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Scientific articles

Aplicación de la metodología del ABP en el tema de genética de poblaciones

Application of the PBL methodology in the topic of population genetics

Aplicação da metodologia PBL no tema de genética de populações

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Resumen

A lo largo de más de 10 generaciones, profesores de la licenciatura en biología de la Facultad de Ciencias de la UNAM han observado un rendimiento consistentemente bajo entre sus estudiantes, en el tema de "Genética de poblaciones" (GP), de la asignatura de genética, particularmente en la asimilación y apropiación de conocimientos y habilidades. Se planteó que estos resultados podrían deberse a un estilo de enseñanza eminentemente mecanicista que no genera una reflexión profunda de los temas centrales de la asignatura, esto planteó la interrogante: ¿la aplicación de una estrategia didáctica basada en el Aprendizaje Basado en Problemas (ABP) podría mejorar los aprendizajes esperados y desarrollar habilidades, principalmente las de pensamiento crítico en este tema?

Dados estos antecedentes, se realizó una investigación cuasi-experimental con la participación de 102 estudiantes, distribuidos en dos grupos: 43 estudiantes que cursaron el tema bajo un esquema de enseñanza tradicional, mientras que 59 lo hicieron desde un enfoque didáctico basado en el ABP, por equipos. A estos equipos, formados aleatoriamente, se les encomendaron actividades relacionadas con la interacción biológica entre anemia y malaria en las regiones de Asia y África. Los resultados de aprendizaje obtenidos, luego de las evaluaciones aplicadas a los estudiantes, mostraron que el ABP fue eficaz para mejorar sustancialmente su rendimiento, así como sus habilidades de pensamiento crítico, mientras que el grupo que siguió un modelo de enseñanza tradicional mostró grandes dificultades en las etapas más complejas del tema.

Palabras clave: Aprendizaje activo, Aprendizaje basado en problemas, Enseñanza, Genética, Innovación pedagógica, Pensamiento crítico.

Abstract

Throughout more than 10 generations, professors of the undergraduate degree in biology at the Sciences School of the National Autonomous University of México (UNAM) have observed a consistently low performance among their students, in the subject of "Population Genetics" (PG), as part of the genetics course, particularly in the assimilation and appropriation of knowledge and skills. It was suggested that these results could be due to an eminently mechanistic teaching style that does not generate a deep reflection of the central themes of the subject, this raised the question: could the application of a didactic strategy based on Problem-Based Learning (PBL) improve the expected learning and develop skills, mainly critical thinking skills in this subject?

Given this background, quasi-experimental research was carried out with the participation of 102 students, distributed in two groups: 43 students studied the subject under a traditional teaching scheme. At the same time, 59 did it from a didactic approach based on PBL, by teams. These teams, formed randomly, were assigned activities related to the biological interaction between anemia and malaria in the Asian and African regions. The learning results obtained, after the evaluations applied to the students, showed that PBL was effective in substantially improving their performance, as well as their critical thinking skills, while the group that followed a traditional teaching model showed great difficulties in the more complex stages of the subject.

Keywords: Activity learning, Problem-based learning, Teaching, Genetics, Teaching method innovations, Critical thinking.

Resumo

Há mais de 10 gerações, os professores do curso de biologia da Faculdade de Ciências da UNAM observam um desempenho consistentemente baixo entre seus alunos na disciplina de “Genética de Populações” (GP), na disciplina de genética, particularmente na assimilação e apropriação de conhecimento e habilidades. Foi sugerido que esses resultados podem ser devidos a um estilo de ensino eminentemente mecanicista que não gera uma reflexão profunda sobre os temas centrais da disciplina, o que levantou a questão: a aplicação de uma estratégia de ensino baseada na Aprendizagem Baseada em Problemas (ABP) poderia melhorar o aprendizado esperado e desenvolver habilidades, principalmente de pensamento crítico sobre esse tópico?

Diante deste contexto, foi realizada uma pesquisa quase experimental com a participação de 102 alunos, distribuídos em dois grupos: 43 alunos que estudaram a disciplina sob um esquema de ensino tradicional, enquanto 59 o fizeram a partir de uma abordagem didática baseada no PBL, por equipes. Essas equipes formadas aleatoriamente foram encarregadas de atividades relacionadas à interação biológica entre anemia e malária nas regiões da Ásia e da África. Os resultados de aprendizagem obtidos, após as avaliações aplicadas aos alunos, mostraram que o PBL foi eficaz em melhorar substancialmente o seu desempenho, bem como as suas capacidades de pensamento crítico, enquanto o grupo que seguiu um modelo de ensino tradicional demonstrou grandes dificuldades nas etapas mais complexas do ensino.

Palavras-chave: Aprendizagem ativa, Aprendizagem baseada em problemas, Ensino, Genética, Inovação pedagógica, Pensamento crítico.

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Introduction

The current training requirements for professionals imply a comprehensive education, in which students are prepared to face the new demands of the working world. In this framework, the aim is to promote the development of different capacities, skills, and aptitudes of human beings (Luy-Montejo, 2019) in the transmission of knowledge. Currently, it is necessary for students to acquire significant learning that allows them to develop as individuals with the capacity for analysis, reasoning, and decision-making, as well as to create a link with the world around them to propose solutions to current problems (Corbacho & De, 2009).

Teaching science at all educational levels is a challenge, as it often relies on traditional, merely expository models, in which the teacher transmits knowledge in a categorical and univocal manner, and in which knowledge is not related to aspects of the student's daily lives, so it becomes abstract and barely linked to meaningful experiences. This type of teaching often causes students to lack motivation and interest in the subject, and to develop a low level of analysis and critical thinking (Martínez & Ibáñez, 2006; Corbacho & De, 2009). Taking the above into consideration, it is necessary to improve science teaching strategies to encourage comprehensive development in students, especially in areas where understanding and application of knowledge are required, such as the genetics branch of the biology area. Advances in Genetics have contributed to the understanding of a variety of biological phenomena that impact different areas such as medicine, agriculture, biotechnology, anthropology, ecology, etc.

On this aspect, Iñiguez & Puigcerver (2013) point out:

> Genetics is one of the most difficult and conceptually difficult areas of biology to understand; on the other hand, it is one of the subjects that can motivate students the most, since they can easily find applications in real life.

The topic of “Population Genetics” (hereinafter, PG) is a clear example of what was mentioned by Iñiguez & Puigcerver (2013), in that this branch of genetics is responsible for analyzing and comparing genetic variation between individuals based on the determination of allelic and genotypic frequencies, as well as predicting the genetic variation of said populations over time (Pierce, 2014), so its approach constitutes a mathematical vision of the distribution, as well as the dynamics of alleles and genotypes within and between populations (Hartl & Clark, 2007). Given its abstraction and complexity, PG is a branch of genetics that is particularly difficult for students of different educational levels.

