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Can ChatGPT Enhance Chemistry Laboratory Teaching? Using Prompt Engineering to Enable AI in Generating Laboratory Activities

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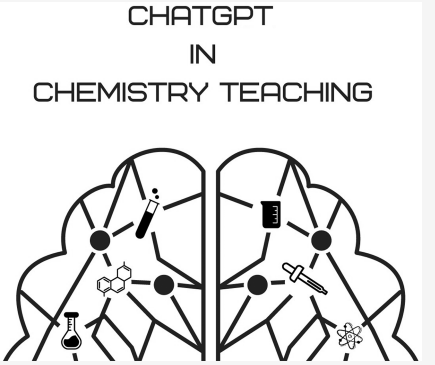
ABSTRACT: The rapid evolution of Artificial Intelligence (AI) is profoundly shaping our society. Among various AI tools, ChatGPT stands out for its user-friendly nature and wide accessibility to the public. However, despite their countless potential benefits, these tools also face significant challenges, especially in sensitive areas like Education. In this publication, we conduct a prompt engineering essay with ChatGPT to understand the potential and challenges of this tool in designing new, high-quality chemistry laboratory activities. We aimed to assess its performance in proposing scientifically and pedagogically suitable protocols for chemistry laboratory activities based on the 11th-grade Portuguese curriculum. The initial exploratory essay was conducted to fine-tune the prompt, followed by the analysis of proposals for the five mandatory laboratory activities in this subject. ChatGPT demonstrates the ability to interpret and reproduce the specialized symbolic language of chemistry, effectively conceptualizing problems and laboratory activities in a clear and understandable manner for a broader audience (i.e., chemistry students). However, it is crucial to highlight the scientific-pedagogical limitations concerning the accuracy and appropriateness of the proposed laboratory activities, particularly in terms of safety and sustainability. Therefore, the use of AI in education should be approached critically and reflectively. While AI holds immense potential to transform the dynamics of teaching and learning, the role and expertise of the Chemistry teacher remain of the utmost importance to ensure the scientific and pedagogical quality of Chemistry classes.



KEYWORDS: *High School/Introductory Chemistry, Laboratory Instruction, Internet/Web-Based Learning, Professional Development*

■ ChatGPT: AN INTRODUCTION

In recent years, technological advancements have been progressing at a rapid pace, leading to an increasingly significant social impact. Alongside these advancements, new forms of interaction between humans and machines have emerged, such as chatbots, which are becoming more prevalent in daily life. As Zawacki-Richter et al.[1] refer, the utilization of chatbots has witnessed substantial growth, and projections suggest a further surge in their adoption in the forthcoming years.

In this way, one of the chatbots which is gaining prominence among the general user population is ChatGPT. It is an AI tool that employs the GPT (Generative Pretrained Transformer) language to produce answers to user inquiries.[2] Released on November 30, 2022, this tool quickly captured public attention, garnering over a million new user registrations within its first week of availability to the public.[3] Described as a language model optimized for dialogue, ChatGPT can respond to questions in a manner akin to a human and maintain a contextualized conversation throughout interactions. This AI tool is able to engage in conversations by responding to user prompts, addressing follow-up questions, admitting errors, challenging incorrect assumptions, and refusing inappropriate requests.[4] As a result, ChatGPT has emerged as a promising tool, offering assistance to humans in a wide array of tasks spanning diverse domains and complexity levels.

As Fauzi et al.[5] refer, ChatGPT has multiple applications, including offering valuable information and resources, enhancing language proficiency, fostering collaboration, improving time management and productivity, as well as offering assistance and encouragement. These capabilities have drawn considerable attention from people worldwide, leading to the soaring

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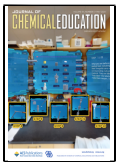

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popularity of ChatGPT, with the tool being employed for diverse purposes.[6]

Education is one area where the use of this tool has been tested. According to Pérez et al.,[7] chatbots are being introduced into the education sector through digital transformation initiatives in some public universities. They prove useful in enhancing service quality and alleviating the workload of teachers, as chatbots can respond to questions and act as educational agents, reinforcing learning, assisting students in problem-solving, breaking language barriers, and providing greater knowledge accessibility.[8,9] This can free teachers to focus on other tasks and improve their teaching methods. Ausat et al.[10] also reinforce this idea, stating that technology can contribute to enhancing the quality of the teaching and learning process and offer better training for those involved.

