theory with practice, teaching students about material use in products and associated safety measures for real-world chemical application.

Question 5. How can the functional group of a dye be determined using IR and NMR spectroscopy?

Analytical techniques (question 5)

Studying the identification of dye functional groups with IR and NMR spectroscopy equips students with analytical chemistry skills, vital for analyzing chemicals in research and industry.

Question 6. Define physical adsorption and chemical adsorption

Question 7. What are the main forces involved in physical and chemical adsorption?

Understanding chemical processes (question 6 & question 7)

Exploring physical and chemical adsorption and their forces enhances students' grasp of chemical processes, crucial for catalysis, environmental science, and materials science. Understanding these adsorption differences is key to comprehending chemical process mechanisms.

In-Lab Activity

The "in-lab activity" section students have described for studying silica gel as a potential adsorbent has several educational impacts, particularly for students engaged in experimental sciences:

- **Understanding experimental methods (section 2.1.1):** This section educates students on different experimental methods (chromatography column usage, thermal stirring method, and non-thermal stirring method) and their applications. Students learn how to set up and conduct experiments, a crucial skill in scientific research. The variety in methods also illustrates the concept of experimental design and how different approaches can be used to investigate the same scientific question.
- **Critical thinking and analytical skills:** By comparing different methods and assessing their effectiveness, students develop critical thinking skills. They learn to analyze data, make comparisons, and draw conclusions based on empirical evidence. This process is fundamental in all scientific disciplines.
- **Optimization techniques (sections 2.1.2, 2.1.3, 2.1.4):** Students learn about the optimization of experimental conditions (such as silica gel quantity, stirring time, and stirring speed) and how these variables can affect the outcome of an experiment. This part of the activity emphasizes the importance of variable control and fine-tuning experimental conditions for optimal results.
- **Practical application of theory (section 2.2):** Evaluating the mechanism of color adsorption by silica gel helps bridge the gap between theoretical knowledge and practical application.

This aspect of the lab work helps students understand how theoretical concepts are applied in real-world scenarios.

- **Laboratory skills and safety practices:** A detailed list of materials and equipment used in the experiments familiarizes students with laboratory apparatus and their proper use. It also underscores the importance of safety practices in the lab, such as using gloves, face masks, and lab coats.
- **Understanding material science and chemistry:** Through this activity, students gain a deeper understanding of material science, particularly the properties of silica gel and its applications in adsorption processes. They also learn about the chemical principles underlying adsorption processes.
- **Data interpretation and presentation skills:** The requirement to visually compare treated and untreated solutions and to repeat processes for accuracy teaches students about the importance of precise data collection, interpretation, and presentation. These are essential skills for any scientific research.
- **Problem-solving skills:** Throughout the activity, students are engaged in problem-solving, particularly when optimizing experimental conditions. They learn to think creatively and systematically to overcome experimental challenges.

Post-Lab Activity

The post-lab activity described offers an enriching educational experience for students, encompassing various aspects of science and sustainable practice. This is an analysis of the educational impact for each section:

- **Comparative analysis of solvent effects on ^{1}H NMR spectra (section 3.1):**
  - *Analytical reasoning:* Engaging in a comparative analysis between $CDCl_3$ and CD_3OD solvents deepens students' understanding of solvent-induced shifts in ^{1}H NMR spectroscopy. This activity cultivates the students' ability to discern how different deuterated solvents can affect the visibility and position of proton signals, particularly those of functional groups like phenolic OH.
  - *Integration of theory and practice:* Through this comparison, students experience a practical demonstration of the theoretical principles of NMR spectroscopy. They witness the interplay between solvent properties and hydrogen bonding interactions, enhancing their grasp of the underlying chemistry and the practical considerations when choosing a solvent for NMR analysis.
- **Visual assessment of treated solutions (section 3.2):**
  - *Skill development:* Enhances observational skills and understanding of semi-quantitative analysis methods.
  - *Conceptual understanding:* Provides practical insight into how varying concentrations affect solution color, reinforcing concepts of dilution and concentration in chemistry.
- **Photometry test using UV-Vis spectroscopy (section 3.3):**
  - *Technical proficiency:* Familiarizes students with advanced analytical tools like UV-Vis Spectroscopy, an essential skill in analytical chemistry.
  - *Quantitative analysis:* Encourages precise quantitative analysis, enhancing understanding of spectroscopic techniques and their application in determining solution composition.
- **Biological test using mung beans (section 3.4):**
  - *Practical application of theory:* Demonstrates the real-world impact of water treatment on biological systems, which is crucial for understanding environmental science and ecology.
  - *Experimental skills:* Cultivates skills in biological experimentation and data recording, essential for careers in biology and environmental science.
- **Reusing silica gel in construction materials (section 3.5):**
  - *Innovation and sustainability:* Promotes innovative thinking by exploring the sustainable reuse of materials, an important aspect of environmental science and engineering.
  - *Interdisciplinary learning:* Integrates concepts from chemistry, materials science, and civil engineering, demonstrating the interdisciplinary nature of scientific problem-solving.
- **Rationale for using treated silica gel in construction (section 3.6):**
  - *Critical analysis:* Encourages students to critically evaluate the properties of materials and their suitability for specific applications, a key skill in materials science and engineering.
  - *Understanding material properties:* Provides insight into how chemical treatments can alter material properties, enhancing their understanding of materials chemistry.

RESULTS AND DISCUSSION

Purpose of the Study Using Unknown Chemicals

In the realm of chemistry education, the integration of practical experiments plays a pivotal role in enhancing student engagement and deepening understanding of complex concepts from real life. Among the myriad techniques employed, the method of introducing students to unknown compounds stands out as particularly effective (Oyster, 1932). This educational strategy not only challenges students to apply theoretical knowledge in real-world scenarios but also fosters a comprehensive suite of analytical, cognitive, and soft skills essential for scientific inquiry. By engaging in the identification of unknown compounds through methods such as IR and NMR spectroscopy, students are thrust into the heart of chemical investigation, mirroring the step-by-step processes used by professional chemists. This paper explores the pedagogical benefits of this approach, detailing how it prepares students for advanced studies and professional challenges, thereby contributing to a more dynamic and interactive learning environment. There are many benefits that the students can be developed (Oyster, 1932):

- *Increases interest and engagement:* Incorporating unknown compounds into experiments significantly boosts interest and engagement among beginners. Instead of merely following predefined instructions, students face practical problems that require critical thinking and problem-solving skills. This approach transforms routine experiments into intriguing challenges, fostering a deeper interest in the subject matter.
- *Enhances practical skills:* Identifying unknown compounds demands precise techniques and meticulous attention to detail. This process helps students refine their laboratory skills, encouraging careful handling of equipment and materials. As a result, students develop better laboratory practices and reduce the likelihood of careless mistakes.
- *Provides immediate practical value:* Using unknowns in experiments provides immediate practical value, illustrating the necessity of specific techniques and their applications to real-world problems. This hands-on experience helps beginners understand the relevance of their work and see the direct connection between theoretical concepts and practical applications.
- *Encourages independent thinking:* Working with unknown compounds encourages students to think independently and apply their knowledge creatively. Instead of relying on given answers, students must use their analytical skills to identify the compounds. This fosters a sense of autonomy and confidence in their problem-solving abilities.
- *Improves understanding of concepts:* Through the process of identifying unknowns, students gain a deeper understanding of fundamental concepts such as melting points, boiling points, and chemical reactions. This practical approach makes theoretical knowledge more tangible and easier to grasp, reinforcing learning and enhancing comprehension.

For educators, they can significantly enrich the learning experience, helping students develop essential skills, think independently, and connect theoretical concepts to practical applications.

Structural Analysis of An Unknown Dye Structure

Importantly, we are focusing on how a chemical impacts the natural environment through functional groups that can be toxic to organisms in the ecosystem. Furthermore, in this study, we directly use widely available industrial dyes, making it challenging to determine their exact structural formulas. However, we believe that the precise identification of the functional groups present in these industrial dyes and demonstrating their effects on organism growth are more important. Using unknown chemicals also sparks curiosity and interest, and notably, it opens up a broader scope for developing similar experiments based on an open-minded approach.