In addition, based on the experience of teachers on this subject, most courses on this topic are taught in a traditional way since the teacher teaches the formulas to do the calculations or the equations of the established laws, and the students limit themselves to copying and applying these formulas. Although the students manage to solve problems similar to those posed by the teacher, this does not imply that they understand the subject in depth or have the opportunity to apply this knowledge to real problems, causing this knowledge to be ephemeral and meaningless.

Given this background, in this work, teachers of the Genetics I subject and a specialist in didactics developed and implemented a teaching strategy based on Problem-Based Learning (PBL) to teach the PG topic from an innovative approach aimed at solving the negative aspects described above. The strategy implemented by the teachers was based on PBL, considered one of the most efficient teaching strategies. This learning-centered instruction method emerged as a response to the disconnection between what was learned in the classroom and the challenges of the workplace, as stated by Paredes-Curin (2016): "One of the advantages of PBL is that it allows students to develop problems that they will have to solve in their future work world, it also allows them to solve complex concepts simply [...] (Guevara, 2010)".

In this work, the use of the PBL strategy was based on confronting the students of the bachelor's degree in biology with a real problem based on the anemia-malaria relationship that will be duly described in the "Methods and Materials" section of this same work.

The objective of this work is to determine whether the implementation of the PBL strategy in the PG subject favored the interest, analytical capacity, critical reasoning, and acquisition of relevant knowledge of the students in this subject, compared to a group of students who were taught the subject in a traditional way (master class).

By carrying out this work, and by comparing the data obtained from the group of students who participated in this new educational experience and the results of the groups that studied the PG topic from a traditional teaching (master class), we seek to elucidate the following question that underpins the purpose of this research: Does the implementation of PBL improve the integration of abstract concepts, meaningful learning and critical thinking compared to traditional methods?

Materials and methods

Study population

This study involved 102 students with an average age of 22 years, who were taking the subject of Genetics I for the first time. They were enrolled in six groups belonging to the fifth semester of the bachelor's degree in biology (plan 1997) of the Faculty of Sciences of the UNAM. In order to compare the effectiveness of the PBL teaching strategy, the population was divided into two randomly selected samples: one in which the PBL strategy was implemented (three groups, with a total of 59 students) and a second sample in which the class was taught in a traditional way on this subject (three groups, with a total of 43 students). The teachers who applied the PBL teaching strategy are professors of the Sciences School who have taught the subject of genetics for more than 20 semesters, under the guidance of a professor specialized in didactics from the Sciences School and with the support of a student of the biology degree from the same Faculty.

PBL and development of critical thinking

Lugo *et al.* (2022) mention that PBL as a teaching methodology is aimed at promoting the development of critical thinking in students. Saiz & Rivas (2008) define critical thinking as: "[The] ability to argue, to pose hypotheses, to make probability judgments, to decide or solve complex problems well," having as fundamental components reasoning, decision-making, and problem-solving.

Following the scheme proposed by Gutiérrez *et al*. (2012), the PBL process is carried out in successive stages, which are detailed below: 1) The problem is presented to the students (this must be motivating enough to arouse their curiosity); 2) A brainstorming session and feedback are held; 3) Clues are identified (clues to understanding the problem); 4) Learning needs are identified (how much they know and what they need to learn); 5) Possible explanations are formulated in the form of hypotheses, and a work plan is made; 6) The student has time for independent study or self-directed learning; and finally, 7) A discussion of the new knowledge is carried out to validate or reject the formulated hypotheses.

Authors such as Vizcarro & Juárez (2008) indicate that there are various techniques used to apply PBL depending on the number of students. However, as Gutiérrez et al. (2012) point out, all the techniques have in common a similar structure that is carried out in successive stages: definition of the problem; formulation of hypothesis; and validation of the hypothesis. They also point out that there are various techniques used to apply PBL depending on the number of students, such as the so-called:

"7 leaps or Maastricht steps" used for a maximum of 20 students, the "4 phases Hong Kong style" for a maximum of 60 students and the "4x4 Alcalá Model" that is applied in groups of between 60 and 130 students. However, as Gutiérrez et al. (2012) point out, all the techniques have in common a similar basic structure with the following components: definition of the problem; formulation of hypothesis; and validation of the hypothesis.

Approach to teaching strategy

The teaching strategy developed for the topic of "Population Genetics" (PG) in the subject of Genetics I is described below, based on the following expected learning outcomes (ELO), included in the subject program:

- Students will understand the methods for calculating the proportion of a genetic variant (allelic frequency) and the incidence of each genotype (genotypic frequency) in a natural population.
- The students apply the Hardy-Weinberg (HW) mathematical model, which helps to estimate whether a population is affected by evolutionary pressures, and based on this determine the allelic and genotypic frequencies in natural populations.

To achieve these expected learning outcomes, in this work a didactic proposal was designed and implemented using the PBL methodology, which allowed for motivating the students' capacity for analysis, deduction, and criticism, through activities that integrate the analysis and application of basic concepts. In this proposal, students were involved in a real problem on the PG topic. To do so, the biological relationship between malaria and sickle cell anemia was used, due to its impact on global health because of high prevalence, morbidity, and lethality.

Malaria is an infectious disease caused by the *Plasmodium* parasite that is transmitted by the bite of female Anopheles mosquitoes. In 2020, it was estimated that there were 241 million cases and 627 thousand deaths caused by malaria worldwide, of which 90% occurred in Africa (World Health Organization [WHO], 2021). On the other hand, sickle cell anemia is a genetic disease that is due to the inheritance of two mutant alleles that cause a malformation of red blood cells.

It is known that heterozygous individuals, who possess one mutant and one regular allele, present some resistance to malaria (Williams & Obaro, 2011) since the life cycle of the parasite that takes place in erythrocytes is affected (World Health Organization [WHO], 2022). Since the highest incidence of malaria occurs in Asia and Africa, these two regions were chosen to develop the educational proposal.

In this context, the PBL proposal consisted of assigning the students the role of World Health Organization (WHO) commissioners to participate as advisors to the regional group for malaria control. As part of the group's functions, they were tasked with analyzing the biological relationship between anemia and malaria to predict the regions that would have a greater probability of *Plasmodium*, which causes malaria, reproducing efficiently and to propose how to allocate the necessary resources over the next five years for the treatment of malaria in these regions.

This proposal has the following considerations:

- The entire sequence has as a common thread the relationship between anemia and malaria, which is a real and motivating context.
- Students take on the role of a WHO commissioner.
- Activities are proposed that promote dialogue, the ability to search for information, collaborative work, and the confrontation of ideas.
- Activities allow feedback between students and teachers, with the aim of reinforcing aspects that were not clear.
- The evaluation of the teaching proposal considers the expected learning outcomes of the students, as well as the level of satisfaction they felt from having participated in the development of a non-conventional learning proposal.

