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Meaninful learning of stereochemistry using medicinal plants as contextualization through a virtual learning environment platform

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ABSTRACT

This study aims to report the application of a Potentially Meaningful Teaching Unit (PMTU) as didactic methodology, to remotely teach about stereochemistry through the utilization of Google Classroom, a virtual learning environment. The activity took place during the suspension period of face-to-face classes, due to the COVID-19 pandemic and involved the participation of two secondary school classes of students from a high school located in the central region of the state of Rio Grande do Sul, Brazil. Based in Ausubel's Meaningful Learning theory, a PMTU intends to overcome the student's dependence on mechanical memorization. The methods for applying a PMTU rely on fostering scenarios that utilize students' prior knowledge as a starting point for addressing scientific concepts. This Teaching Unit approached the topic of stereoisomery with an emphasis on the usage of medicinal plants. The approach initially began by selecting medicinal plant species to be studied, considering which species had either enantiomers or diastereoisomers in their molecular structure and were understandable through a stereochemical perspective. The proposal was entirely developed through a virtual learning environment and utilized various technological didactic resources. The rationale for developing this proposal is justified by the numerous difficulties related to the learning process in the field of stereoisomery, which is often considered a challenging subject within Organic Chemistry. This challenge is attributed to the level of abstraction required for the three-dimensional visualization of molecules and understanding the role of these structures in reactivity properties, a problem that was exacerbated by the suspension of face-to-face classes. The findings suggests that the PMTU facilited student participation by employing various resources, which helped overcome the challenge of remotely addressing the concept of stereochemistry, with evidence of meaningful learning.

KEYWORDS: Virtual learning environments; Contextualization of content; Science teaching; Courseware; Educational technology.

Aprendizagem significativa de estereoquímica utilizando plantas medicinais como contextualização por meio de ambiente virtual de aprendizagem

RESUMO

Objetivamos neste trabalho relatar a elaboração e aplicação de uma Unidade de Ensino Potencialmente Significativa (PMTU), para o ensino de estereoquímica utilizando o Google Sala de aula como Ambiente Virtual de Aprendizagem. A atividade ocorreu durante o período de suspensão das aulas presenciais, em função da pandemia do novo coronavírus. Participaram do estudo estudantes do Ensino Médio da região Central do Rio Grande do Sul. Alicerçada na teoria de aprendizagem significativa ausubeliana, uma PMTU objetiva superar a forte dependência da memorização mecânica, promovendo situações que utilizam os conhecimentos prévios dos alunos como ponto de partida para o ensino de conceitos científicos. Assim, essa unidade abordou a estereoisomeria com foco em plantas medicinais. Partindo da seleção de espécies que apresentam, em seus princípios ativos, enantiomeria ou diastereoisomeria e que podem ser compreendidas por meio da perspectiva da estereoquímica, a proposta foi desenvolvida integralmente por meio de um ambiente virtual de aprendizagem e diferentes recursos didáticos tecnológicos. Justifica-se o desenvolvimento dessa proposta devido às dificuldades de aprendizagem no campo da estereoisomeria, apontada como um tópico desafiador da Química Orgânica, devido ao nível de abstração para a visualização tridimensional de moléculas e a compreensão da influência da estrutura nas propriedades e reatividade, desafio potencializado pela suspensão das aulas presenciais. Os dados coletados ao longo do processo indicam que a PMTU propiciou a participação dos discentes por meio do uso de diferentes recursos, auxiliando na superação da problemática de abordar remotamente o conceito, com evidências de aprendizagem significativa da temática e conceitos científicos.

PALAVRAS-CHAVE: Ambiente virtual de aprendizagem; Contextualização do conteúdo; Ensino de ciências; Material didático; Tecnologia educacional.

INTRODUCTION

The need for adequacy regarding the usage of Information and Communication Technologies (ICT), as well as their respective applications in teaching activities, has been a challenging issue faced by many teachers worldwide due to the recent COVID-19 sanitary crisis. Such transition, which occurred rapidly and unexpectedly, has made it possible to develop several teaching methods in global schooling, and has also reinforced the utilization of ICT as an improvement tool for students' learning (Dietrich et al, 2020). Such adaptation promoted the effective expansion of students' abilities, as well as both methods and knowledge development processes by providing tools to support them (Santos et al, 2020).