While using chatbots as teaching assistants has its advantages, it is essential to highlight that ChatGPT and other chatbots have limitations and can make mistakes, which, in more sensitive areas, such as education, can lead to additional issues. In this sense, the use of an appropriate prompt can help optimize the quality of outputs generated by ChatGPT.[11] This optimization is often empirical and achieved through iterative refinement (which is the foundation of prompt engineering), combining AI and linguistics mediated by user experience. Prompt engineering has become a widely used method to enhance the effectiveness of LLMs (Large Language Models, like ChatGPT) through the creation of well-crafted instructions.[12] With the emergence of tools like ChatGPT, prompt engineering has been gaining increasing importance, as it enables the optimization of AI capabilities through the input provided to it. In this sense, according to Lo[11] and Heston and Khun,[13] an effective structured prompt should encompass four fundamental aspects: "Clarity and Precision", enabling the AI model to break down information into blocks (tokens) for optimal processing; "Contextual Information", contextualizing the request for the AI model to return more meaningful outputs; "Desired Format", and "Verbosity Control" to ensure the output's format, extent, and level of detail meet the user's expectations.

With the emergence of ChatGPT and its competitors, education is predicted to undergo dramatic changes.[14,15] Therefore, as suggested by Clark,[16] its use, particularly in education, should be supervised and complemented by the work of specialists (in this case, teachers and educators), ensuring a quality and enriching educational experience.

Considering that Artificial Intelligence is shaping the society in which we live, these authors consider it essential to promote AI literacy among the population, particularly among chatbot users, to equip them to face the challenges of this era. In this regard, countless students and scholars have begun using chatbots such as ChatGPT, Bing Chat, Bard, Ernie, and similar ones to carry out a wide range of tasks of diverse natures.[17,18] Undoubtedly, education, in general, and science education, in particular, can benefit from the potential of ChatGPT to produce study-support content and even support the preparation of theoretical or practical-laboratory classes. However, for AI to be an added value, it is necessary for those involved in the teaching and learning process to possess satisfactory levels of AI and scientific literacy.

■ ChatGPT IN CHEMISTRY LABORATORY TEACHING

In the case of chemistry, it is an experimental science by nature. In this regard, practical-laboratory work in Chemistry classes is considered one of the most effective strategies to enhance learning in this field.[19] As Agustian and Seery[20] emphasize, laboratory work is a core component of the chemistry curriculum. Several authors,[21−23] including the American Chemical Society,[24] highlight laboratory activities as a means to promote success in learning chemistry. Hands-on laboratory activities are essential for enhancing the quality of chemistry education from elementary to higher education levels.[24]

Hence, several authors,[21,22,25−28] argue that experimental work in Chemistry is one of the most effective teaching approaches that not only enhances content learning but also develops important skills and competencies essential to the students' education. Therefore, it is natural for current Chemistry curricula to include laboratory teaching.[21] In Portugal, the authors' familiar context, the current Chemistry curricular documents incorporate mandatory laboratory activities at the preuniversity level, and such practices are also strongly encouraged even at lower education levels. However, one of the main obstacles to laboratory teaching in Chemistry is the high costs associated with the allocation of dedicated facilities and specialized apparatus, purchase of consumables, and consistent implementation of waste management protocols.[29] In this regard, it is common for school laboratories to face shortages or even a lack of materials/reagents to carry out the laboratory activities outlined in textbooks. Therefore, considering these potential constraints, the teacher must be able to innovate and, whenever necessary, seek alternative activities that allow achieving the learning objectives proposed in the curriculum of the subject, using the materials and resources available to them.

In contemporary society, one of the primary goals of Education is to prepare citizens capable of adapting to the constant social challenges of the ever-evolving modern world, at an increasingly rapid pace.[30] Artificial Intelligence is becoming increasingly integrated into our society, and the advent of tools such as ChatGPT makes it more accessible to the public. Therefore, there is an emerging need for educational reflection on promoting scientific and technological literacy among future citizens, enabling them to understand and critically utilize AI technologies.[31]

In this context, it could make sense to answer the following question: What challenges does ChatGPT bring to Chemistry Education, and how could it impact the (laboratory) teaching of this subject?

