DEVELOPING PROBLEM-SOLVING SKILLS IN CHEMISTRY STUDENTS THROUGH PROJECT-BASED LEARNING

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Abstract

This article outlines the efforts undertaken to enhance the Advanced Organic Chemistry course at the third-year level by integrating transferable skills into the curriculum, thus improving the employability of students. The study demonstrates the potential of practical classes in promoting problem-solving and creative thinking skills, which are essential for achieving higher-order learning outcomes that are sought after by businesses and institutions hiring chemistry graduates. To achieve this, the course was redesigned to include a project that each student had to complete during their 12 days of allocated laboratory sessions, based on cutting-edge research, providing relevant and up-to-date information on the latest developments in the field. Students were given the freedom to make their own choices throughout the project, promoting initiative, self-confidence, problem-solving, and time-management skills. The project focused on developing technical skills crucial to research laboratories, instilling a curiosity-driven and research-oriented mindset that would enable students to face unforeseen challenges in their professional lives.

Keywords: *project-based learning, enhancing employability, problem- solving, creative thinking, laboratory teaching, organic chemistry, undergraduate students*

1. INTRODUCTION

The job market receives a significant influx of undergraduate students every year [1]. As competition continues to intensify, students must become better prepared to compete effectively.

Chemical and pharmaceutical companies represent a significant job market for chemistry students [2]. This sector is a vital contributor to the global economy, as highlighted by Ann Clayton in her book "Insight into a Career in Pharmaceutical Sales," where she notes that the pharmaceutical industry is one of the largest, most stable, and fastest-growing businesses worldwide [3]. As the Financial Times Stock Exchange (FTSE) 100-listed pharmaceutical companies such as GlaxoSmithKline and AstraZeneca face ever-evolving challenges to maintain their competitive edge, the demand for creative individuals is on the rise. To meet this demand, a new and complementary approach to laboratory learning is necessary, allowing students to realize their potential while addressing the needs of the industry.

In a laboratory, students are faced with a challenging and intricate learning environment that requires them to handle a large volume of written and verbal instructions. These instructions encompass a broad spectrum of topics, ranging from the correct usage of equipment and adherence to safety protocols, to underlying theoretical concepts and feedback garnered from conducting experiments. Navigating this environment can be overwhelming due to the vast amount of information that needs to be absorbed and applied effectively [4–6].

Undergraduate labs can be stressful for students and can lead to feelings of stress when they are not able to perform well in class or on assignments [7–9]. A high level of stress can reduce students' ability to concentrate on their studies and it can make it difficult for them to memorize facts and limit their ability to think critically [10].

At many Higher Education institutions, Chemistry courses employ a traditional expository approach, with students following detailed recipe-style instructions to conduct experiments [11]. Pre-laboratory work is often minimal [12–14], which leaves little room for promoting problem-solving or creative thinking activities that are crucial for higher-order learning outcomes [15,16], particularly in preparing for their future careers [17]. Therefore, it is essential to utilize teaching methods that incorporate relevant practical experience to support theoretical understanding [14,18–20].

Promoting critical thinking and problem-solving learning is critical in laboratory environment. The ability to not only observe and note experimental measurement data, but also to deal with unexpected observations and adjust opinions that can deepen the understanding of the theory [6,21]. The importance of shifting the focus from task-oriented managing and completion of laboratory work to open discussions about chemistry background in the experiment and sharing ideas and solutions to problems has already been addressed in the literature [22–24]. Encouraging students to prepare their own experimental plan and engage in conversations with other students and staff members can promote their engagement with practical classes. It can also foster a deeper understanding of the material, rather than simply memorizing it [25,26]. By employing critical thinking that entails comparing new data to existing data, students can take action, based on those comparisons, and make necessary adjustments to improve their experimental outcomes. Promoting critical thinking and problem-solving during laboratory classes provides students with more independence and can improve their confidence as future chemists [21].

By utilizing critical thinking skills, students can compare new experimental data with existing data and adjust their methods accordingly to improve their experimental outcomes. Fostering critical thinking and problem-solving abilities during laboratory classes can enhance students' independence and boost their confidence as aspiring chemists.

1.1 Aims

The aim of this project was to improve the organic chemistry laboratory learning experience for third-year undergraduate students by incorporating more problem-solving, multi-step projects. These projects were designed not only to challenge and improve students' creative thinking skills during practical classes, but also to increase their engagement in hands-on learning, an essential component of any university-level course [27]. To this end, the practical module included synthetic projects that were aligned with the industrial standards sought by chemical companies when recruiting new employees.