During the period of remote emergence teaching, there was widespread use of applications, which were referred to as Virtual Learning Environments (VLEs), as well as their functionalities (Vasconcellos; Tamariz & Batista, 2019). According to Koch and Passerino (2011, p. 1), the use of these applications has worked as a mediation for cognitive processes which promotes a more frequent organization as well as monitoring of knowledge development by students.

The Google Classroom platform is a free-to-use VLE environment that can be accessed by a computer, in its browser version, or by mobile devices. It is a virtual space that is meant to provide pedagogical support, both inside and outside the school environment. It also contributes to the promotion of collaborative learning through the utilization of several virtual resources (Martins et al, 2019).

Hence, in this study, we report the results of using a teaching unit based on Ausubel's (2003) Meaningful Learning Theory. This teaching unit was designed to teach stereoisomery through the topic of medicinal plants and has been developed as an educational product. The teaching unit was applied during the teaching of two groups of students, and it was developed in a secondary school located in the central region of the state of Rio Grande do Sul.

Throughout the implementation of the Unit, it was necessary to completely reorganize the activities and the teaching resources, due to the global pandemic of COVID-19, which led the researchers to the following research question: "How can we apply a Potentially Meaningful Teaching Unit using a remote teaching environment?" Thus, it organized the application of a 5 lesson sequence utilizing different teaching resources based on ICTs. The application took place by contextualizing the subject with the topic of medicinal plants and sought to overcome the strong resistance to learning shown by the students regarding the mechanical memorization that, according to Graulich (2015), is often presented by students when they are confronted with the concepts of Organic Chemistry fields.

MEANINGFUL LEARNING AND THE USE OF *PMTU'S*

David Ausubel's Theory of Meaningful Learning considers that learning is a process through which new information interacts in a non-literal and non-arbitrary way with what we know. (Ausubel, 2003; Moreira, 2011). A so-called literal interaction refers to mechanical learning, limited to reproducing the

knowledge presented in the teaching activity in the way that was received, without connections with previous ideas. At the same time, the connection of the new information should be made with relevant (non-arbitrary) prior ideas. For this reason, it is a learning process that often has less chance of remaining in the cognitive structure in the long term. However, when there is a connection between new information and previous knowledge, such interaction results in the construction of personal meanings elaborated in a "non-literal" way, characterizing meaningful learning (Tavares, 2004).

The teacher, therefore, aims to facilitate the construction of these logical relationships by selecting basic ideas and starting from broader concepts towards the most restricted and specific (progressive differentiation), and then returning to broader concepts (integrative reconciliation). Integrative reconciliation consists in the construction and reconstruction of conceptual relationships since new concepts have been incorporated into the cognitive structure and need to be reorganized. This type of learning should start from previous knowledge, which is considered by Ausubel, Novak, and Hanesian (1980) to be crucial for achieving meaningful learning.

Thinking about systematizing these ideas to put them into practice in the classroom, Moreira (2011) proposes the creation of potentially meaningful materials, with a good structure and logical triggering that make sense to the group to which certain content is intended. These materials are called Potentially Meaningful Teaching Units (PMTU) which are teaching sequences that aim at meaningful learning, as opposed to mechanical learning, and, therefore, can contribute to higher quality learning (Moreira, 2011). Briefly, the PMTU is composed of the initial *situation*: which aims to map the previous knowledge of students. *Initial problem-situation:* a problem-situation of an introductory level, seeking to give meaning to the concept. *Deepening of knowledge:* approach from progressive differentiation. *New problem situation:* questions with a higher level of depth, evidencing the correspondences and contradictions between the concepts.*Individual summative evaluation:* test evidencing the capture of meanings. *Final integrative class:* seeks integrative reconciliation between concepts. *Learning assessment:* evidence should be sought for understanding meanings and the ability to use knowledge for different situations throughout the implementation of the PMTU, focusing on collaborative activities, and ending it with an individual summative assessment. *Evaluation of the PMTU itself:* In order to improve teaching strategies, to assess the perspective of students (Schittler; Moreira, 2014).

THE POTENTIALLY MEANINGFUL TEACHING UNIT AND THE CONTEXT OF ITS APPLICATION

The PMTU was applied to 42 secondary school students throughout the school period in a secondary school located in the central area of Rio Grande do Sul. The implementation of the PMTU has occurred during the teaching of the Organic Chemistry discipline, with only 2 hours of classes per week.