Implementation of the teaching strategy

In the curriculum for the Bachelor's degree in Biology, the subject of genetics is organized into two sessions of three hours each per week, so the syllabus of the subject includes six hours for teaching the subject of genetics. Taking the above into account, the implementation of the teaching strategy was carried out in two sessions of three hours each, divided into two stages corresponding to the implementation of the strategy.

To assess the knowledge acquired by the students, the first part of an additional session was required. It is important to note that the students who did not participate in the implementation of the PBL strategy were taught the PG topic using a traditional expository method; only the activities of the experimental group and not the control group are described.

First stage (session 1)

In the first stage, the objective was for students to understand and calculate allelic and genotypic frequencies in natural populations, and to establish methods for determining them. In this first stage, the subject's teachers presented a general overview of the biological relationship between sickle cell anemia and malaria using a digital resource.

At this particular point, it is worth mentioning that, although PBL stipulates that no *a priori* explanations should be given on the topic, but that all knowledge acquired should be the result of research carried out by the students, it was necessary to offer this explanation since, otherwise, the time available (two sessions of three hours each) for teaching the topic would have been exceeded. This did not limit the students' research autonomy.

The activity carried out by the students was to identify the region's most susceptible to malaria infections based on their relationship with sickle cell anemia using real data on the number of individuals with or without sickle cell anemia from six regions of Manipur, India, modified from Shah *et al*. (2012). To this end, teams of three students were randomly formed, assuming the role of WHO commissioners. Each team investigated, using digital resources, consulting books, articles, etc., how to obtain allelic and genotypic frequencies; they presented them to the group and the most appropriate method for calculating these frequencies was discussed as a group.

From this information and the data provided, each team constructed a ranking table with the results of the calculations of sickle cell anemia allele and genotype frequencies for each region of Manipur. Based on their results, they ranked the regions of Manipur based on the highest probability of malaria, taking into account the frequency of heterozygous sickle cell carriers. Finally, the teams drew a conclusion.

It is worth mentioning that the students who were taught this topic using the traditional classroom method were also asked to write a conclusion, although this activity was carried out as an exercise after class.

First stage evaluation

To conclude the first stage, a peer evaluation of the hierarchy table was carried out, both for the students who received the traditional class and the PBL group; for this, a rubric was used where an evaluation with four items was considered:

a) Table content: The information management that each team used to rank the regions of Manipur was evaluated.

b) Calculations of allelic and genotypic frequencies: the correct implementation of the formulas for obtaining allelic and genotypic frequencies from the data provided was considered.

c) Ranking of regions: The analysis and use of allelic and genotypic frequencies obtained by the students were evaluated, along with their ranking of the regions of Manipur based on anemia.

d) Conclusions: Students determined which region of Manipur was most affected by malaria, considering all the above aspects, allowing teachers to assess whether the learning had been assimilated.

For each of these areas, they were evaluated with four hierarchical levels of performance: notable, good, sufficient, and insufficient. The rubric with the description of each category is shown in Annex 1. The co-evaluation of the table allowed us to establish whether the students adequately calculated the allelic and genotypic frequencies and integrated, analyzed, and organized this information to hierarchize the different regions based on the anemia-malaria relationship.

Second stage (session 2)

In the second stage, corresponding to the second three-hour session, the objective was for students to apply the knowledge acquired in the previous session and use the Hardy-Weinberg (HW) model.

At this stage, the teachers asked the students, in their role as WHO commissioners, to allocate the necessary resources over the next five years for the treatment of malaria in three African countries: Tanzania, Congo, and Nigeria. To do so, they were provided with a map that was adapted from Piel *et al*. (2010) showing the allele frequencies of sickle cell anemia in these countries. The teams then carried out the following activities:

- Each team investigated the HW model to understand the conditions and parameters it uses.
- They discussed how to obtain allele and genotype frequencies with this model.
- The teams applied the HW model to estimate the allelic and genotypic frequencies of sickle cell anemia and based on this establish the populations most vulnerable to malaria, with the aim of allocating the resources destined to combat this disease in African countries.

Finally, at this stage, students were asked to prepare a report in which they allocated and justified the resources allocated to control malaria.

Second stage evaluation

The second stage was evaluated through a report that biologically justified the allocation of resources intended to combat malaria, where the students established their criteria for the allocation of resources. The evaluation considered the following items:

- *General structure of the report and writing* refers to the expository structure used to develop the introduction, methodology, results, and analysis.
- *Methodology is* the part where students had to justify and describe the procedures used.
- *Data and calculations* refer to the management of data and the proper performance of calculations.
- *Results*, consisted of the representation of the results (graphs, tables),
- *Interpretation of the results and conclusions*, where the allocation of resources was taken into account considering the results obtained.

The rubric for the second stage evaluation is shown in Annex 2.

Strategy feedback

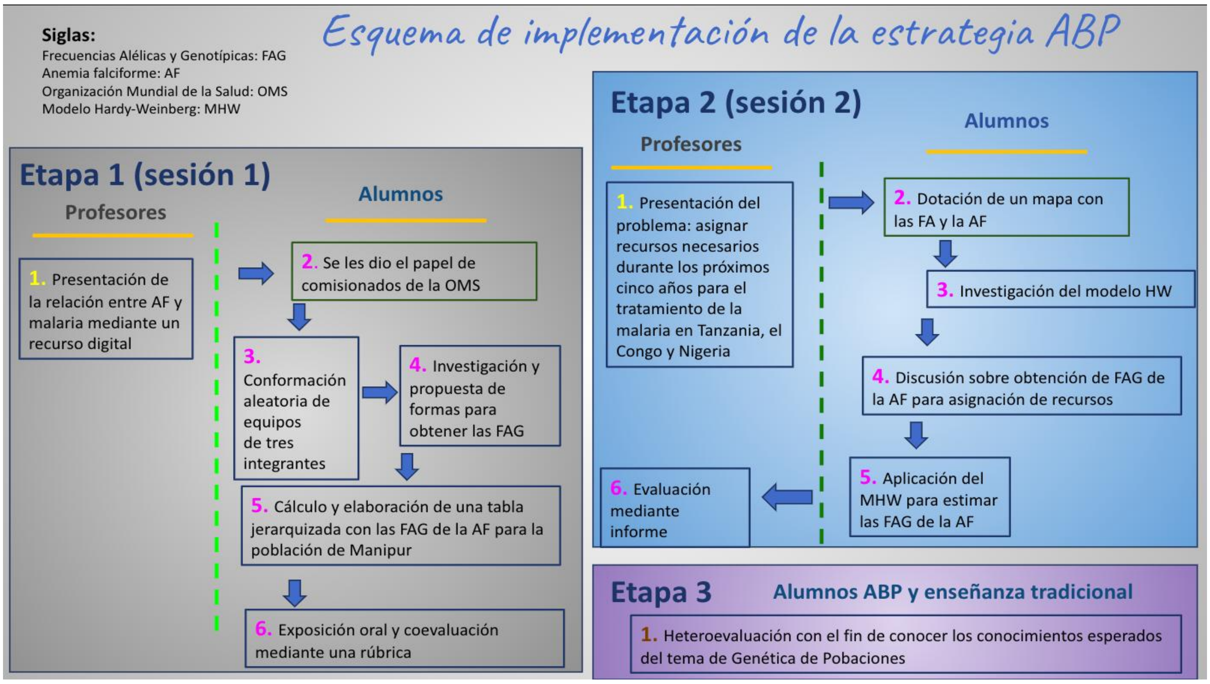
At the end of the second stage, students were asked to write an opinion regarding the strategy implemented for this topic. The comments were categorized based on keywords (pleasant, interesting, attractive, and fun) and classified based on two criteria: activity dynamics and learning obtained.