1.2 Drawbacks of our previous approach

The previous module had two types of summative experiments with different point values: twenty and 40. The 20-point experiments only required a single chemical step and had to be completed within two days or less of lab time. The 40-point experiments, on the other hand, involved two or three chemical steps performed concurrently, and had a time limit of three to four days of lab time. To complete the lab course, students had to finish experiments with a total points value of 120, choosing from 12 experiments, eight of which were worth 20 points and four of which were worth 40 points. They were given a total of 12 days to finish all lab work.

The experiments were designed to incorporate both concepts from second- and third-year organic chemistry courses, as well as modern developments in research. Prior to conducting any practical work, all students were required to complete a short Hazard Assessment Data Sheet for each experiment, which was checked by a staff member during lab classes. The experiments were structured in a straightforward manner and were supported by detailed written instructions, which led many students to rely on recipe-style instructions rather than attempting to understand the underlying chemistry. When asked what they did when their experiment failed, all surveyed students indicated that they simply followed the instructions without considering the underlying chemistry.

Students were given the opportunity to talk to academic staff about their experiments and chemistry during their lab classes, but only a few took advantage of this. Their main focus was on completing their experiments quickly and finishing their labs as soon as possible. The old system was perceived as easy and unengaging, with students prioritizing their grades. Many students did not enjoy the lab work due to their lack of understanding, finding it stressful.

The lab course was seen as a standalone module, disconnected from their other courses. To address this, we implemented a strategy of having students prepare preliminary questions about the reaction mechanisms and theoretical concepts underlying their experiments, linking them to material taught in other classes. These questions were submitted at the beginning of the course and graded along with their final write-up. However, many students admitted in the survey that they did not revisit their questions after submission.

The Academic Staff Demonstrators attempted to foster an environment where students felt comfortable asking questions about their lab work and results during class. However, in a busy lab setting, this often required the staff to shift their focus away from the experiments and safety, which posed a challenge. Due to limited time and students' lack of confidence in practical and theoretical chemistry, the Academic Staff Demonstrators found it difficult to engage in one-on-one discussions with every student. As a result, some students viewed these interactions as uncomfortable.

2. TOWARDS A CREATIVE THINKING APPROACH

The objective of our level 3 Advanced Organic Chemistry laboratory course project was to integrate problem-solving and creative thinking skills into the curriculum. This was accomplished by replacing single or double step experiments with longer, multi-step experiments that would spark the students' imagination, foster skill development, and prepare them for the job market. To align with the requirements of potential employers, local industry leaders were consulted to identify the qualities they sought in new recruits. Among the commonly cited skills were time management, teamwork, problem-solving, creative thinking, general lab skills, and health and safety awareness.

3. MEASURES TO ENHANCE STUDENTS' SKILLS

To equip students with the necessary skills, a proactive approach was taken that included several measures.

3.1 Health and safety

Safety is a top priority for employers in the industry. This was reflected in the project by implementation of detailed Health and Safety procedures in the laboratory. These procedures highlight the importance of safe working practices and require the completion of a COSHH assessment, as well as noting key safety information in the laboratory notebook, such as how to handle particularly harmful reagents. Students were also required to complete a pre-lab quiz to aid their memory and ensure they were adequately prepared for the lab, as well as to help with cognitive offload [28] These safety measures require careful attention to detail, including reading and checking all chemicals and reactions. To further reinforce the importance of Health and Safety, students were interviewed about these procedures during lab classes.

3.2 Time management

Effective time management is a highly valued skill across all industries in today's job market, as supported by research [29–31].

Kearns and Gardiner's [32] research highlights the positive impact that time management skills can have on student outcomes and academic success. Effective time management enables students to develop coping strategies that help them manage competing demands, prioritize tasks, achieve better grades, reduce stress, and enhance productivity, positioning them for success in their future endeavours. Notably, good time management skills can also serve as a buffer against stress [33], and are associated with lower levels of anxiety and higher performance in higher education [32]. However, students often struggle to balance their academic responsibilities with their personal lives, leading to time mismanagement, poor sleep patterns, and increased stress levels [34,35].

To improve students' time management skills, a six-week lab session was allocated for a multi-step project spread over 12 days, without a designated task schedule for each session. This approach encouraged students to plan and manage their time carefully while facing various challenges and deadlines. The project included strict deadlines to test their ability to learn and perform under pressure. Students were expected to research their projects and develop a plan to conduct their experiments within the given lab time. The project consisted of a six-step synthetic pathway, some of which could be conducted simultaneously. By managing their time effectively, students were given the opportunity to purify their product again, if needed.