We developed the summary of the PMTU in Table 1, there was a further deepening of the subject for each type of stereoisomers and was followed by an

individual summative assessment. All tasks were carried out through the Google Classroom platform.

Table 1

PMTU Synthesis - Stereoisomers in Medicinal Plants

Class	PMTU stage	Strategy/ Resources used
1	Presentation of the PMTU proposal Initial Situation	Investigative questionnaire via *Google Forms* regarding habits and knowledge in relation to the theme. *Google Meet* discussion of excerpts fro*m* the documentary "Nem santas nem do diabo: O potencial inexplorado das plantas medicinais." ("Neither saints nor the devil: The unexplored potential of medicinal plants.")
2	Initial problem situation I Deepening the content *isomers cis-trans, E, Z* New problem-situation I	Form via *Google Forms* for Interpretation of structural formulas in traces of diastereoisomer pairs present in plants. Synchronous class via *Google Meet with* theoretical exposure of content with the aid of slides and molecular models. Form via *Google Forms* for new interpretation of structures in dashes.
3	Initial problem situation II Deepening of content - enantiomers New problem situation II	Form via *Google Forms* for interpretation of simplified structural formulas of pairs of enantiomers present in Medicinal Plants. Synchronous class via *Google Meet Theoretical* content exhibition with the aid of slides and molecular models. Assembly and visualization of enantiomer molecules in 3D, in the *Molecular Constructor application.*
4	Final integrative class Learning assessment in the OPS	Synchronous class via *Google Meet with synthesis* of themes, models and concepts, elaborated in LIFO. Conceptual map making using the *Cmap* Cloud online *tool.*
5	Individual so do back evaluation Assessment of the PMTU itself	Test evaluation with exercises of/ or adapted from selective processes using *Google Forms.* Questionnaire application via *Google Forms.*

Source: Own Authorship (2020).

RESULTS AND DISCUSSION

Whereas the assessment of students' learning along the PMTU application implies the usage of several instruments, the following section merely presents a summary of the outcomes achieved in each of its stages, intending to provide a concise overview of the data.

a) Introduction to the PMTU proposal: a questionnaire (Table 2) was conducted focusing on student's habits as well as previous knowledge regarding the usage of medicinal plants, the objective consisted mainly of identifying any potential subsumption and assessing their need to use a previous organizer. The questionnaire was applied synchronously via GForms (Google's online forms environment), and the questionnaire link was provided during the synchronously scheduled video class via Google Meets and was attended by 42 students over sessions that took up approximately 25 minutes.

Table 2

Investigative Questionnaire

Questions used in the Initial Questionnaire
1) In your family environment do you usually use plants for the purpose of treating symptoms and/or health problems?
☐Never ☐Rarely ☐Sometimes ☐ Often ☐Always
2) In your family environment do you usually buy herbal medicines (herbal)?
☐Never ☐Rarely ☐Sometimes ☐Often Always ☐
3) Do you consider medicinal plants as reliable sources of health treatments?
☐I do not consider it partly to ☐consider ☐Other, justify _____
4) Among the plants below, mark those that you know and/or have used and describe their usefulness for health:
◦ Lemon Grass, ◦ Lemon Balm, ◦ Anise, ◦ Star anise, ◦ Cinnamon, ◦ Clove, ◦ Boldo, ◦ Mint, ◦ Eucalyptus, ◦ Lemon/Orange. ◦ Lavender. ◦ Basil
5) Do you know anyone who is busy cultivating, preparing or indicating the use of medicinal plants?
6) About question 5), explain, comment or report what this person does:
7) In your opinion, what is the relationship between scientific, chemical and pharmacological knowledge and popular knowledge related to medicinal plants?

Source: Own Authorship (2020).