In this regard, Humphry and Fuller[2] present a reflection on the potential use of ChatGPT by preuniversity students to write the discussion and conclusion of a chemistry experimental activity. From their work, these authors highlight that although ChatGPT does not excel in chemical analysis or stoichiometry of chemical reactions, it can be highly beneficial in assisting students with certain calculations and improving their writing skills. Taking into account the strengths of using this tool and based on the experimental results of an activity concerning the determination of copper density, the authors used a prompt asking ChatGPT to write a lab conclusion statement (including statistics) about the experiment. According to the authors, the text generated by ChatGPT was written with greater accuracy than most reports produced by students; however, the response was general and vague. So for students to utilize ChatGPT efficiently, they must comprehend the chemical principles underlying their queries, be adept at formulating suitable questions, and subsequently evaluate the responses generated by ChatGPT.[2] Similarly, Ausat et al.[10] also noted regarding the application of ChatGPT in educational settings, it is important

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Table 1. Essential Learnings Regarding Laboratory/Experimental Work in Chemistry for the 11th Grade of Schooling[32]

Domain	Essential Learnings
Chemical equilibrium	Experimentally determine the yield in the synthesis of a compound, evaluating the obtained results.
	Investigate, experimentally, changes in chemical equilibria in aqueous systems by varying the concentration of reactants and products, formulating hypotheses, evaluating procedures, and communicating the results.
Reactions in aqueous systems	Plan and perform an acid−base titration, interpreting the meaning of neutralization and equivalence point.
	Organize an electrochemical series through laboratory reactions between metals and aqueous solutions of salts containing cations of other metals, evaluating procedures, and communicating the results.
	Experimentally investigate the effect of temperature on the solubility of a solid solute in water, formulating hypotheses, controlling variables, and evaluating the results.

Table 2. Most Significant Prompt Testing

Iteration	Prompt tested
1	• Imagine you are a Chemistry teacher in Portugal, teaching a class of 11th-grade students aged between 16 and 17 years. Your goal is to teach them about Chemical Equilibrium. What is your action plan?
2	• Create a lesson plan for teaching the aforementioned topic.
3	• Create a lesson plan to teach the following Essential Learning: Experimentally determine the yield in the synthesis of a compound, evaluating the obtained results.
4	• Present a protocol for a laboratory activity that enables teaching chemistry topics related to this essential learning.
5	• Imagine you are a Chemistry teacher with a class of 25 students and have 100 min of laboratory class. You are going to teach 11th-grade students in Portugal, aged between 16 and 17 years, about Chemical Equilibrium. Plan a laboratory activity to teach these students the Essential Learning: 'Experimentally determine the yield in the synthesis of a compound, evaluating the obtained results.' Provide a detailed protocol for the activity to enable students to work autonomously.
6	• Imagine you are a Chemistry teacher with a class of 25 students and have 100 min of laboratory class. You are going to teach 11th-grade students in Portugal, aged between 16 and 17 years, about Chemical Equilibrium. Plan a detailed real laboratory activity to teach these students the Essential Learning: 'Experimentally determine the yield in the synthesis of a compound, evaluating the obtained results.' Provide a detailed protocol for the activity to enable students to work autonomously.
7	• Create a real laboratory activity, with real reagents, and a detailed protocol to assist 11th-grade students (17 years old) in conducting the activity to 'Experimentally determine the yield in the synthesis of a compound, evaluating the obtained results.'

to recognize that technology serves solely as a tool and cannot entirely replace the role of those involved in the educational process. Indeed, as mentioned by Leon and Vidhani,[8] "ChatGPT Needs a Chemistry Tutor Too" (p. 3859). So, unlike the reflection of Humphry and Fuller,[2] which focuses on the potential of ChatGPT as an auxiliary tool for students, our reflection centers on the other pole of the teaching-learning dynamic: the teacher. Being in this "pole", AI and ChatGPT, in particular, could make a significant contribution as a facilitating and innovative agent, assisting the teacher to enliven classroom dynamics.