3.3 Collaboration and teamwork

In today's job market, teamwork is highly valued and is considered to be more important than grade point average [36]. As a result, it is crucial for undergraduate chemistry programs to include the development of teamwork skills [37]. Effective pedagogies must be adopted to structure learning environments that enable students to develop teamwork skills alongside disciplinary learning. To achieve this, students should practice these skills and receive feedback on their progress [38]. Project work that is appropriately designed can offer opportunities for student groups to work together over extended periods [39–41].

Students view teamwork and collaboration as tasks that involve team-based assessment and necessitate a deep approach to learning and studying [42]. By working together, students can enhance their collaboration, team unity, and cultural diversity skills, resulting in a more comprehensive educational experience that expands the range of skills they acquire. As there is a recognized skills gap among science graduates, the development of teamwork skills is particularly important [43].

Teamwork is a fundamental component of undergraduate laboratory work, allowing students to learn from one another and share their knowledge and skills [36,44,45]. Collaborating with peers helps students develop communication skills, which are essential in any professional setting. It also enables students to learn how to collaborate with others effectively and manage their time efficiently. Additionally, teamwork can help students develop leadership skills and work well under pressure. Working in a team can be enjoyable and fosters strong relationships among peers [46].

In undergraduate laboratories, teamwork can take many forms. In this project, students were encouraged to work together to troubleshoot problems and develop solutions. They were also encouraged to share knowledge and skills, such as how to use laboratory equipment or perform specific techniques, while adhering to laboratory safety protocols and conducting experiments responsibly.

Emphasizing the benefits of teamwork from the beginning, although the project was completed individually, students were informed about the advantages of working with colleagues, as teamwork often leads to better outcomes.

3.4 Lab skills, problem solving and creative thinking

Acquiring lab skills, problem-solving abilities, and creative thinking are crucial aspects of undergraduate laboratory work [45,47] and play a vital role in preparing students for their future professions.

Learning lab skills is necessary for students to use laboratory equipment correctly and safely conduct experiments [39,48], which is a critical aspect of any scientific field to ensure experiments are carried out responsibly.

Problem-solving skills are also important as they help students identify and overcome obstacles [49], which is crucial in any professional setting to achieve success.

Creative thinking is equally crucial in developing new approaches and innovative solutions to problems [6,47], leading to breakthroughs in research and development across various fields.

To develop these skills, students were engaged in multi-step reactions that demanded the application of familiar techniques along with new challenges such as handling pyrophoric chemicals and cannulae. The project was designed to promote problem-solving through creative thinking, with students tasked to find solutions to challenges encountered while progressing through the project. Different spectroscopic and analytical techniques (including Nuclear Magnetic Resonance (NMR), Infrared spectroscopy (IR), Ultraviolet spectroscopy (UV), Mass spectra (MS), and Gas Chromatography (GC)) were employed to monitor reaction progress and product purity, providing students with a comprehensive education to equip them for successful future careers.

4. EVALUATION OF PEDAGOGIC APPROACH

To assess the learning outcomes of the redesigned practical module, various methods were employed, including regular questioning, surveys with open-ended and tick-box questions analysed through Thomas [50], Likert [51], and Osgood et al. [52] formats, and focus groups. The data presented in this article reflects the results obtained over two years of running the project. In the first year, feedback was collected from students after each weekly session through a Postgraduate Demonstrator who asked students about their overall impression and progress of the experiment individually. These answers were recorded for future analysis at the end of the project.

Surveys were utilized as a means of gathering students' impressions. The surveys included open-ended questions, such as "What did you learn during the experiment?" and "What would you improve?" alongside closed questions, such as asking students to rank their experience on a scale of 1 to 10. This provided a benchmark for future comparisons (see Figure 1).

In addition, focus groups were conducted after completing the project. Participants were asked various questions to gather their feedback on their overall impression of the project, the learning outcomes achieved, the clarity of marking guidelines, and their level of satisfaction. A total of 48 students participated in the organized focus groups across the two years of the project. Furthermore, follow-up semi-structured interviews were conducted with fourth-year students who had participated in the project during their third year, in order to assess the impact and benefits of the project over a longer period of time. Across the two years of the project, 60 students completed the online survey.