Regarding their questionnaire responses, there were only 08 students stated that they rarely ever make use of medicinal plants, whereas 01 students declared having a lack of trust concerning the utilization of medicinal plants for medicinal purposes. Among the mentioned plants, the most commonly reported were the following: Boldo, citrus plants (such as orange and lemon), mint, and cinnamon. Furthermore, 29 of them stated that they had never known anyone whose occupation had to do either with growing, processing, or prescribing the use of medicinal plants, a sign which indicates a lack of valorization of the popular knowledge related to the use of natural therapies. When asked about what kind of people possess knowledge concerning the use of natural medicine resources, most students claimed that the majority of those who were familiar with such resources usually consisted mainly of elderly women. In most of the cases, the students drew up complementary correlations between popular knowledge and scientific knowledge. The outcome of this analysis provided a baseline for the remaining steps of the PMTU.

b) Starting situation: It was shown a documentary film produced by Universidade Federal de São Paulo, UNIFESP, which was entitled “Nem santas nem do diabo: O potencial inexplorado das plantas medicinais” (Neither holy nor the Devil: The untapped potential of medicinal plants, available on Youtube (2019). The documentary addresses both social and environmental issues in an attempt to help the students manifest their previous knowledge. This documentary was chosen for its wide coverage within the Brazilian context, thus supporting the subsequent progressive differentiation of concepts. After presenting parts of the documentary, synchronously via Google Meets, a brief discussion was held based on the major topics addressed, raising several questions that guided to answer some of the alternative conceptions that were previously expressed. During the discussion, they addressed questions related to Brazilian pharmacological studies, and also Brazilian unknown potential of species belonging to the national flora. Moreover, there was also an opportunity to share both educational and personal life experiences regarding the subject of medicinal plants. The whole activity had an approximate duration of 30 minutes.

c) Initial Problem-Situation: To introduce the study subject (diastereomers), the initial problem-situation (Figure 1) was conducted via an online questionnaire through GForms synchronously, a time of approximately 20 minutes was assigned to complete the task. The aim was to assess each student's previous knowledge as well as their capacity to interpret structural formulae using two-dimensional visualization. The students were introduced to the two-dimensional structural formula of citral's cis/trans isomers, which is one of the active ingredient found in lemon grass and lemon balm, which have anti-inflammatory and anxiolytic action, with the anti-inflammatory effect being more pronounced in the neral isomer. The aim was to spark their chemical interpretation regarding the molecular structures and their respective biological activities starting by investigating some concepts as well as some propositions related to the subject, such as connectivity, spatial configuration, spatial conformation, and nomenclature. The figures corresponding to this and other problem situations presented below present texts written in Portuguese, as they are excerpts from the page of the proposed form, and for this reason, their texts are described in the body of the chapter.

Figure 1

Initial problem situation I - diastereoisomers

Source: Own Authorship (2020).

To analyze their answers, all of the 40 valid responses were organized via a Google Docs spreadsheet, which was linked to the survey mentioned above. Out of the total amount of students, there were 37 students who could solve the situation by mentioning some aspects related to the molecular structure (for instance, the difference between the different isomers is based on the fact that one carbonic chair is “more open” while the other is “more closed”, which is an attempt to establish a correlation between their previous knowledge about carbonic chains classification); there were also 2 students who wrongly linked the molecular structure and the image of the plant, a macroscopic characteristic. The answers were subcategorized according to specific aspects of connectivity (n = 11) and configuration (n = 19).

When it comes to the nomenclature, there were 19 students who affirmed that both of them had the same name, although there were 10 who claimed that the two structures had different names, which is incorrect since each chemical compound does have a specific name and the chemical aspects are already taken into account in the nomenclature of the compound.

d) Delving into the subject: This phase was meant as an introduction to scientific concepts for the students, which at first involved broader questions, and subsequently addressing concrete and more specific subjects (progressive

differentiation). Using an expository lecture, it was presented a contextualization regarding the diastereoisomeric properties that can be found among many species of medicinal plants. Activities were conducted synchronously through the Google Meet platform and relied upon tools such as presentation slides, devised models, and sample kits, all of which were meant to simplify and facilitate structures' visualization in three dimensions as well as the comprehension concerning cis/trans nomenclatures systems. This activity had an approximate duration of 20 minutes.

e) New situation - problem I: To assess both progressive differentiation and integrative reconciliation concerning the most relevant discussed topics, it became clear the need to establish a correlation between the previously discussed concepts with new examples. Therefore, we requested the interpretation of the newly presented structural simplified formulas from diastereoisomers found in medicinal plants (Figure 2). At this stage, the isomers analyzed were the *E/Z* isomers of eugenol, present in laurel, cloves, and boldo, and which has antioxidant, analgesic, and antimicrobial activity, used, among other applications, in dental treatments. High concentrations have neurotoxic effects, and biological activities are found in the mixture of isomers.