Knowledge assessment (final)

In order to assess the acquisition of the expected knowledge on the subject of PG, the first minutes of a third session were used to apply a hetero assessment, carried out by the teachers to the students who participated in the PBL strategy, as well as to those in the traditional class. This assessment consisted of five questions that were about knowledge, comprehension, and application (Annex 3), which measured the expected learning. The precision in calculations, the understanding of concepts, and the application of the model provided information about the effectiveness of the PBL teaching strategy in traditional teaching.

Figure 1 shows a summary diagram of the stages, identifying which ones the students who followed the PBL methodology participated in:

Figure 1. PBL strategy implementation scheme



Source: Own elaboration

Results

First stage (session 1)

To determine the effectiveness of the teaching strategy in the first stage, both the students who received the traditional class and those in the PBL group did a peer evaluation using a rubric, which allowed to establish whether the students understood and calculated the allelic and genotypic frequencies adequately, as well as whether they were able to rank the regions of Manipur, India, and draw a conclusion. The frequency of teams for each of the categories is shown in Figure 2 and was different depending on the category evaluated. In the category "content of the table," no differences were found between the teams that received the traditional class and the teams with the PBL strategy.

Figure 2. Team performance by category and area of Co-evaluation

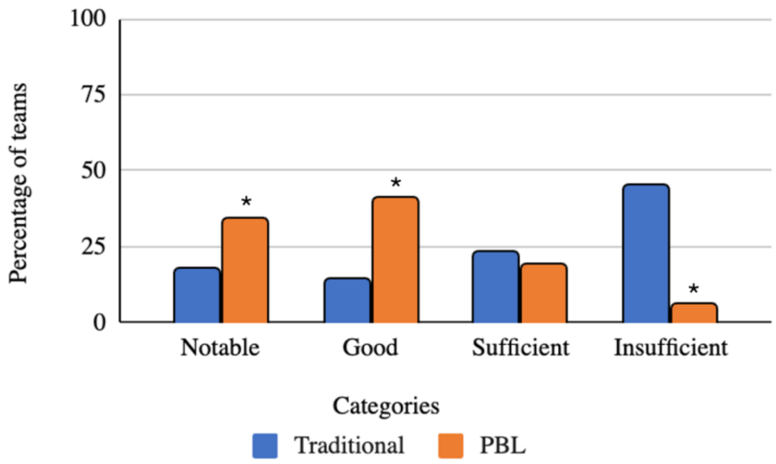
	Content of the table		Calculations of allelic and genotypic frequencies		Regional ranking		Conclusions	
	Tra	PBL	Tra	PBL	Tra	PBL	Tra	PBL
Notable	11	17	8	17	4	11	1	10
Good	7	12	6	12	3	13	1	18
Sufficient	4	3	3	2	5	6	2	4
Insufficient	0	0	5	1	10	2	18	0
Total	22	32	22	32	22	32	22	32

Source: Own elaboration. Tra: Traditional, ABP PBL: Problem-based learning. The data represents the frequency of teams by category of each of the areas considered in the rubric.

For the category "calculations of allelic and genotypic frequencies", it was observed that 23% of the traditional teaching teams were placed in the "insufficient" category, while only 3% of the teams in which PBL was implemented were in this category, such that the strategy contributed to a greater number of students being able to perform the relevant calculations.

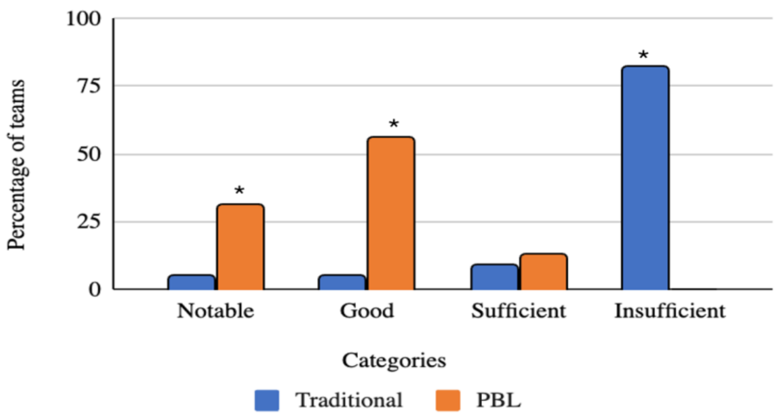
The most obvious differences were observed in the areas of 'regional ranking' (Fig. 3) and 'conclusions' (Fig. 4), where the PBL teams demonstrated a greater capacity to analyze and apply the lessons learned.

Figure 3. Student performance in the ranking of regions in Manipur, India (traditional class vs PBL)



Source: Prepared by the authors. The data represent the percentage (%) of teams in each of the categories of the co-evaluation for the ranking of regions. The asterisk * indicates statistical differences with the z-test of proportions, $p<0.05$

Figure 4. Student performance in the "conclusions" category (traditional class vs. PBL)

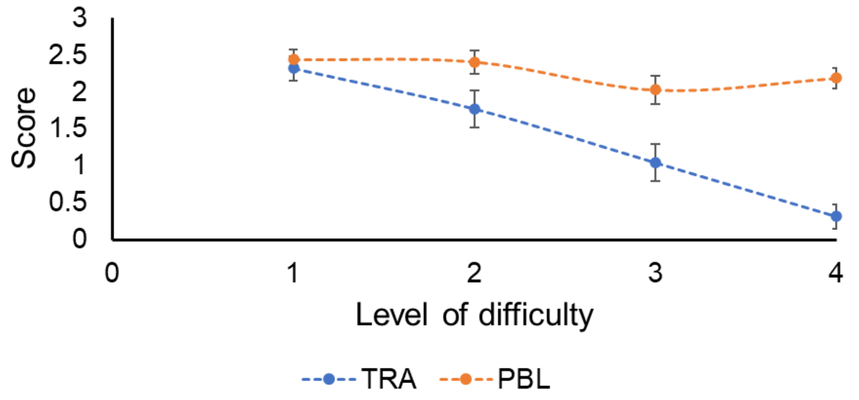


Source: Own elaboration. The data represent the % of teams in each of the categories of the evaluation of the conclusions section. The * indicates statistical differences with the z-test of proportions, $p<0.05$

These results suggest that the PBL methodology encourages a higher level of analysis and application of concepts by involving students in active problem-solving and promoting collaborative work.