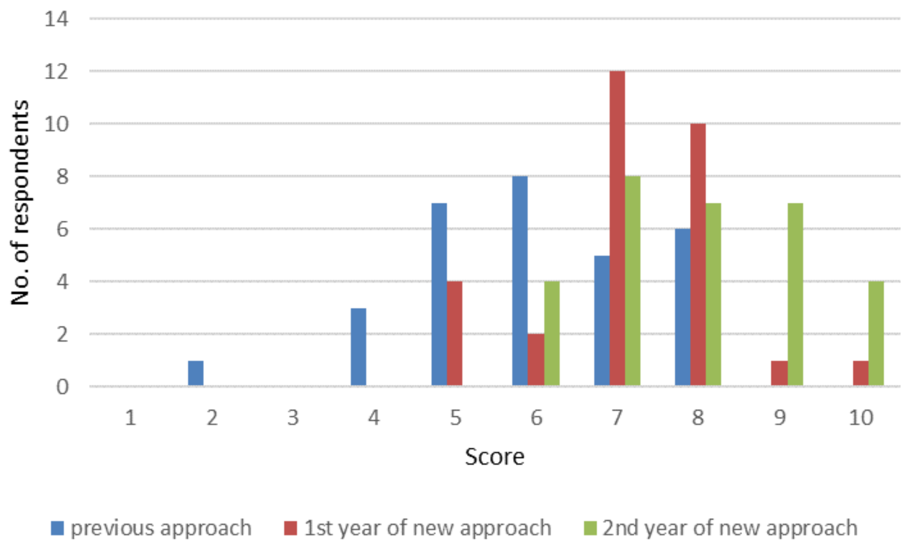

Fig. 1. Students' satisfaction with L3 Advanced Organic labs assessed through a survey using a Likert scale ranging from 1 (very poor) to 10 (excellent). The general satisfaction with the project increased over the two years period.

5. DISCUSSION

All students successfully completed the project within the allotted timeframe. Completion times varied from five days ahead of schedule to the final minute before the deadline, resulting in a well-distributed spread of project completion times among the students.

Students responded positively to the new approach for undergraduate labs. They described the project as challenging, interesting and exciting. One student said, 'I really liked the labs this year', while another commented that 'the project was challenging but very interesting'. Students were required to plan their time and come up with ideas when things were not working. One student commented, 'the project was challenging as I had to plan my time and come up with ideas when things were not working but when I finished I was very proud of myself'.

The project gave students good insight into the complexity of chemistry and how it can be applied in practice, with one student stating, 'I like seeing how something learned in theory actually is more than just theory – it works in real life as well'. It took them a few weeks to complete all the steps of the project, which showed them how complicated chemistry can be. The lab course gave them the experience of what it would be like to work in synthetic chemistry.

According to the students who participated in the project, longer projects were less stressful than shorter multiple experiments, which had a more positive effect on learning their practical skills and understanding of the chemistry background. They described the labs as less stressful because they did a project rather than many short experiments, which made it easier to organise and manage their time. The longer project made it easier for them to understand why they were doing what they were doing and made the experience more meaningful. The project-based approach was less stressful and more manageable, which allowed them to focus on learning and understanding the material.

Despite the challenges, the students found the lab course both challenging and enjoyable. They found the project interesting and appreciated the opportunity to apply the theory they had learned in class. They also indicated that they had to look up scientific papers to better understand the material, but they liked that they could then apply what they had read in their experimentation ('I liked that I read something in the paper and then I could try it myself'). Moreover, the longer project gave them a sense of accomplishment and made them feel like real chemists. Overall, while the experience was challenging, the students were able to learn new skills and techniques through the project-based approach.

Students appreciated the project's flexibility that allowed them to plan and execute their reactions according to their own abilities and schedules. Survey results showed that students who completed the project earlier and achieved excellent results possessed strong time management and organizational skills, often developed through extracurricular activities such as outreach programs or sports clubs. However, this created a disadvantage for students who did not participate in extracurricular activities or outreach programs, as they did not have the opportunity to develop their time management and organizational skills outside of their curriculum. To address this, pre-laboratory materials were introduced to guide students on how to prepare for lab sessions more efficiently.

The students expressed satisfaction with the additional training provided for the use of pyrophoric materials in the synthetic projects, which allowed them to comprehend the safety and broader applications of these reagents. Initially, some students faced challenges for example with remembering to clamp the bottles of reagent and ensuring proper drying of syringes while transferring it to their reaction vessels. To address this issue, brief revision sessions were introduced for students scheduled to perform a reaction involving pyrophoric reagents that day. This intervention proved successful in helping students achieve better results. The revision sessions were led by a designated demonstrator, responsible for monitoring the quality of the reagents and solvents used in the experiment, and supervising students on the day of the experiment.

The students were deeply involved in their projects and exhibited a strong motivation to learn beyond earning marks. When dissatisfied with the purity or yield of their product, many took the initiative to repurify or repeat the reaction. In addition, they actively engaged in discussions about their projects with both peers and demonstrators. Furthermore, students demonstrated an ability to draw on relevant literature beyond the required material, and were able to articulate their understanding of the reactions and laboratory techniques with clarity and precision.

