MODESTUM EURASIA Journal of Mathematics, Science and Technology Education, 2025, 21(7), em2669
ISSN:1305-8223 (online)
OPEN ACCESS Research Paper https://doi.org/10.29333/ejmste/16606

Improving biology learning in high school with ChatGPT: A case study in Morocco

Soumia Baroud [1*], Mustafa El Alaoui [1], Rachid Janati Idrissi [1], Najat Boucetta [1,2], Ghizlane Ghariz [1], Hakima Seghir [3]

[1] Research team in Pedagogical engineering and science didactics, Higher Normal School of Tetouan Abdelmalek Essaadi University, Tetouan, MOROCCO
[2] Higher Institute of Nursing Professions and Health Techniques of Tétouan, MOROCCO
[3] Mathematics, Informatics, and Pedagogical Engineering Team, Mathematical and Informatics Modeling Laboratory, Higher normal school of meknes, Moulay Ismail University, Meknès, MOROCCO

Received 08 December 2024 ▪ Accepted 07 June 2025

Abstract

Genetics is a fundamental discipline in biology, of interest both in scientific and professional fields. However, concepts such as meiosis can be complicated for students to understand. This study aims to evaluate the effect of ChatGPT on improving the cognitive performance of secondary school students in genetics. To this end, a quasi-experimental design was conducted with second-year baccalaureate students from a high school in Morocco, using a pre- and post-test with two groups. The experimental group (EG) utilized ChatGPT as an innovative pedagogical tool, while the control group (CG) studied using traditional teaching methods. The study showed a significant improvement in the post-test scores of students in the EG, confirming that ChatGPT, when used as a pedagogical technology, enhances the effectiveness of artificial intelligence (AI) in education. It was found that students in the EG demonstrated better cognitive abilities in understanding and solving problems related to genetics compared to those in the CG. This suggests that AI technologies such as ChatGPT can facilitate deeper learning, promote critical thinking, and support complex concept mastery more effectively than traditional approaches. The results of this study can guide future research and educational practices by illustrating how AI technologies can be optimized to enhance student learning outcomes, increase engagement, and address learning challenges in science education. Despite the potential benefits of ChatGPT in the field of education, concerns remain about the risks associated with this technology, raising important ethical questions that require collective reflection to mitigate its dangers.

Keywords: ChatGPT, genetic, technology, meiosis, learning, t-test

INTRODUCTION

Science teaching is important to the country's human, social, and cultural development, as it provides learners - future citizens - with a sense of creativity and scientific ability. For this reason, Morocco is particularly interested in the sciences, especially the biological sciences. One of the most important and recent disciplines in terms of scientific and technical progress is genetics, a discipline currently considered transversal. It finds applications in diverse fields such as agriculture, the pharmaceutical industry, and medicine, and arouses great social interest (Nussbaum et al., 2015). Given the growing importance of genetics in various fields, it is essential to enable secondary school pupils and university students to acquire sufficient knowledge about scientific information. This will help them to understand current issues related to this discipline, such as GMOs, cloning, gene therapy human genome sequencing, etc.) to train highly qualified executives (Silar, 2020).

Several studies in science didactics have shown that Moroccan students face considerable difficulties in learning scientific disciplines, responsible in part for

✉ soumiabaroud1995@gmail.com **(*Correspondence)** ✉ mustafaelalaoui666@gmail.com ✉ rachjanati@yahoo.fr
✉ boucettanajat1970@gmail.com ✉ ghizlanesvt@gmail.co ✉ hakima.seghir8@gmail.com

Contribution to the literature

- It focuses on the role of ChatGPT in helping students' understanding of challenging concepts such as meiosis.
- It examines how ChatGPT improves learning outcomes and academic performance among biology students.
- The integration of ChatGPT into teaching practices significantly contributes to better academic results and increased student engagement, thereby promoting notable progress in learning and academic success.

mediocre academic results and unfavorable attitudes. These difficulties can also quickly put them in a situation of failure or push them to abandon their studies (Alagui et al., 2020). Studies have shown that these difficulties are not only linked to knowledge itself and the representations students and teachers have of science but also to teacher's pedagogical practices (Mathé et al., 2008; Robert & Rogalski, 2002; Séré et al., 1997; Welzel & Haller, 1998). Furthermore, it is necessary to improve the teaching and learning of biological sciences and genetics particularly, in Moroccan schools to produce future citizens who think as scientists and to create an intrinsic meaning to learning.