Finally, when relating the level of difficulty of each item with the score obtained in the co-evaluation, it is evident that the performance of the students with the PBL strategy was superior to that of those with traditional teaching for the first part of the activity (Fig. 5).

Figure 5. Relationship between the level of difficulty of each subject vs. the score obtained by the groups with the traditional class compared to the PBL strategy



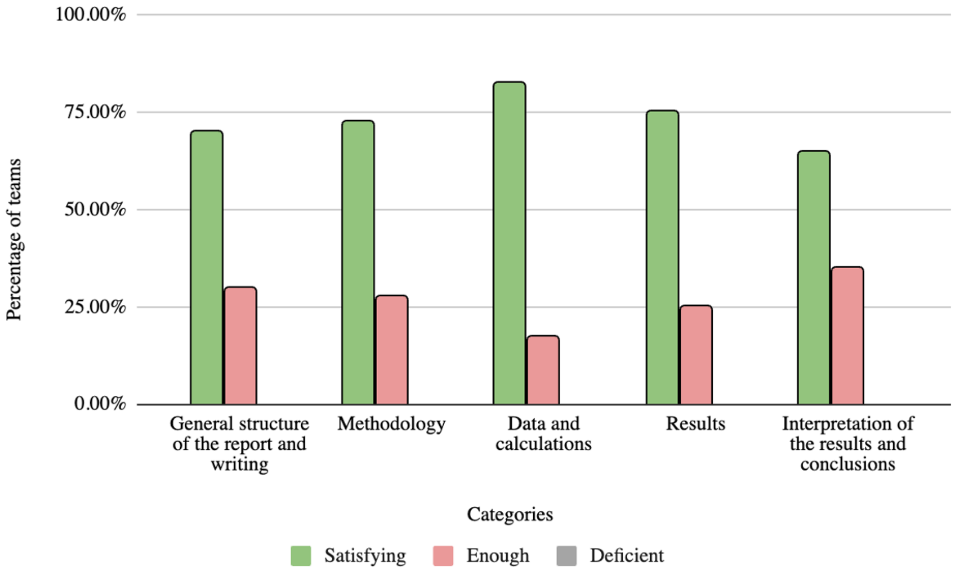
Source: Prepared by the authors. The data represent the average score obtained for each level of difficulty. To obtain this relationship, a level of difficulty was assigned to each item of the co-evaluation (Table content: 1, Calculations of allelic and genotypic frequencies: 2, Ranking of regions: 3 and Conclusions: 4) Tra: Traditional, PBL: Problem-based learning.

Second stage (session 2)

At this stage, the teams, acting as WHO commissioners, prepared a report to determine which African countries should be allocated resources for malaria treatment. The results of the evaluation of this report are shown below, considering each area.

In general, the reports presented a coherent structure, well-justified methodologies, correct calculations, and clear results through the appropriate use of graphs and tables, as shown in Figure 6. Based on the “analysis of results” section, resources to combat malaria were allocated taking into account the results obtained. This shows that the students were able to integrate and apply the knowledge they acquired during the strategy and that it also allowed them to develop their analytical, reasoning, and decision-making skills.

Figure 6. Team performance in the evaluated areas of the final report for resource allocation, prepared by the students who received the PBL strategy



Source: Own elaboration

Student opinions on the PBL strategy

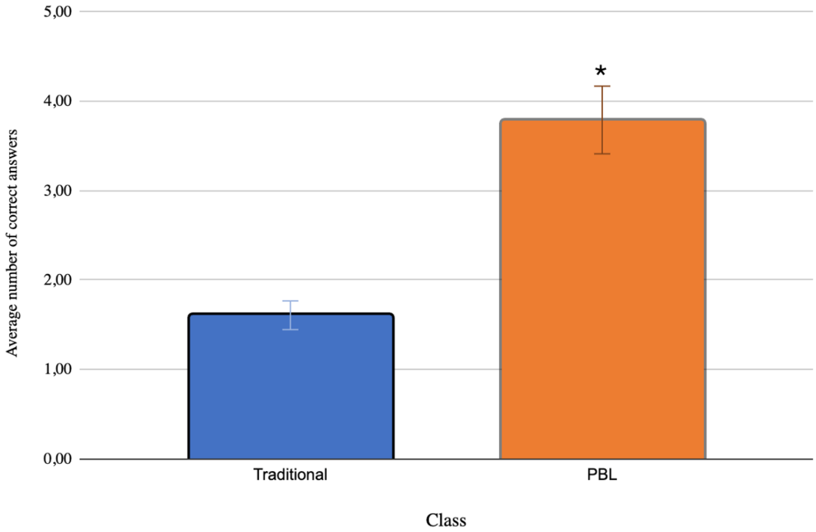
Finally, the students' opinions regarding the PBL strategy applied to the PG topic were open and categorized based on keywords, which were mostly favorable (*93%*). The comments were classified based on two criteria: a) Dynamics of the activity and, b) Learning obtained. Regarding the dynamics, they found it pleasant (*50%*), interesting (*21%*), attractive (*11%*) and fun (*18%*). Regarding the learning obtained criterion, the students considered that the activity allowed them to apply the concepts and knowledge of the PG topic in a real situation (*33%*), as well as to learn the basic concepts and calculations of the topic (*28%*). They also expressed that this dynamic made it easier for them to understand and reinforce concepts of the PG topic (*26%*) and finally, they mentioned that it allowed them to understand this activity (*13%*). These results suggest that the PBL strategy, by promoting active and situational learning, promotes greater participation, understanding of concepts, and connection with real problems in the Population Genetics topic.

Final evaluation

The final assessment consisted of five questions covering theoretical knowledge, practical calculations, and understanding of the Hardy-Weinberg model and its application in population genetics (Annex 3). This assessment was carried out on all 102 students who participated in the PBL class and the traditional class. The difference in performance was statistically significant ($p < 0.05$), confirming the effectiveness of the

PBL strategy compared to the traditional method, as shown in Figure 7.

Figure 7. Comparison of performance in the final evaluation between traditional class and PBL class



Source: Own elaboration. The data show the average number of correct answers obtained by each class. The * indicates statistical differences with the student t-test, $p<0.05$

These results reflect that the PBL strategy promotes deeper and more meaningful learning by involving students in active problem-solving and the application of theoretical concepts in practical contexts.