The ability to perform multistep synthesis that transforms simple starting materials into products with greater complexity is a cornerstone of modern organic chemistry and is an essential skill for chemistry students [53–56]. It involves careful planning and the use of previous experience and skills.

The students appreciated the opportunity to gain experience in planning and modifying the synthesis process to meet a specific schedule and produce high-purity materials. One of the most interesting aspects of these projects was that they allowed students to observe how molecules are built up and how this affects the pattern of NMR spectra. These multistep projects emphasized problem-solving and critical thinking skills, as well as transferable skills such as planning and time management that are highly valued by employers in many fields beyond Chemistry.

Year three students provided feedback on their experience with the lab, which focused on the challenges they faced, their understanding of the theory, and their overall lab experience. Year four project students, in follow-up interviews, reflected on their experience in the L3 Advanced Organic Lab and appreciated the benefits of longer projects that prepared them more realistically for their final projects. They recognized the value of multistep synthesis training and the opportunity to practice important soft skills such as time management and teamwork ('talking to my classmates about the project and listen to their perspective on how to approach the different steps was very useful', 'I liked that we could discuss the theory like a team, it really helped me to get ready for my final year').

The primary challenge of this course was to identify projects that had an equivalent level of difficulty, number of synthetic steps, employed similar techniques, and generated equivalent amounts of data. During the initial year of the program, one project was found to be more challenging than the others, causing an issue.

To resolve this, a new experiment was incorporated in the subsequent year, which was intentionally created to be of similar complexity and data yield as the rest. After completing the course, students were surveyed about the fairness and overall satisfaction of the project. The feedback was encouraging, with students expressing contentment with the new changes, affirming that the difficulty level was equivalent, and appreciated using the same procedures.

Here are some comments from students in response to the new changes:

'I think the difficulty of the projects was comparable. But I wish I could do them all. They all seemed to be very interesting.'

'I think the projects were comparable and had a similar level of difficulty. It was good that we all used the same methods in our projects so we could compare them and discuss our experience with other groups.'

Despite the positive feedback, in the future, it would be beneficial to incorporate more diverse projects to offer students more variety and larger rotations, avoiding the repetition of the same experiments every year.

The feedback from students at the conclusion of the experiment was very positive and encouraging, particularly from those intending to pursue a career in industry. They expressed a high level of engagement from the beginning and welcomed the experience. They valued this opportunity before progressing to more advanced projects during their final year course as it provided them with a solid foundation for future endeavours in their field.

6. CONCLUSIONS

A project-based approach was introduced to enhance the undergraduate labs, which contained strict yet feasible deadlines, clear but general guidelines, and the incorporation of challenging situations that students had not encountered before. Instead of providing a detailed step-by-step guide, students were encouraged to manage their own time and develop creative problem-solving skills within a specified timeframe. The objective was to equip students with the skills, including soft skills, that industry employers are seeking, as they will encounter comparable challenging scenarios in their future jobs. According to the received feedback, the students appreciated the challenge and felt better prepared to face their future as chemists. They found this approach less stressful and were more motivated to learn rather than just aim for a good grade.

The new projects provide students with an opportunity to experience real-life organic materials chemistry. By performing a multi-step synthesis, students transform a simple starting material into products with greater complexity, and analyse the structure-property relationships using a range of analytical and spectroscopic techniques. These projects allow students to gain hands-on knowledge and experience in a growing field, particularly in the industry sector.

This approach enables students to develop essential laboratory skills and multidisciplinary synthesis techniques that will aid their progress as chemistry students. By practicing already-acquired laboratory skills and learning new techniques, students must learn to plan their work and manage their time effectively. Furthermore, they must handle the reactants with caution. Although these projects are optimized for completion over a 12-day period of 6-hour daily sessions, they can be adapted to fit other schedules. This timeframe also allows for the repetition of two reactions if necessary.

Students found the new project-based approach to be challenging but interesting, and they appreciated the opportunity to plan their time and generate ideas when faced with obstacles. Upon completion, students felt a sense of pride in their accomplishments.

There is a potential for further development and study in undergraduate labs. A promising area for improvement is the pre-lab resources, which can be refined to enhance students' preparedness for practical sessions. The integration of team-based projects or assessments can also be considered to foster greater collaboration and teamwork among students. Furthermore, it is recommended to evaluate the current assessment structure and implement changes to prioritize team-oriented evaluations, which could lead to future enhancements.