Infrared spectroscopy analysis

The comprehensive analysis of the IR spectrum indicates that the sample contains a variety of functional groups. The broad peak at 3,446 cm^{-1} suggests the presence of hydroxy groups, indicative of alcohols or phenols (Klein, 2020; Pavia et al., 2001). The peaks at 3,003 cm^{-1} and 1,604 cm^{-1} suggest the presence of aromatic compounds or alkenes, confirmed by the characteristic C-H and C = C stretching vibrations (Klein, 2020; Pavia et al., 2001).

The peaks at 1,481 cm^{-1} and 1,404 cm^{-1} indicate the presence of C-H bending vibrations, which are common in alkane structures (Jones & Cole, 1952; Pavia et al., 2001). The C-O stretching vibration at 1,159 cm^{-1} suggests the presence of alcohols, ethers, or esters (Pavia et al., 2001). The peaks at 821 cm^{-1} and 615 cm^{-1} further support the presence of aromatic structures or specific C-H bending patterns (Pavia et al., 2001).

The absence of distinct C-H stretching vibrations in the alkane region (2,850-3,000 cm^{-1}) in the IR spectrum can be attributed to several factors. The dominance of strong O-H stretching vibrations, the prevalence of aromatic and alchemic structures, the sample composition, and the instrument's sensitivity all contribute to this observation. Thus, it is essential to have a better approach to confirm the main possible functional groups in the unknown compound (**Figure 2**).

Nuclear magnetic resonance spectroscopy analysis

Transitioning to the realm of ^1H NMR spectroscopy, the analysis is graced by a broad signal encircling the 10 ppm mark, reinforcing the hypothesis of a phenolic O-H group's presence (Dietrich et al., 1966) in $CDCl_3$. For further confirmation, we found that this signal disappeared when changing the solvent CD_3OD. Protons situated on a benzene ring is substantiated by a spectrum of signals ranging from 6.5 to 8.0 ppm, also typical for aromatic functional group. Besides, the singlet peak at 3.127 ppm equal to three protons suggests the protons adjacent to an electronegative group, can be an isolated methyl group (CH_3) bound with oxygen or nitrogen atom. This stretching signal corresponding to C-H sp^3 bonds is not observed on IR spectroscopy.

Briefly, the combined analysis of IR and ^1H NMR spectra reveals the presence of an aromatic system in the compound, indicated by aromatic C = C and ^1H NMR signals, and the absence of carbonyl groups, excluding aldehydes, ketones, and carboxylic acids. The C-O stretching in the IR and downfield ^1H NMR signals suggests the compound is phenolic, with the O-H group attached to the aromatic ring.

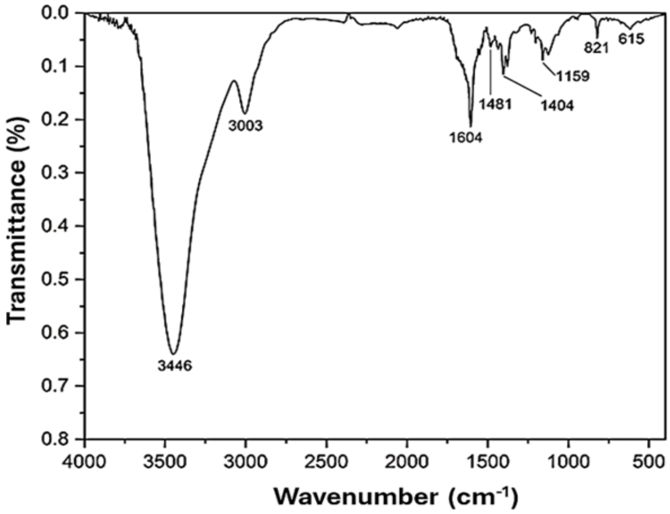

Figure 2. IR spectrum of the unknown dye (Source: Authors' own elaboration)