Discussion

The PG topic, which is part of the 1997 curriculum for the Bachelor's degree in Biology at the UNAM'S School of Science, UNAM, is taught at the end of the course, which usually limits the time dedicated to this topic during classes. This area of genetics is essential for the training of future generations of biologists in Mexico. The goal is for graduates to be able to pose and solve fundamental problems in biology from different points of view, applying their knowledge to solve research problems or problems in other related disciplines (School of Science, n.d.).

The teaching, using a traditional approach, of a subject as complex and abstract in its content as PG, causes learning to be because it does not promote an analysis or understanding of the use of mathematical models for the professional life of students; traditional teaching is limited only to the substitution of data in mathematical formulas and problem-solving without a context that involves students or motivates them to actively participate in their learning; on the other hand, PBL teaching allows for more dynamic and integrative learning. A study carried out by Luy-Montejo (2019), aimed at reviewing whether PBL influences the development of emotional intelligence in university students, confirms that this teaching strategy promotes the integral development of students, enhancing both academic skills and soft skills necessary for their personal, academic and professional success. This suggests that PBL is an effective methodology to improve students' adaptation to the work environment and promote positive coexistence in society.

Compared to students who followed a traditional class, the results of the first stage of this study show that the 59 biology students with bachelor's degrees in biology at UNAM's School of Science who were tested with the PBL strategy performed better. These students not only managed to meet the expected learning outcomes of the PG topic, but they also managed to propose a hierarchy of the regions of Manipur, India; not only that, but they were also able to draw conclusions in accordance with the calculations and analyses they performed. In contrast, the students in the traditional class presented similar responses to each other, without being able to rank the regions or draw conclusions.

These findings are consistent with previous studies such as those by Hurtado & Salvatierra (2020) and Parra *et al*. (2018, p. 665), who reported that students who received PBL-based teaching improved "[...] significantly their academic performance and level of critical thinking", compared to the group of students who were taught the course using a traditional approach.

The study by Cruz *et al.* (2021) reveals that the inclusion of the PBL strategy in the use of Digital Manufacturing (DM) allowed students to address complex problems, stimulate innovation, and collaboration, develop critical skills, as well as highlight the importance of this integration to promote innovative learning experiences and address authentic problems.

In the results of the second stage of our study, it was observed that the group of students in which the PBL strategy was implemented proposed different solutions to the problem posed. The PBL teaching strategy provided students with the ability to consider other factors not specific to biology and that had not been raised by teachers, such as political, economic, social, and geographic factors, highlighting that the group that received the class from a PBL strategy developed critical thinking in the face of the problem posed. Without a doubt, this is a reflection of what Villalobos *et al.* (2016) maintain in relation to the development of critical thinking and self-regulation that emerge in the implementation of educational schemes that encourage students to seek and deduce their own solutions and conclusions.

In this regard, different researchers, including Acosta et al. (2020) and Lugo et al. (2022), agree that PBL encourages the development of critical thinking, "[...] so that students and teachers do not passively accept reality, but instead question themselves, ask questions, investigate, generate ideas and propose solutions to problems." In this sense, Quintero et al. (2017) point out that:

> Critical thinking competency takes on importance in today's society because the worker must achieve knowledge, action, and being. According to Facione (2011), this competency is related to thinking about a specific topic with collaborative and non-competitive development. This process is supported by liberal education since one learns to learn by oneself and in collaboration with others.

In turn, Paredes-Curin (2016) concludes that "[...] students improve their self-learning skills every time they collect information, study, organize and present results, given that PBL allows them to reflect on their successes and errors and improve their learning as they learn and investigate more about the subject."

The assessment instrument in our study showed that students who received the PBL class applied the acquired knowledge better to solve problems on this topic, unlike students who received the traditional class, who failed to obtain a passing grade. The students in the PBL class acquired significant learning on the PG topic since, based on the calculations of allelic and genotypic frequencies, as well as the application of the Hardy-Weinberg mathematical model, they were able to propose a comprehensive solution, thanks to the development of critical thinking. Thanks to this work and the monitoring of the evaluations carried out, it was possible to verify that the students who received the class with the PBL teaching strategy were able to investigate, interpret, analyze, and understand, which coincides with what was indicated by Núñez-López et al. (2017) who in their study point out that: "there was evidence that analysis, reflection, synthesis, interpretation, and inference (typical of critical thinking) are applicable when using the PBL technique."

Despite the overall success of the PBL strategy, we identified some limitations that should be considered in future implementations. In this regard, it was observed that one limitation was the absence of a diagnostic test to identify students' prior knowledge before implementing PBL since with an assessment of this type it would have been possible to identify students who, for one reason or another, had prior knowledge of the subject (repeat test takers, long extras, etc.) and who would have influenced the response to the PBL strategy. However, the number of these cases, according to the historical patterns of enrollment in the subject of genetics, is insignificant and does not directly influence the results obtained.

Teachers consider that another factor is the time to teach the PG topic since it was limited, so it is necessary to adjust the rubric so that each of the sections is more specific and detailed, as well as to make the evaluation process more agile since the PBL methodology is concrete and punctual according to the scheme proposed by Gutiérrez et al. (2012).

To conclude this section, we can state that the results of this study show that Problem-Based Learning not only favors the development of critical and applied skills in complex subjects such as PG but also contributes to the comprehensive training of students, preparing them to face real-world problems from an interdisciplinary approach.

Conclusion

The purpose of this work was to determine whether the implementation of a PBL strategy in the subject of Population Genetics (PG) could help students acquire meaningful learning compared to the traditional teaching of this subject. The application of the PBL teaching strategy in a subject that is difficult for students to understand, such as PG, helped students acquire more significant knowledge, allowed them to integrate and assimilate mathematical concepts that are difficult to abstract, and encouraged the development of their critical thinking.

The strategy used in this work was more effective than traditional teaching since, with the PBL strategy, students were able to structure their responses without the application of mathematics representing complications for them, and they could focus more on solving the problems posed in the strategy, using the formulas and results as tools, not as steps to follow or mechanical procedures to achieve their objectives.

The implementation of the strategy allowed them to meet the learning objectives of the PG topic: calculate allele frequencies, and genotype frequencies and apply the Hardy-Weinberg model through dynamic and attractive activities for students. They were able to integrate previous and new knowledge from a future vision as professionals. This favored the capacity for research, interpretation, and implementation of mathematical tools for solving real problems, and active, collaborative, and significant learning in the groups where the strategy was applied.

Returning to the initial question of this study, related to the effectiveness of PBL in generating meaningful learning and developing critical thinking in students and whether the application of this methodology could be more effective than traditional teaching, we can conclude that, indeed, the PBL strategy was a tool that allowed us to better take advantage of the time limitations to which the PG subject is restricted, as well as significantly improving learning and the development of critical thinking.