So, in this work, in a prompt engineering exercise, we attempted to understand to what extent ChatGPT can serve as a valuable aid in Chemistry Education for planning high-quality laboratory classes on this subject. Thus, we focused our essay on the current curriculum documents for the final year of schooling, during which Chemistry is a mandatory subject (11th grade) in Portugal because the covered Chemistry contents are of a higher level of complexity. The addressed Chemistry contents fall under the domains of *Chemical Equilibrium* and *Reactions in Aqueous Systems* and are taught in 3 weekly lessons of 90 to 105 min each, with one of these lessons usually dedicated to practical-laboratory work. Table 1 presents the references (*Essential Learnings*) to laboratory/experimental work, as outlined in the current Chemistry curricular documents in Portugal.

Taking this into consideration and as described in more detail in the following section, we questioned ChatGPT to propose a lesson plan and/or a protocol for an experimental activity that would be scientifically and didactically appropriate, allowing students to achieve the learning objectives proposed in each selected *Essential Learning*, in a school laboratory setting.

PROCEDURES

This essay commenced at the beginning of June 2023, employing an exploratory approach to generate an effective structured prompt[13] aimed at eliciting comprehensive responses from ChatGPT aligned with the proposed objectives. Using a previously unused free user account on ChatGPT (to avoid any previous conversations that could influence the chatbot's response), a series of iterations was carried out to ensure that the prompt used was suitable for the output generated by ChatGPT to meet the proposed objectives. In Table 2, the most relevant iterations of this process are presented and are discussed below.

It is important to note that the intention here was to utilize an initial prompt tailored to the purpose of this essay, remaining as open as possible to understand the accuracy or inaccuracy of the output generated by ChatGPT. Therefore, based on the analysis of the response obtained for this initial prompt, the prompts for the subsequent iterations were designed, as presented in Table 2, aiming to understand which information was relevant or not to provide to ChatGPT, to enable it to generate a scientifically accurate laboratory activity that aligns with pedagogical standards and facilitates the achievement of the proposed learning objectives.

The response provided by ChatGPT for the first iteration presented some relevant topics for structuring a lesson (e.g., "Introduction to the topic", "Explanation of chemical equilibrium", "The Law of Chemical Equilibrium", "Factors affecting equilibrium", "Practical examples", "Exercise resolution", "Practical project", "Assessment and continuous feedback", "Historical context", and "Relationship between chemical equilibrium and other areas of Chemistry"). However, despite being well-written, the response was too vague, lacking concrete examples and specific information, such as simple classroom

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experiments to demonstrate "changes in equilibrium under different conditions".

In an attempt to acquire more detailed insights into addressing the topic of Chemical Equilibrium, ChatGPT was prompted (2nd iteration) to develop a lesson plan for teaching this topic to 11th-grade students. In this second iteration, the proposed ideas were, once again, too generic (e.g., "Calculation of the equilibrium constant (K) for chemical reactions" or "Laboratory experiment: Observation of equilibrium changes in a reaction with varying factors").

As no details were provided regarding the proposed educational resources, ChatGPT was asked to create a more focused lesson plan to teach Essential Learning related to an experimental procedure (Iteration 3). However, the issues related to the level of detail in the laboratory activity plan persisted. Additionally, the suggested approach by ChatGPT to cover this Essential Learning in three 50 min lessons remained too vague, as it presented topics for three lessons rather than a single, more detailed and specific lesson. In sequence, after the fourth iteration, ChatGPT provided a detailed and, apparently, suitable protocol for determining the yield of the synthesis reaction of silver chloride from the reaction of an aqueous solution of silver sulfate with an aqueous solution of sodium chloride. Nonetheless, there were some inconsistencies in the laboratory protocol. For instance, in the "synthesis process", the following statement was made:

> *In a 250 mL beaker, add 50 mL of sodium chloride (NaCl) solution and 50 mL of silver sulfate (Ag2SO4) solution. The reaction will produce a precipitate of silver chloride (AgCl) and sodium nitrate (NaNO3).*

There is a clear scientific error in ChatGPT's response, as the reaction of the aqueous solution of sodium chloride with the aqueous solution of silver sulfate would generate a precipitate of silver chloride and sodium sulfate solution. Furthermore, this chemical reaction is considered complete[33] (given that the solubility of silver chloride in water is very low, $K_s = 1.6 \times 10^{-10}$), meaning that the reaction yield will be considered 100%.