REFERENCES

1. HESA (2022) *Higher Education Student Statistics: UK, 2020/21 - Student numbers and characteristics*. Available at: https://www.hesa.ac.uk/news/25-01-2022/sb262-higher-education-student-statistics/numbers (Accessed: 4 April 2023).
2. Prospects.ac.uk (2022) *What can I do with a chemistry degree?* Available at: https://www.prospects.ac.uk/careers-advice/what-can-i-do-with-my-degree/chemistry (Accessed: 28 March 2023).
3. Clayton, A. (2005) *Insight Into A Career In Pharmaceutical Sales*. 7th edition. Pharmaceuticalsales.Com Inc.
4. Agustian, H.Y. and Seery, M.K. (2017) 'Reasserting the role of pre-laboratory activities in chemistry education: a proposed framework for their design', *Chemistry Education Research and Practice*, 18(4), pp. 518–532. Available at: https://doi.org/10.1039/C7RP00140A.
5. Seery, M.K. *et al.* (2019) 'Unfinished Recipes: Structuring Upper-Division Laboratory Work To Scaffold Experimental Design Skills', *Journal of Chemical Education*, 96(1), pp. 53–59. Available at: https://doi.org/10.1021/acs.jchemed.8b00511.
6. Brederode, M.E. van, Zoon, S.A. and Meeter, M. (2020) 'Examining the effect of lab instructions on students' critical thinking during a chemical inquiry practical', *Chemistry Education Research and Practice*, 21(4), pp. 1173–1182. Available at: https://doi.org/10.1039/D0RP00020E.
7. Haider, S.I. (2017) 'Effect of Stress on Academic Performance of Undergraduate Medical Students', *Journal of Community Medicine & Health Education*, 07(06). Available at: https://doi.org/10.4172/2161-0711.1000566.
8. Malarvili, R. and Dhanapal, S. (2018) 'Academic stress among university students: A quantitative study of generation Y and Z's perception', *Pertanika Journal of Social Sciences and Humanities*, 26, pp. 2115–2128.

9. Oyewobi, L.O. *et al.* (2020) 'Influence of stress and coping strategies on undergraduate students' performance', *Journal of Applied Research in Higher Education*, 13(4), pp. 1043–1061. Available at: https://doi.org/10.1108/JARHE-03-2020-0066.

10. Frazier, P. *et al.* (2019) 'Understanding stress as an impediment to academic performance', *Journal of American college health: J of ACH*, 67(6), pp. 562–570. Available at: https://doi.org/10.1080/07448481.2018.1499649.

11. Kirschner, P.A. (1992) 'Epistemology, practical work and Academic skills in science education', *Science & Education*, 1(3), pp. 273–299. Available at: https://doi.org/10.1007/BF00430277.

12. Hodson, D. (2005) 'Teaching and Learning Chemistry in the Laboratory: A Critical Look at the Research', *Education Quimica*, 16. Available at: https://doi.org/10.22201/fq.18708404e.2005.1.66134.

13. Hofstein, A. and Mamlok-Naaman, R. (2007) 'The laboratory in science education: the state of the art', *Chemistry Education Research and Practice*, 8(2), pp. 105–107. Available at: https://doi.org/10.1039/B7RP90003A.

14. Reid, N. and Shah, I. (2007) 'The role of laboratory work in university chemistry', *Chemistry Education Research and Practice*, 8. Available at: https://doi.org/10.1039/B5RP90026C.

15. Bloom, B.S. *et al.* (1956) *Taxonomy of educational objectives : the classification of educational goals. Book 1, Cognitive Domain*. Longman. Available at: http://repository.vnu.edu.vn/handle/VNU_123/89975 (Accessed: 4 April 2023).

16. Anderson, L. *et al.* (2001) *Taxonomy for Learning, Teaching, and Assessing, A: A Revision of Bloom's Taxonomy of Educational Objectives, Abridged Edition*. 1st edition. New York: Pearson.

17. Sandi-Urena, S. *et al.* (2011) 'Students' experience in a general chemistry cooperative problem based laboratory', *Chemistry Education Research and Practice*, 12(4), pp. 434–442. Available at: https://doi.org/10.1039/C1RP90047A.

18. Hofstein, A. and Lunetta, V.N. (1982) 'The Role of the Laboratory in Science Teaching: Neglected Aspects of Research', *Review of Educational Research*, 52(2), pp. 201–217. Available at: https://doi.org/10.3102/00346543052002201.

19. Hofstein, A. and Lunetta, V.N. (2004) 'The laboratory in science education: Foundations for the twenty-first century', *Science Education*, 88(1), pp. 28–54. Available at: https://doi.org/10.1002/sce.10106.

20. Lyall, R.J. (2010) 'Practical work in chemistry: chemistry students' perceptions of working independently in a less organised environment', *Chemistry Education Research and Practice*, 11(4), pp. 302–307. Available at: https://doi.org/10.1039/C0RP90010A.