Figure 2

New situation - problem I - diastereoisomers

Source: Own Authorship (2020).

Through this new problem situation, it was possible to ascertain students' integrative reconciliation, as they could now manage to identify different structures according to the *E/Z* and *cis/trans* nomenclature system, which evidenced both the development of concepts related to nomenclature as well as their ability to identify formulas based on a two-dimensional (2D) visualization.

f) Initial problem situation II: The first step was to bring up the subject of enantiomers and to associate it with previously studied concepts, seeking to achieve progressive differentiation as well as integrative reconciliation. The application was intended to denote commonalities and dissimilarities when comparing the molecular structures (Figure 3), as well as encourage further reflection concerning the distinct biological activities. The molecules used for the analysis were the *R/S* isomers of citronellal, an active ingredient present in eucalyptus, mint, and cinnamon, which has antifungal and antioxidant properties.

Figure 3

Initial problem situation II - enantiomers

Source: Own Authorship (2020).

The problem-solving activity had been made accessible through a link that was sent in the chat of the Google Meet platform at the beginning of the 4th lesson and had been answered by 38 students. The duration of the whole activity was about 30 minutes, with a gap of 18 minutes separating the first and the last response. Overall, 27 students were declaring that both structures presented were distinct; on the other hand, 11 students declared that both structures were different representations of the same molecule. Also, there were 17 students who were able to identify that the difference between the two molecules consisted in the spatial orientation on one of the ligands relying only on the previous knowledge about how bonds are represented in the tetrahedral carbon (on the plane, ahead, and behind the plane).

g) Further exploration on content: To point out similarities and differences with regard to previous situations or examples, as well as provide additional examples

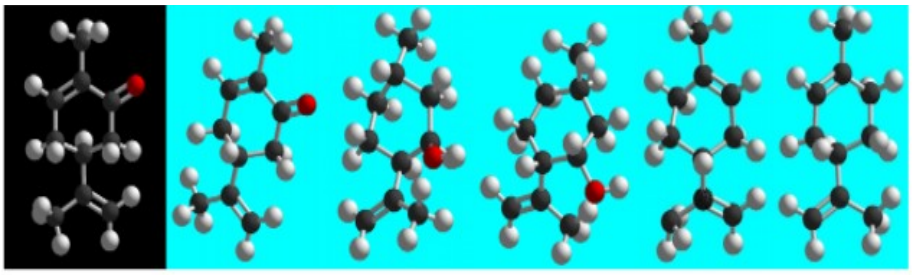
and, thus, foster the broadening of students' cognitive structure, there was also a second expository class, in which we provided a contextualization regarding stereoisomers of medicinal plants as well as molecular enantiomers through the use of didactical resources such as slides presentation as well as molecular models.

The intention here was to develop the ability to use spatial visualization in three dimensions. The explanation was conducted synchronously via the Google Meets platform, which was approximately 20 minutes long.

h) New situation - problem II: To dig evidence on how meanings with deeper levels of complexity were constructed by the students, referring to three-dimensional representations, a collaborative activity was carried out with the mediation of the teacher. To foster teamwork, we provided several representations showing the enantiomeric structures of different compounds: carvone, limonene, and menthol. The students were given the responsibility of assembling and visualizing a pair of enantiomers in three dimensions using a mobile phone application named “Molecular Constructor”. They were asked to complete the activity asynchronously. Also, a step-by-step guide on how to use the application has been prepared and made available on the class board. After assembling the molecules, all students had to save and attach their files to the workspace which was created inside the Google Classroom platform (a few samples of their work can be seen in Figure 4.

Figure 4

Enantiomers mounted with the Molecular Constructor app



Source: Own Authorship (2020).