This fourth interaction confirmed that generic and broad prompts yield responses that are equally generic and vague. Therefore, upon establishment of a satisfactory structure for the proposed laboratory activity protocol based on the Essential Learnings (despite the limitations of this AI tool), it was possible to refine the prompt in an attempt to optimize the outputs of ChatGPT, aligning with the proposed learning objectives of this experiment. The prompt introduced in the fifth iteration stemmed from this exercise, that is, the details of the intended laboratory lesson were incorporated into the prompt used in the fourth iteration—including the duration of the lesson, number of students in the class, contextualization with grade level, age, and country—in an attempt to ascertain which information would be considered in the output generated by ChatGPT. Note that the expression "detailed real" was added to the sixth iteration's prompt because when tested (without the word "real") for other Essential Learnings, in some instances, the generated output suggested exploring virtual activities such as simulations. The term "detailed" was also included in the prompt to obtain additional information, such as the necessary materials for the laboratory activity, the solution to be used, and/or its respective concentration, which had not been provided in some trials using the prompt from the fifth iteration. Subsequently, as result of this prompt engineering exercise, the final and refined prompt, further reduced (because it was found that some of the contextual information provided did not translate into tokens interpreted by the AI, e.g., the number of students per class or the country where the classes are taught), was generated (Iteration 7), trying to address the four fundamental aspects of a prompt previously presented,[11,13] and used for the ensuing discussion of the presented results.

RESULTS

Through pilot tests, we successfully refined a prompt that enabled us to obtain a detailed laboratory activity protocol in a generalized manner with a single interaction. Consequently, we employed the prompt to request a laboratory activity proposal, along with the corresponding protocol, from ChatGPT. The aim was to assist 11th-grade students in attaining the learning objectives outlined in their respective Essential Learnings. The prompt given to ChatGPT was as follows: "Create a real laboratory activity, with real reagents, and a detailed protocol to assist 11th-grade students (17 years old) in conducting the activity for [Essential Learning]".

As an illustrative example, we present a part of the laboratory activity proposal (along with the corresponding protocol) generated by ChatGPT for the objective of "determining experimentally the yield in the synthesis of a compound, evaluating the obtained results".[32] The complete laboratory activities and their respective protocols proposed by this tool can be found in the Supporting Information. We made the following request to ChatGPT:

> *Create a real laboratory activity, with real reagents, and a detailed protocol to assist 11th-grade students (17 years old) in conducting the activity to 'Experimentally determine the yield in the synthesis of a compound, evaluating the obtained results.'*

In seconds, ChatGPT provided the response presented in Activity 1 of the Supporting Information.

From a chemical perspective, the proposed laboratory activity is appropriate and suitable for achieving the intended objectives: synthesis of a substance and determination of the yield of the process. In terms of conceptual and procedural learning in chemistry, the activity proves to be highly enriching, as it involves the application of various chemical knowledge and laboratory techniques previously learned in the Portuguese context. Additionally, the note regarding the proposal's adaptability based on the availability of materials and reagents is noteworthy. However, the proposal, being directed at preuniversity students, does reveal some educational shortcomings. Some of these are minor issues, such as

- In the *Preparation of ethyl acetate reagent*, it is mentioned that the student should "Weigh a known amount of glacial acetic acid using an analytical balance and record the obtained value". However, it is considered relevant to provide an approximate indication of the mass of the reagent to be measured.
- In the *Extraction and drying of ethyl acetate*, the addition of "a small amount of anhydrous calcium chloride to the beaker to remove any trace of moisture" is referred to without indicating this substance in the Required Materials section.
- The limitations of ChatGPT in presenting chemical formulas with subscript numbers are also noted.

A corrected and simplified protocol for this activity is presented in the Supporting Information.