21. Holmes, N.G., Wieman, C.E. and Bonn, D.A. (2015) 'Teaching critical thinking', *Proceedings of the National Academy of Sciences*, 112(36), pp. 11199–11204. Available at: https://doi.org/10.1073/pnas.1505329112.

22. Cooper, M.M. and Kerns, T.S. (2006) 'Changing the Laboratory: Effects of a Laboratory Course on Students' Attitudes and Perceptions', *Journal of Chemical Education*, 83(9), p. 1356. Available at: https://doi.org/10.1021/ed083p1356.

23. Walker, J.P., Sampson, V. and Zimmerman, C.O. (2011) 'Argument-Driven Inquiry: An Introduction to a New Instructional Model for Use in Undergraduate Chemistry Labs', *Journal of Chemical Education*, 88(8), pp. 1048–1056. Available at: https://doi.org/10.1021/ed100622h.
24. Xu, H. and Talanquer, V. (2013) 'Effect of the Level of Inquiry on Student Interactions in Chemistry Laboratories', *Journal of Chemical Education*, 90(1), pp. 29–36. Available at: https://doi.org/10.1021/ed3002946.
25. Horowitz, G. (2014) 'Intrinsic motivation of students utilizing a project-based organic chemistry laboratory curriculum', in *Research based undergraduate science teaching*. Charlotte, NC, US: IAP Information Age Publishing (Research in science education), pp. 333–378.
26. Galloway, K.R. and Bretz, S.L. (2015) 'Using cluster analysis to characterize meaningful learning in a first-year university chemistry laboratory course', *Chemistry Education Research and Practice*, 16(4), pp. 879–892. Available at: https://doi.org/10.1039/C5RP00077G.
27. Kahu, E.R. (2013) 'Framing student engagement in higher education', *Studies in Higher Education*, 38(5), pp. 758–773. Available at: https://doi.org/10.1080/03075079.2011.598505.
28. Risko, E.F. and Gilbert, S.J. (2016) 'Cognitive Offloading', *Trends in Cognitive Sciences*, 20(9), pp. 676–688. Available at: https://doi.org/10.1016/j.tics.2016.07.002.
29. Gehani, R.R. (1995) 'Time-based management of technology: A taxonomic integration of tactical and strategic roles', *International Journal of Operations & Production Management*, 15(2), pp. 19–35. Available at: https://doi.org/10.1108/01443579510080391.
30. Claessens, B.J.C. *et al.* (2007) 'A review of the time management literature', *Personnel Review*, 36(2), pp. 255–276. Available at: https://doi.org/10.1108/00483480710726136.
31. Alvarez Sainz, M., Ferrero, A.M. and Ugidos, A. (2019) 'Time management: skills to learn and put into practice', *Education + Training*, 61(5), pp. 635–648. Available at: https://doi.org/10.1108/ET-01-2018-0027.
32. Kearns, H. and Gardiner, M. (2007) 'Is it time well spent? The relationship between time management behaviours, perceived effectiveness and work-related morale and distress in a university context', *Higher Education Research & Development*, 26(2), pp. 235–247. Available at: https://doi.org/10.1080/07294360701310839.
33. Misra, R. and McKean, M. (2000) 'College students' academic stress and its relation to their anxiety, time management, and leisure satisfaction - ProQuest', *American Journal of Health Studies*, 16(1), pp. 41–51.
34. Hardy, L. (2003) 'Helping students de-stress - ProQuest', *The Education Digest*, 68(9), pp. 10–17.
35. van der Meer, J., Jansen, E. and Torenbeek, M. (2010) '"It's almost a mindset that teachers need to change": first-year students' need to be inducted into time management', *Studies in Higher Education*, 35(7), pp. 777–791. Available at: https://doi.org/10.1080/03075070903383211.
36. Kondo, A.E. and Fair, J.D. (2017) 'Insight into the Chemistry Skills Gap: The Duality between Expected and Desired Skills', *Journal of Chemical Education*, 94(3), pp. 304–310. Available at: https://doi.org/10.1021/acs.jchemed.6b00566.