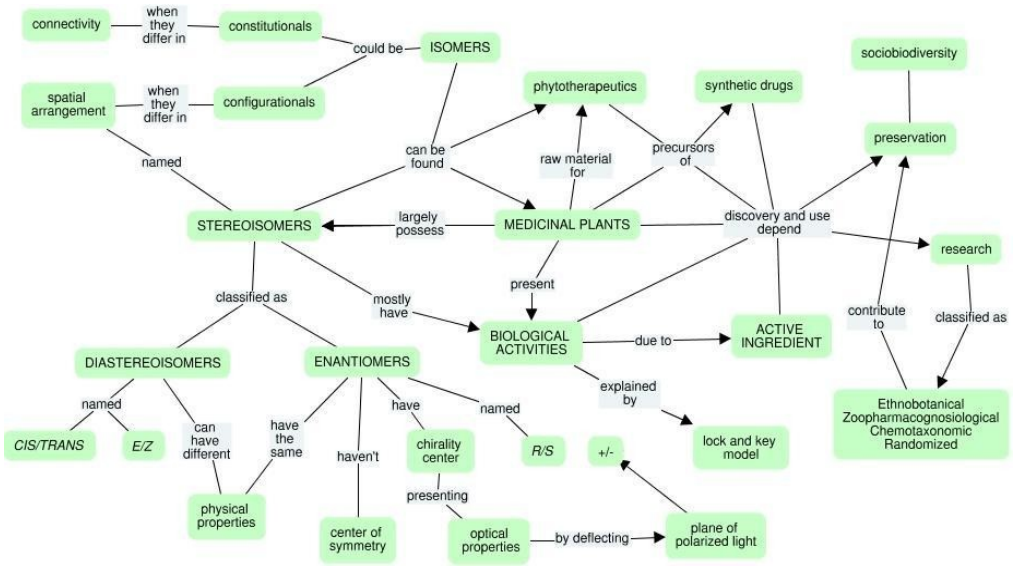
To use the application, it was necessary to provide asynchronous support since the students showed certain difficulties due to the frequent exchange of knowledge and perceptions, not to mention their difficulty in realizing if they were drawing the same structure but from different angles. Another difficulty was that when they were drawing enantiomers, some of the students had to develop a better spatial vision. The use of concrete models, such as illustrations, animations, modeling, and simulations, was able to help with the difficulties in visualizing molecular structures on a three-dimensional spatial plane which, therefore, would ease the solving process of issues involving stereochemistry. It is well known that spatial vision skills have been considered as the main issue concerning learning involving this field of organic chemistry studies (Habraken, 1996; WU; SHAH, 2004). Besides the issues related to visualization, there is a need for the transition between levels of representation, such as the macroscopic, microscopic, and symbolic (Johnstone, 1991). Moreover, it can be

noticed a deficit concerning previous knowledge which are required to completely comprehend the field, preceding issues related to the visualization in three-dimensional space (Raupp et al, 2020).

i) Concluding summative lesson: To summarize all the theoretical concepts developed along the process, we used an integrative reconciliation activity in the concluding summative lesson. Through reviewing each activity and submitting formative assessments it was shown the convergence among the previously discussed concepts. After the integration of the subjects, which was accomplished through the use of slides as well as molecular models, the students were then assigned an individual task involving the elaboration of a concept map that would allow them to assess the occurrence of progressive differentiation and integrative reconciliation processes. The use of concept maps enables the learner to build and rebuild their conceptual relationships, to harmoniously incorporate newly emerging meanings in conjunction with existing ones (Moreira, 1998). In Figure 5 an example of one concept map is shown. The concept map provides clear evidence of meaningful learning concerning the concepts addressed since it promotes the aggregation of structural concepts (at the microscopic level), chemical function, and biological activity, in addition to biodiversity elements.

Figure 5

Conceptual Map on Stereoisomers and Medicinal Plants



Source: Own Authorship (2020).

Students were asked to divide themselves into groups of up to 3 members so that they could perform the task of building their concept maps. The activity was performed asynchronously and had a deadline of two weeks. A Google Classroom activity was opened for submitting their maps, and it was recommended that they send their maps as images. It was also recommended that they use the free online tool called "CmapCloud", which was specifically developed for the arrangement and organization of conceptual maps. Some groups chose to use other online resources with which they were already familiar, such as the

websites http://www.mindmaister.com/pt and http://www.goconqr.com/pt-BR, to develop their concept maps.

k) Assessment of learning in PMTU: Intending to gather clear evidence of meaningful learning regarding the subject, and also concepts associated with stereoisomery, the assessment was performed in a procedural perspective and, hence, was developed according to the logs generated during the PMTU and also based on observations formulated towards an end of the PMTU. In addition to building the concept map, as a final evaluation, there was also an individual summative evaluation, which was performed as test, to assess the achievement of learning objectives. All in all, it included 15 questions about stereoisomerism, with 14 objective questions and one descriptive question. The application took place in the last class planned for the PMTU, it was done synchronously and had a duration of approximately 60 minutes. However, there were 4 students who were unable to finish the test during the stipulated time, therefore the test form was available for 2 more days after the synchronous application. In total, 30 valid responses were collected, of which 19 students achieved an average grade higher than 70%.