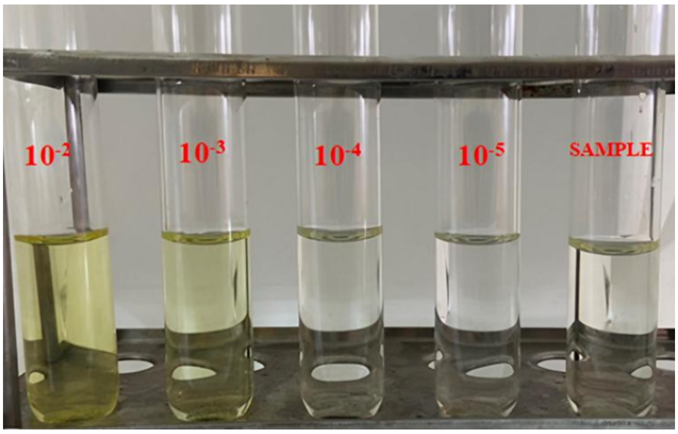

Figure 3. Visual assessment for semi-quantitative assessment of dye concentration (g/L) (Source: Authors' own elaboration)

Silica Gel: A Potential Adsorbent

It was found that the chromatography was less effective and thermal methods less favored due to energy consumption, so the non-thermal method compromised silica gel's structure, necessitating filtration. In particular, the non-thermal method with 30 g of silica gel in each time provided the most optimal mass and the stirring time for the non-thermal 200 mL solution in the dye adsorption process, 25 minutes with two times of 500 rpm (revolutions per minute) stirring provided the most optimal time by faithful SH-II-4C stirrer.

Based on the visual assessment in **Figure 3** and the UV-Vis spectroscopy results in **Figure 4**, the students achieved a high treatment efficiency of 99.8% using silica gel. The visual test demonstrated results comparable to the UV-Vis test, suggesting that the visual method can be a low-cost and faster alternative for determining dye filtration yield. However, the non-thermal stirring method compromised the gel's structure, leading to fine particles in the solution. They filtered the water to remove these particles, observing minimal dye removal by the filter paper. Thus, future experiments are planned to investigate water recovery efficiency post-treatment, crucial for understanding the process's overall effectiveness and its impact on water conservation and management.

Mung Bean Germination Test

The mung bean seed germination assay is a crucial short-term method for assessing genotoxicity in eukaryotic systems (Kapanen & Itävaara, 2001; Wang, 1990). This assay effectively demonstrates the impact of pollutants on plant growth, especially when agricultural soil is irrigated with wastewater (Khan & Malik, 2018; Nor et al., 2021). **Figure 5** displays the growth of mung beans under three different water treatments: untreated water, regular water, and treated water. The mung beans watered with untreated water exhibit inconsistent and less vigorous growth, with several beans showing minimal sprouting with the average length is 12 cm. In contrast, those watered with regular water and treated water display more uniform and healthier growth with close average lengths 18 cm and 16 cm, respectively, indicating better conditions for sprouting. This highlights the similar conditions of treated water and regular water for mung bean cultivation. These results are well-fitted with the Singh's study where the tartrazine–a food dye can reduce the germination of mung bean (Singh, 2017). Since the dye contains aromatic rings, the functional group has a detrimental impact on plant vitality by interfering with the normal cellular activities of plants, leading to compromised tissue function and overall plant health (Dutta et al., 2024; Lellis et al., 2019).

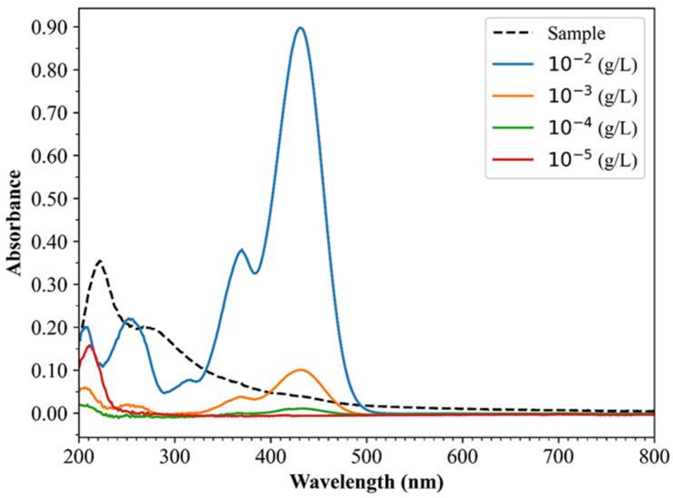

Figure 4. UV-Vis spectrum for quantitative assessment of dye concentration (Source: Authors' own elaboration)