Additionally, from a didactic-pedagogical perspective, the authors identify the major flaws in this proposal for activity

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proposal. First, the management of time is challenging, given the heating and cooling times required for the synthesis and extraction of the synthesized substance. Completing the activity within the available class time is difficult. Second, and most notably, the toxicity of the substance being synthesized is a significant concern. Ethyl acetate is a highly flammable liquid and vapor (H225), causes serious eye irritation (H319), and may cause drowsiness or dizziness (H336). Handling this substance by students, who may have limited chemistry skills, in school laboratories that might lack adequate ventilation and vapor extraction poses a risk to their health.

In Portugal, the authors of textbooks, in general, propose the synthesis of acetylsalicylic acid from the reaction of salicylic acid with acetic anhydride, catalyzed by concentrated sulfuric acid, to achieve the learning objectives proposed by this Essential Learning (see Activity 1 of the Supporting Information). These reagents present fewer hazards when manipulated by students, and the synthesis and extraction of acetylsalicylic acid can be completed within the time of a laboratory class.

Conversely, the proposed laboratory activity to meet the Essential Learning "investigate experimentally the effect of temperature on the solubility of a solid solute in water, formulating hypotheses, controlling variables, and evaluating the results" also deserves careful consideration. ChatGPT was asked the following:

> *Create a real laboratory activity, with real reagents, and a detailed protocol to assist 17-year-old students in conducting the activity to 'Experimentally investigate the effect of temperature on the solubility of a solid solute in water, formulating hypotheses, controlling variables, and evaluating the results.'*

And it returned the response presented now in Activity 5 of the Supporting Information.

Unlike ChatGPT's proposal presented in the first example, this time, its suggestion is entirely inadequate from a chemical and didactic perspective. According to the guiding Essential Learning of this activity, the student is supposed to investigate the effect of the temperature on the solubility of a solid solute. However, the protocol proposed by ChatGPT contains numerous flaws that prevent the student from drawing any conclusions regarding the solubility of a solid solute with temperature, mainly because the solubility of sodium chloride in water does not change significantly with varying temperature.[33] In particular:

- The mass of sodium chloride and the volume of water to be measured are not mentioned in the *Preparation of solutions* but would be relevant to provide a reference value to guide the student throughout the activity.
- The study of the influence of temperature on solute solubility is presented as optional in the *Heating of samples (optional)* section. The proposed procedure in this section does not allow the student to draw any conclusion because if the solute is already completely dissolved in the solvent at room temperature (indicating that the mixture is a solution), no change in the solubility of the solute can be observed/recorded as the solution is heated (without significant solvent evaporation). Since the solubility of sodium chloride (and most salts, in general) increases with temperature,[33] observing the formation of "any visible solid residue" as the solution is heated is impossible.

Additionally, unlike the first presented activity, ChatGPT includes a Safety Protocol in this case, emphasizing precautions for handling and disposing of the reagents, which was crucial information for the ethyl acetate synthesis activity but was not included by ChatGPT.

According to Morais and Araújo,[19] in the Portuguese context,

> *students investigate the influence of temperature on the solubility of potassium nitrate in water by tracing the solubility curve of this salt. The use of this salt is suggested, due to the large variation of its solubility in water at different temperatures and the low risk in its handling (p. 775).*

To determine the solubility of potassium nitrate at a given temperature, a certain mass of potassium nitrate is mixed with a certain mass of water, and the mixture is heated until all of the solute dissolves. The temperature at which the first potassium nitrate crystals precipitate is recorded.