Future lines of research

After implementing the educational innovation project based on the Problem-Based Learning (PBL) methodology for teaching Population Genetics (PG), various opportunities arise to investigate its impact and effectiveness in learning and understanding complex concepts.

Firstly, an important action would be to implement a medium or long-term follow-up of the group of students with whom this teaching methodology was implemented, to evaluate the impact on the understanding and application of the concepts learned and the skills acquired.

On the other hand, a comparison could be made between PBL and other innovative or traditional teaching methodologies to evaluate the differences in academic performance, knowledge retention, and student motivation.

Finally, it is proposed to explore and apply other teaching methodologies, such as Case Studies or Challenge-Based Learning (CBL), to diversify teaching strategies and multimedia resources that allow opening avenues to explore new and better formulas that benefit the student learning process.

References

Acosta, A. D., Miyashiro, M. N., & Coronado, D. M. (2020). Bases epistemológicas y metodológicas para el abordaje del pensamiento crítico en la educación peruana. *Revista Inclusiones: Revista de Humanidades y Ciencias Sociales*, *7*(4), 68-87. https://www.revistainclusiones.org/index.php/inclu/article/view/302

Corbacho, V., & De, P. (2009). Enseñanza de la genética en la educación de nivel superior: dificultades para comprender conceptos y resolver problemas. *Enseñanza de las Ciencias*, (Extra), 1020-1023. https://ddd.uab.cat/record/129612

Cruz, R. I., Serrano, C. L., & Rodríguez, B. J. (2021). Modelo de mejoramiento productivo: una aplicación de la fabricación digital incorporada al aprendizaje basado en proyectos (ABP) en la educación superior. *Formación universitaria*, *14*(2), 65-74. https://doi.org/10.4067/S0718-50062021000200065

Facione, P. (2011). Critical Thinking: What it is and why it counts?. http://www.Student.uwa.edu.au/__data/assets/pdf_file/0003/1922502/Critical-Thinking-What-it-is-and-why-it-counts.pdf

Facultad de Ciencias. (s.f.). *Perfil Profesional*. Universidad Nacional Autónoma de

México. https://archive.fciencias.unam.mx/licenciatura/resumen/201

Guevara Mora, G. (2010). Aprendizaje basado en problemas como técnica didáctica para la enseñanza del tema de la recursividad. *InterSedes*, *11*(20). https://revistas.ucr.ac.cr/index.php/intersedes/article/view/1019

Gutiérrez Ávila, J. H., De la Puente Alarcón, G., Martínez González, A. A., & Piña Garza, E. (2012). *Aprendizaje basado en problemas: un camino para aprender a aprender*. Universidad Nacional Autónoma de México, Colegio de Ciencias y Humanidades. https://doi.org/10.22201/cch.9786070239021p.2007

Hartl, D. L., & Clark, A. G. (2007). *Principles of population genetics*. Sinauer and Associates. https://doi.org/10.1093/jhered/esm035

Hurtado Serna, M., & Salvatierra Melgar, Á. (2020). Aplicación del Aprendizaje Basado en Problemas (ABP) de John Barell en la comprensión literal. *Revista Educación*, *44*(2), 67-79. https://doi.org/10.15517/revedu.v44i2.38256

Íñiguez Porras, F. J., & Puigcerver Oliván, M. (2013). Una propuesta didáctica para la enseñanza de la genética en la Educación Secundaria. *Revista Eureka sobre Enseñanza y Divulgación de las Ciencias* *10*(3), 307-327. http://hdl.handle.net/10498/15441

Lugo, J. P., Rossel, Y. O., & Veitía, J. R. (2022). El pensamiento crítico en el contexto universitario: una vertiente del aprendizaje basado en problemas. *Warisata-Revista de Educación*, *4*(10), 34-54. https://doi.org/10.61287/warisata.v4i10.3

Luy-Montejo, C. (2019). El Aprendizaje Basado en Problemas (ABP) en el desarrollo de la inteligencia emocional de estudiantes universitarios *Propósitos y Representaciones*, *7*(2), 353-383. https://doi.org/10.20511/pyr2019.v7n2.288

Martínez Aznar, M. M., & Ibáñez Orcajo, M. T. (2006). Resolver situaciones problemáticas en genética para modificar las actitudes relacionadas con la ciencia. *Enseñanza de las Ciencias*, *24*(2), 193-206. https://doi.org/10.5565/rev/ensciencias.3800

Núñez-López, S., Avila-Palet, J., & Olivares-Olivares, S. (2017). El desarrollo del pensamiento crítico en estudiantes universitarios por medio del Aprendizaje Basado en Problemas. *Revista Iberoamericana de Educación Superior*, *8*(23), 84-103. https://doi.org/10.22201/iisue.20072872e.2017.23.249

Organización Mundial de la Salud [OMS]. (2021). *Informe mundial sobre la malaria 2021, Datos regionales y tendencias*. Organización Mundial de la Salud. https://www.who.int/es/publications/m/item/WHO-UCN-GMP-2021.09

Organización Mundial de la Salud [OMS]. (2022). *Informe mundial sobre la malaria 2022*. Organización Mundial de la Salud.

https://www.who.int/publications/i/item/9789240064898

Paredes-Curin, C. R. (2016). Aprendizaje basado en problemas (ABP): Una estrategia de enseñanza de la educación ambiental, en estudiantes de un liceo municipal de Cañete. *Revista electrónica educare*, *20*(1), 119-144. https://doi.org/10.15359/ree.20-1.6

Parra, D. A. H., Monobe, A. R., & Barceló, V. C. (2018). Aprendizaje basado en problemas como estrategia de aprendizaje activo y su incidencia en el rendimiento académico y pensamiento crítico de estudiantes de medicina. *Revista Complutense de Educación*, *29*(3), 665. https://doi.org/10.5209/RCED.53581

Piel, F. B., Patil, A. P., Howes, R. E., Nyangiri, O. A., Gething, P. W., Williams, T. N., Weatherall, D. J., & Hay, S. I. (2010). Global distribution of the sickle cell gene and geographical confirmation of the malaria hypothesis. *Nature Communications*, *1*(1). https://doi.org/10.1038/ncomms1104

Pierce, B. A. (2014). *Genetics: A conceptual approach*. Macmillan.