Figure 5. Mung bean test in three different waters: untreated water, regular water, and treated water (Source: Authors' own elaboration)

Additionally, silica gel is supposed to capture dye molecules through a chemical bond, mainly retaining the dyes via silicon-oxygen (Si-O) bonds and hydrogen bonds. This interaction is the key to holding the dyes in place. The process is likely aided by the heat produced when water contacts silica gel, which may accelerate the reaction. Moreover, a small number of dye molecules may cause slight yellowing of the water when stirred with the silica gel at lower temperatures, suggesting that some dyes are also physically adhered, albeit to a lesser extent, alongside the dominant chemical bonding. **Figure 6** shows a simplified model to describe the dye adsorption mechanism on the silica gel surface (Christy, 2014).

Silica Gel: A Potential Metal Ion-Contaminated Water Treatment

In addition to dye removal, this study tackles the critical issue of heavy metal pollution, focusing on the problematic Fe (III) ion. The research employed heat stirring and column chromatography methods to evaluate silica gel's capacity to treat water contaminated with Fe (III) ions. The detailed schemes are shown in the supporting information, as shown in Scheme S1 and

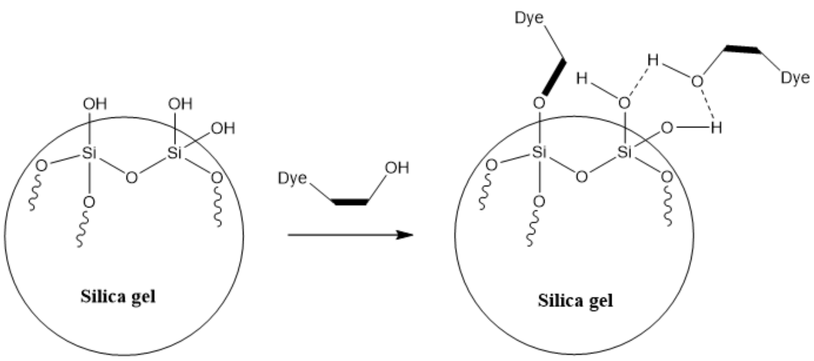

Figure 6. The simplified model for dye adsorption on silica gel (the dashed line represents hydrogen bonding, illustrating the interaction between the dye molecules and the silica gel surface & the thin filled box symbolizes the core structure of the dye) (Source: Authors' own elaboration)

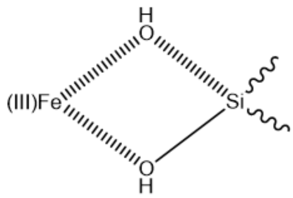

Figure 7. OH bridges between Fe (III) hydroxy complex and silanol group in silica gel (Source: Authors' own elaboration)

$$[Fe(H_2O)_6]^{3+} \rightarrow [Fe(H_2O)_5OH]^{2+} \rightarrow [Fe(H_2O)_4(OH)_2]^{+} \rightarrow [Fe(H_2O)_3(OH)_3]$$

Figure 8. Scheme 1. Hydrolysis of Fe (III) ion

scheme S2. Besides, the effectiveness of these approaches was assessed through biological tests using mung beans and a visual examination of the water before and after treatment. For easier comparison, we can use the solution of 5% phenol in ethanol as an indicator to test the Fe (III) ion appearance. Solutions with varying concentrations of Fe (III) display distinct shades of purple (or blue, depending on the solvent)(Soloway and Wilen 1952) upon the addition of an equal number of indicator drops. The color intensity directly correlates with the Fe (III) concentration, illustrating the reaction's sensitivity to iron ion levels.

The results revealed that silica gel acts as a reactant or a catalyst, transforming Fe (III) ions into Fe (OH)3 precipitates. The study also found that the heat stirring method, specifically using a digital display laboratory thermostatic magnetic heating stirrer (HJ-3) set to the lowest stirring level, was more effective in removing heavy metal ions than the chromatography column method. We suggest two mechanisms in the precipitation of Fe $(OH)_3$.