l) Evaluation of the PMTU: To conclude, an individual questionnaire was made available through the Google Classroom platform using the Google Forms tool, which presented Likert scale questions and open questions, regarding the PMTU teaching methodology. The evaluation of PMTU from the student's perspective may identify gaps in teachers' mediation work, in addition to enabling the autonomous development of students by promoting an environment in which they have the freedom to express themselves. According to the feedback, the students were satisfied when meeting the challenge of assembling the enantiomeric pairs. Developing the concept map was also pointed out by the students as an important activity. Some students considered the subject matter as motivating. The main negative evaluation about the PMTU was related to the usage of the forms containing the initial problem situations, the students claimed to feel uncomfortable being asked to answer questions before learning the content, besides this point it was also reported to be annoying having to answer many forms during the teaching unit.

FINAL CONSIDERATIONS

The Potentially Meaningful Teaching Unit, PMTU, which was developed in a remote context through the Google Classroom platform and its resources, presented activities with the potential to promote an expansion in the cognitive structure of learners when dealing with the subject of stereoisomerism and the subjects of medicinal plants as well as their biological activities in connection with scientific knowledge and popular knowledge. These activities were developed with different resources and types of evaluations, approached different medicinal plants, and used molecular spatial representations in two-dimensional and three-dimensional views of the active ingredients, as well as their stereoisomeric characteristics. The activity developed with the free application called "Molecular Constructor" proved to be an important teaching resource in solving problems involving visualization in three dimensions. The activities as a whole connect the three levels of representation related to the study of chemistry: the symbolic

level, through the analysis of simplified structural and molecular formulas; the microscopic level, by working with three-dimensional structures; and the macroscopic level through the relationship between molecules and their different biological activities. Finally, the concept map-building activity challenged the students to organize, relate, and deepen the concepts worked on through the use of online tools, such as the "Cmap Cloud" software.

After reviewing the entire paper, it can be argued that despite the challenges posed by the sudden transition to a remote teaching model, the carefully designed PMTU enabled meaningful learning of stereochemistry concepts by students. The strategically selected resources and activities consistently activated students' prior knowledge and pushed them to engage with the content in a deep, connected fashion. The initial questionnaire and documentary served as effective advance organizers, providing a familiar context of medicinal plants upon which students could anchor new scientific ideas. Successive tasks like interpreting isomer structures, building 3D models, and creating concept maps required students to progressively differentiate their understanding of stereochemistry and reconcile any misconceptions. Rather than simply memorizing facts, learners had to grapple with how these concepts applied to the real-world context introduced upfront and construct their organizational frameworks for the knowledge, evidenced by the creative connections displayed in their concept maps. Student reflections further emphasized their awareness of these meaningful learning processes at work.

Thus, while certainly not without difficulty, the PMTU in its adapted remote form nevertheless enabled students to achieve a meaningful, transferable understanding of core stereochemistry principles grounded in their existing cognitive structures. The diversity of languages used to develop activities that involved problem-solving, open and closed questions, molecular modeling, and relationships between different concepts and areas of knowledge in the preparation of concept maps, denote processes associated with meaningful learning such as progressive differentiation, integrative reconciliation, creative thinking, relationships between different levels and areas of knowledge. Even in the context of emergency remote teaching, there was active participation from students, who reported the experience of learning through error as a possibility seen from the PMTU, as well as the importance of the conceptual map for successive integrative reconciliations and progressive differentiations, in addition to narrating satisfaction when achieving the challenge of assembling enantiomeric pairs. The adaptation demanded from the researchers the careful selection of technological teaching resources, and also the appropriation of their use. Considering that all these resources, as well as the Google Classroom VLE, can be used in all educational modalities, it is expected that the PMTU proposal will be a contribution for teachers and researchers who wish to adopt this strategy, both for other content through the use of other themes equally relevant for the meaningful learning of scientific concepts, especially in moments where presential classes can't be held, like during the global COVID-19 pandemic.

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