Quintero, V. L., Palet, J. E. A., & Olivares, S. L. O. (2017). Desarrollo del pensamiento crítico mediante la aplicación del Aprendizaje Basado en Problemas. *Psicologia Escolar e Educacional*, *21*(1), 65-77. https://doi.org/10.1590/2175-3539201702111072

Saiz, C., & Rivas, S. F. (2008). Evaluación en pensamiento crítico: una propuesta para diferenciar formas de pensar. *Ergo*, *Nueva Época*, 22-23, 25-66. https://www.pensamiento-critico.com/archivos/evaluarpcergodf.pdf

Shah, A., Hussain, R., Fareed, M., & Afzal, M. (2012). Gene frequency of sickle cell trait among Muslim populations in a malarial belt of India, i.e., Manipur. *Egyptian Journal of Medical Human Genetics*, *13*(3), 323-330. https://doi.org/10.1016/j.ejmhg.2012.04.001

Villalobos, V., Ávila, J. & Olivares, S. (2016). Aprendizaje basado en problemas en química y el pensamiento crítico en secundaria. *Revista mexicana de investigación educativa*, *21*(69), 557-581. https://www.comie.org.mx/revista/v2018/rmie/index.php/nrmie/article/view/79

Vizcarro, C., & Juárez, E. (2008). *La metodología del aprendizaje basado en problemas*. Universidad de Murcia. http://www.ub.edu/dikasteia/LIBRO_MURCIA.pdf

Williams, T. N., & Obaro, S. K. (2011). Sickle cell disease and malaria morbidity: a tale with two tails. Trends in Parasitology, 27(7), 315-320. https://www.cell.com/trends/parasitology/abstract/S1471-4922(11)00037-7

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Annexes

Annex 1.

Table 1. Heading: Population genetics project in the regions of Manipur, India. Stage 1 (Session 1)

	SCORE AND PERFORMANCE LEVELS			
	Remarkable	**Good**	**Enough**	**Insufficient**
CATEGORIES	**3**	**2**	**1**	**0**
Information (Table Contents)	Include the requested information in an orderly, clear, and complete manner.	It includes the information in an organized and clear manner but is not complete.	It includes some of the requested information but it is not organized or clear.	Does not include the requested information
Data calculation (About data analysis)	They calculated the genotypic and allelic frequencies correctly	They calculated the genotypic frequencies or allele frequencies	They partially calculated the genotypic and allelic frequencies	They did not calculate the genotypic and allelic frequencies properly
Data management (Integration and prioritization of information)	They analyzed and managed the data appropriately to order the six regions	They analyzed and partially managed the data to order the six regions	They analyzed and manipulated the data enough to order the six regions	They did not analyze and manage the data properly to order the six regions
Conclusions (Conclusions from data analysis)	The conclusions presented are concise and supported based on the results in the table.	The conclusions presented are partially concise and supported based on the results in the table.	The conclusions presented are not very concise and are based on the results of the table.	The conclusions presented are not concise nor supported based on the results in the table.

Source: Own elaboration

Annex 2.

Table 2. Heading: Report from the African regions. Stage 2 (Session 2)

	SCORE AND PERFORMANCE LEVELS		
	Satisfying	**Enough**	**Deficient**
CATEGORIES	**2**	**1**	**0**
General structure of the report and writing (Expository structure to develop the introductory approach, methodology, results, and analysis)	The report has coherence between sections and excellent writing and spelling.	The report is not clear and has spelling and writing errors.	The report has no connection between the sections and poor writing and spelling.
Methodology (Justify and describe the procedures used)	They clearly explain the methodology and justify each step	The explanation of the methodology is imprecise and does not justify all the steps used.	The methodology used does not correspond to the initial approach
Data and calculations (Handling appropriate data and calculations)	Based on the data provided, they perform the relevant calculations in an appropriate manner.	They partially use the data provided and/or perform some calculations incorrectly.	They do not perform the relevant calculations from the data provided
Results (Representation of results)	They use graphs and/or tables to represent their results.	The graphs and tables used are not suitable to represent your results	It does not make any graphical or tabular representation of its results
Interpretation of results and conclusions (Allocation of resources based on results)	Allocation of resources based on the analysis of the results, also taking into account other factors (ethical, environmental, evolutionary, etc.)	Allocation of resources based on analysis of results without taking into account other factors (ethical, environmental, evolutionary, etc.)	Allocation of resources without taking into account the analysis of results or other factors (ethical, environmental, evolutionary, etc.)

Source: Own elaboration

Annex 3.

Figure 8. Final evaluation

Evaluación final genética de poblaciones

Nombre: ____

1. El albinismo ocurre en ciertos nacimientos en una población y se debe a un alelo recesivo, su frecuencia de aparición es de 1 en 14 400 ¿Cuántos individuos se esperan que sean heterocigotos en una población de 10 000 personas?

a) 9834

b) 9916

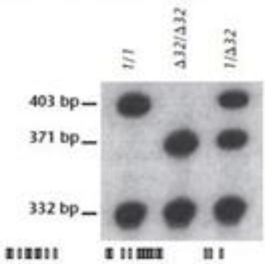
c) 9999

d) 165

2. Una condición anémica en el hombre llamada talasemia está determinada por un par de alelos. El genotipo TM/TM produce una anemia grave (talasemia mayor), el genotipo TM/TN genera una anemia benigna (talasemia menor) y los individuos regulares son TN/TN. En una población se encontró que 4 individuos presentaban talasemia mayor, 400 talasemia menor y 9596 regulares.

¿Cuál es la frecuencia genotípica?

3. La figura muestra una electroforesis en gel de fragmentos de DNA de alelos del gen CCR5 que es receptor del virus VIH-1 de 100 individuos, estos fragmentos fueron obtenidos a través de enzimas de restricción. Cada linea revela un genotipo individual. El alelo 1 de este receptor es silvestre y permite el ingreso del virus a la célula, el mutante ?32 produce una proteina más corta y no funcional del receptor. Individuos con el genotipo 1/ ?32 son susceptibles a la infección del virus y presentan un progreso lento a desarrollar SIDA, individuos con el genotipo ?32 / ?32 son resistentes a la infección del virus. (Modificado de Klug W. S. 2016).



Calcula las frecuencias alélicas de este gen en la población analizada

4. La ley de Hardy-Weimberg describe cómo son afectadas las frecuencias alélicas y genotípicas por la reproducción y los principios mendelianos. ¿Cuál de las siguientes declaraciones corresponde a los supuestos de este modelo?

a) Los individuos sobreviven con la misma probabilidad y hay migración

b) La población es infinitamente grande y la selección natural actúa

c) Las frecuencias alélicas son iguales en la población y la tasa de mutación baja

d) Los cruzamientos en la población son al azar y sin flujo génico

5. La mayoría de los osos americanos son color negro, sin embargo ocasionalmente aparecen osos blancos en ciertas regiones de la Columbia británica, Kermit Ritland y sus colegas determinaron que el color blanco se debe a una mutación recesiva (g), el alelo silvestre es para el color negro (G). Ritland y sus colegas llevaron a cabo un muestreo para determinar la dinámica de esta población de osos americanos. Estos son los resultados:

G/G 42

G/g 24

g/g 21

Con base en estos resultados apoya a esta investigación y determina si la población está o no en equilibrio y que implica para para las futuras generaciones de dicha población de osos.

Source: Own elaboration