For using the heating stirrer method, a mixture of iron(III) solution and silica gel are heated, and Fe $(OH)_3$ precipitate can form through a reaction between iron ions and hydroxy species. These hydroxy species are proposed to bond with silanol groups via available OH-bridges in polynuclear iron(III) hydroxy complexes, as shown in **Figure 7** (Moreton, 2002). We suggest that the hydroxy groups in silanol can break under heat, subsequently reacting with iron ions to precipitate as Fe $(OH)_3$.

For using column chromatography method, the hydrolysis of iron(III) ion, as shown in **Figure 8**, can be intensified as the gel absorbs moisture (Moreton, 2002), where the water molecules are assumed to be withdrawn from Fe $(H_2O)_3(OH)_3$ (Flynn, 1984) complex by silica gel to form precipitate as Fe $(OH)_3$.

Although the observed transformation of ions into a solid form under two mechanisms presents a promising avenue for future research, employing more sophisticated techniques are necessary to enhance the understanding and efficiency of silica gel in heavy metal ion remediation, especially clarifying whether the role of silica gel in this case is as a reactant or a catalyst.

Closing the Loop

A key highlight of this research is the "closed-loop experiment" approach, where the silica gel after the water-treatment test was repurposed as a building material, substituting sand in cement mixtures. This not only provided an effective method for water contamination treatment but also promoted a circular economy by repurposing a waste product (Laius et al., 2024). This approach exemplifies sustainable practice in environmental management, turning waste into a valuable resource and reducing the ecological footprint of industrial activities. Not only does the research indicate the potential to replace natural sand, but it also highlights the application potential in addressing the scarcity of sand as a construction material. The used silica gel is mixed with cement for building application, shown in **Figure 9**. It is clear that the stirring process in heated water mechanically alters the structure of silica gel particles, making them more angular. This transformation could enhance their adhesion to cement used in construction, potentially improving the material's bonding properties. However, for chemicals adsorbed on the silica gel surface, their properties (e.g., hydrophobicity or hydrophilicity), and the formation of coatings can either increase or decrease friction, or changes in surface roughness or smoothness. Additionally, particle aggregation and environmental interactions, like humidity, can further influence frictional behavior.

Figure 9. A pot crafted from a cement and used silica gel mixture (Source: Authors' own elaboration)

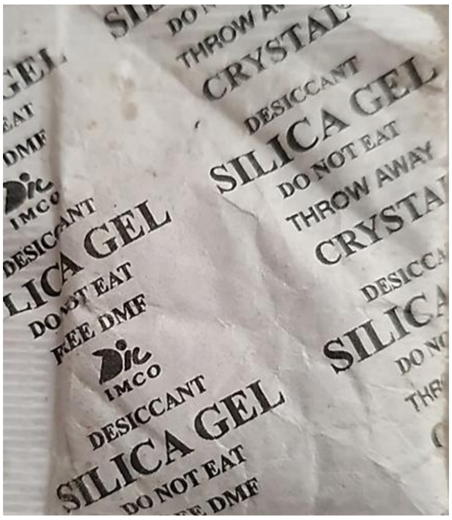

Figure 10. An image of a desiccant bag (Source: Authors' own elaboration)

CONCLUSION

This study explores the impact of laboratory work in high school honors courses and university chemistry education, focusing on the lab-designed approach of using unknown chemicals. Focusing on the use of silica gel in desiccant bags for water treatment, the research presents this method as both a research-based practice and a cost-effective educational tool. It emphasizes the importance of environmental stewardship and sustainable practices, including the investigation of sustainable disposal methods for silica gel to enhance understanding of material lifecycles.

The study also aims to impart significant educational value. It explores silica gel's efficiency in removing water pollutants like dyes and heavy metals and its potential as an alternative construction material. The pedagogical objectives include providing a comprehensive educational experience that emphasizes environmental sustainability and the practical application of chemistry concepts. Laboratory safety is prioritized with specific guidelines for chemical handling and hazard prevention.

The experimental design is divided into pre-lab, in-lab, and post-lab segments, each focusing on deepening the understanding of chemical processes and sustainable methods. The results demonstrate silica gel's effectiveness in pollution treatment and its innovative use in sustainable construction, promoting a circular economy. The study aims to inspire new ways of collecting and recycling silica gel bags, challenging traditional disposal methods as "throw away", as shown in **Figure 10**.

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Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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