37. Quality Assurance Agency for Higher Education (2022) *Subject Benchmark Statement - Chemistry*. Available at: https://www.qaa.ac.uk/the-quality-code/subject-benchmark-statements/chemistry (Accessed: 29 March 2023).
38. Bransford, J.D., Brown, A.L. and Cocking, R.R. (2000) *How People Learn*. Washington, D.C.: National Academies Press. Available at: https://doi.org/10.17226/9853.
39. Davis, D.S., Hargrove, R.J. and Hugdahl, J.D. (1999) 'A Research-Based Sophomore Organic Chemistry Laboratory', *Journal of Chemical Education*, 76(8), p. 1127. Available at: https://doi.org/10.1021/ed076p1127.
40. Tribe, L. and Cooper, E.L. (2008) 'Independent Research Projects in General Chemistry Classes as an Introduction to Peer-Reviewed Literature', *Journal of College Science Teaching*, 37(4), pp. 38–42.
41. Bartle, E.K., Dook, J. and Mocerino, M. (2011) 'Attitudes of tertiary students towards a group project in a science unit', *Chemistry Education Research and Practice*, 12(3), pp. 303–311. Available at: https://doi.org/10.1039/C1RP90037D.
42. Volkov, A. and Volkov, M. (2015) 'Teamwork benefits in tertiary education: Student perceptions that lead to best practice assessment design', *Education + Training*, 57(3), pp. 262–278. Available at: https://doi.org/10.1108/ET-02-2013-0025.
43. Wilson, L., Ho, S. and Brookes, R.H. (2018) 'Student perceptions of teamwork within assessment tasks in undergraduate science degrees', *Assessment & Evaluation in Higher Education*, 43(5), pp. 786–799. Available at: https://doi.org/10.1080/02602938.2017.1409334.
44. Fredrick, T.A. (2008) 'Facilitating Better Teamwork: Analyzing the Challenges and Strategies of Classroom-Based Collaboration', *Business Communication Quarterly*, 71(4), pp. 439–455. Available at: https://doi.org/10.1177/1080569908325860.
45. Overton, T. and McGarvey, D.J. (2017) 'Development of key skills and attributes in chemistry', *Chemistry Education Research and Practice*, 18(3), pp. 401–402. Available at: https://doi.org/10.1039/C7RP90006F.
46. Burnham, J.A.J. (2020) 'Skills for Success: Student-Focused, Chemistry-Based, Skills-Developing, Open-Ended Project Work', *Journal of Chemical Education*, 97(2), pp. 344–350. Available at: https://doi.org/10.1021/acs.jchemed.9b00513.
47. Majid, S. *et al.* (2012) 'Importance of Soft Skills for Education and Career Success', *International Journal for Cross-Disciplinary Subjects in Education*, 2(Special 2), pp. 1036–1042. Available at: https://doi.org/10.20533/ijcdse.2042.6364.2012.0147.
48. Luska, K.L. (2022) 'A Multioutcome, Guided Inquiry-Based Liquid–Liquid Extraction Laboratory for Introductory Organic Chemistry', *Journal of Chemical Education*, 99(12), pp. 4124–4133. Available at: https://doi.org/10.1021/acs.jchemed.2c00396.
49. Dunlap, N. and Martin, L.J. (2012) 'Discovery-Based Labs for Organic Chemistry: Overview and Effectiveness', in *Advances in Teaching Organic Chemistry*. American Chemical Society (ACS Symposium Series, 1108), pp. 1–11. Available at: https://doi.org/10.1021/bk-2012-1108.ch001.
50. Thomas, D.R. (2006) 'A General Inductive Approach for Analyzing Qualitative Evaluation Data', *American Journal of Evaluation*, 27(2), pp. 237–246. Available at: https://doi.org/10.1177/1098214005283748.

51. Likert, R. (1932) ‘A technique for the measurement of attitudes’, *Archives of Psychology*, 140, pp. 5–53.
52. Osgood, C.E., Suci, G.J. and Tannenbaum, P.H. (1957) *The Measurement of Meaning*. University of Illinois Press.
53. Betush, M.P. and Murphree, S.S. (2009) ‘Use of Chiral Oxazolidinones for a Multi-Step Synthetic Laboratory Module’, *Journal of Chemical Education*, 86(1), p. 91. Available at: https://doi.org/10.1021/ed086p91.
54. Utku, Y. *et al.* (2010) ‘Rapid Multistep Synthesis of a Bioactive Peptidomimetic Oligomer for the Undergraduate Laboratory’, *Journal of Chemical Education*, 87(6), pp. 637–639. Available at: https://doi.org/10.1021/ed100202f.
55. Wade, E.O. and Walsh, K.E. (2011) ‘A Multistep Organocatalysis Experiment for the Undergraduate Organic Laboratory: An Enantioselective Aldol Reaction Catalyzed by Methyl Prolinamide’, *Journal of Chemical Education*, 88(8), pp. 1152–1154. Available at: https://doi.org/10.1021/ed1006713.
56. Duff, D.B., Abbe, T.G. and Goess, B.C. (2012) ‘A Multistep Synthesis Featuring Classic Carbonyl Chemistry for the Advanced Organic Chemistry Laboratory’, *Journal of Chemical Education*, 89(3), pp. 406–408. Available at: https://doi.org/10.1021/ed2003687.