In a comprehensive scientific-pedagogical reflection on this essay's five proposed chemistry laboratory activities requested from ChatGPT, it is evident that this tool can accurately describe the proposed laboratory techniques (e.g., "Fill the buret with the prepared sodium hydroxide (NaOH) solution, taking care not to form air bubbles" or "Prepare aqueous solutions of the mentioned chemical substances by dissolving an appropriate amount of each salt in distilled water"). Sometimes, it suggests optional explorations, but only in the electrochemical series activity, the suggestion was appropriate ("Measurement of potential difference (optional): If available, use a multimeter to measure the potential difference (voltage) between the metallic electrodes in each reaction"). However, it does not clarify how this part of the activity could be performed. On the other hand, as previously mentioned, the described techniques do not always allow for achieving the proposed learning objectives adequately. In two out of the five activities, ChatGPT's proposal does not enable students to achieve the proposed chemistry content learning in the curriculum documents, showing scientific, didactic, and/or methodological flaws and inconsistencies. Moreover, as Humphry and Fuller[2] stated, the instructions given by ChatGPT are repeatedly vague and general throughout the five protocols and students need more precise and guided instructions to perform the laboratory activities with greater autonomy. Additionally, concerning the activity proposed to "experimentally investigate changes in chemical equilibria in aqueous systems by varying the concentration of reactants and products", ChatGPT proposes using silver nitrate, which is an expensive and dangerous reagent, causing severe skin burns and eye damage (H314) and being very toxic to aquatic life with long-lasting effects (H410). This activity could be conducted using safer reagents (e. g., aqueous solution of iron(III) nitrate and aqueous solution of potassium thiocyanate). Similarly, as previously discussed, in one of the activities, the synthesis of a substance with high toxicity was suggested, although the learning objectives could be achieved with lower-risk synthesized substances.

Despite the scientific and pedagogical limitations of the responses provided by ChatGPT, which are not always accurate or correct, it is considered that this tool has a significant potential for use in education. However, its responses always require in-depth reflection and guidance from an expert to correct any errors (as if the error made by ChatGPT is highlighted, it has the capability to formulate a more appropriate response) and to specifically request references to didactically relevant aspects for exploring the suggested laboratory activities, including problem-

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solving questions or guiding contexts,[22,34−36] as well as proposing pre- and postlaboratory questions[20] for activity exploration.

CONCLUSION

ChatGPT is an Artificial Intelligence tool that employs the GPT (generative pretrained transformer) language model to generate responses to user input. The utilization of this tool introduces novel challenges to Chemistry Education, necessitating critical analysis and reflection upon them.

Despite the numerous potentialities of this tool—such as its proficient interpretation and reproduction of the symbolic language inherent to Chemistry and its ability to conceptualize problems and laboratory activities in a careful and understandable manner—defining an appropriate prompt for the generated output to meet the expected objectives is not always easy (as observed in this essay). Upon a more detailed reflection on the outputs generated by ChatGPT from the refined prompt, it is possible to highlight several of its limitations, particularly concerning the scientific-pedagogical accuracy and suitability of the proposed laboratory activities. Additionally, there is a lack of criteria in adapting the proposed activities to address safety and sustainability concerns, as well as contextual aspects such as grade level, available class time, and physical space. Therefore, despite the vast potential of Artificial Intelligence, its application in Education requires a critical and reflective approach from an experienced expert. So, despite this tool suggesting laboratory activities that may appear to be well-designed and understandable to the general public (i.e., chemistry students), the necessity for scientific and pedagogical reflection concerning ChatGPT's responses emphasizes further the role that teachers have in the rapidly changing contemporary society. In this context, Artificial Intelligence tools, including ChatGPT, can significantly contribute to transforming teaching and learning dynamics. And it, when employed judiciously, could play a significant role in promoting quality teaching (i.e., acting as a teacher/student assistant), as Humphry and Fuller[2] or Fergus et al.[4] state.

The use of Artificial Intelligence tools in Education will undoubtedly become a growing trend in the very near future. Subsequently, the integration of ChatGPT into Chemistry classes and school laboratories is a natural step forward. However, the use of ChatGPT to access easily and rapidly to laboratory activity protocols, alternative to those presented in textbooks, (e.g., due to material or reagent shortages), presents significant limitations and should be approached critically, reflectively, and with caution. Some of these limitations are inherently linked to the nature of the language model, while others are associated with how users construct prompts suitable for the "understanding" of ChatGPT. Hence, despite AI immense potential to be used in educational contexts, the role and expertise of the Chemistry teacher continue to stand out as essential in ensuring the quality of Chemistry Education.

Meanwhile, given the vast potential for "learning" of Artificial Intelligence, it is important to continue exploring/reflecting on where this path could lead.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00745.

Laboratory activities protocols generated by ChatGPT (PDF)

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Notes

The authors declare no competing financial interest.

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