Previous research have shown that genetics is a difficult discipline for professors to teach and complex for learners to understand and master (Chapel & Marzin, 2009). Many students struggle with genetics due to the intricate concepts and mathematical formulas involved, often requiring additional support to grasp the discipline and succeed in the classroom (Baroud et al., 2022). According to Astolfi (1993), one of the main objectives of teaching biology sciences is to help students acquire the knowledge necessary to understand fundamental concepts, apply these concepts to solve problems, and develop a scientific understanding of their environment and the universe. However, some research indicates that students find it challenging to grasp the fundamental concepts of genetics, including mitosis, meiosis, chromosomes, alleles, the mechanisms of heredity, and Mendelian inheritance (Freidenreich et al., 2011). Based on this research, it seems pertinent to explore effective solutions to minimize learning difficulties across all disciplines, including genetics, and to make Moroccan schools more qualified, efficient, and innovative educational institutions.

One of the reasons most students struggle to understand genetics is its reliance on complex concepts, as mentioned earlier. However, the mechanisms of heredity cannot be fully understood without grasping the meiosis concept. According to Alberts et al. (2007), the meiosis process is fundamental for transmitting genes from parents to offspring, thereby influencing genetic variation and the expression of inherited traits. In other words, a profound comprehension of meiosis is essential for learning and mastering the principles and rules of hereditary transmission. Furthermore, many biology students have misconceptions about meiosis, which is crucial for understanding the basic rules of heredity.

Several studies have stated that technologies have become an essential solution that not only helps students grasp complex concepts but also enables them to apply their knowledge to real-world problems, thereby promoting deeper understanding and retention (Holmes et al., 2019; Kirkwood & Price, 2013; Zawacki-Richter et al., 2019). That makes ChatGPT a potential tool to correct these misconceptions and help to improve the quality of biological education for students in general. It could be utilized for creating interactive learning experiences that engage students and help them better understand biological concepts (Nguyen et al., 2023). Various sectors in Morocco, such as agriculture, health, financial services, and education, have integrated artificial intelligence (AI) (Chouraik, 2024).

Numerous countries have adopted this technology to stimulate innovation and economic development (Adnani & Haounani, 2024). Among the most developed tools, and representing a true revolution, ChatGPT stands out as an AI software used to simplify complex topics, generate ideas, create texts, etc. (Adiguzel, 2023; Dergaa et al., 2024). ChatGPT (generative pre-trained transformer) is a generative AI language model designed to respond to prompts or queries by generating new data (CNPEN, 2023). Recent research shows that the integration of AI into education is still in its early stages. This means that, while these technologies have started to be introduced in educational environments, their use remains relatively new, and their potential has not yet been fully explored or optimized. Studies indicate that AI is still in the early phases of implementation, suggesting that adjustments and improvements will be needed to maximize their effectiveness and impact on learning and teaching (Hwang & Chang, 2021; Smutny & Schreiberova, 2020). Nevertheless, life and earth sciences (LES) education are in an excellent position to study the functionalities of ChatGPT and other AI systems. (AlAbidi et al., 2023; Alneyadi & Wardat, 2023; Bitzenbauer, 2023).

This study examines the use of ChatGPT in secondary schools in Morocco, to improve student learning and achievement in LES. Morocco stands out as a leader in AI, actively seeking to position itself as a recognized global authority. The Moroccan government has officially adopted a strategic initiative to optimize

operational efficiency through AI integration (Adnani & Haounani, 2024). This strategy includes a set of guidelines designed to increase productivity and efficiency in various sectors, improve the quality of public services, and offer new training opportunities for employees (Alnaqbi, 2024; Khan, 2019).

Problem Statement

The characterization of students' difficulties in learning scientific disciplines such as biology, mathematics, physics-chemistry, organic chemistry, etc., has received significant attention to understand the origins and causes and to suggest solutions and remediation strategies (Alibi & Boilevin, 2021; Bouhafs & Karam, 2020; Djarmouni, 2017; Harabi & Kilani, 2019). Studies conducted with students after years of studying biology have shown that genetics is one of the most difficult scientific fields for students at university (Baroud et al., 2022). Nevertheless, students struggle to consolidate their knowledge to master various biological events related to the discipline itself, such as crossover during meiosis, the relationship between phenotypes and genotypes when applying Mendelian rules, chromosomal interpretation, the origin of genetic diversity, etc. (Wynne et al., 2005). These fundamental concepts of genetics are difficult to understand, and they may feel frustrated and demotivated. As a result, they often face difficulties in passing national exams, competitive examinations, and following their university studies (Knippel et al., 2005). This confirms that the teaching of genetics is influenced by transmissive and traditional approaches, such as lectures and textbooks, based on memorization of terms and processes rather than on understanding the fundamental concepts and mechanisms of genetics (Duncan & Reiser, 2007). The challenge, however, lies in developing an innovative and effective method for teaching LES to high school students to improve their academic performance. Morocco's 2015-2030 strategic reform vision aims to create a new, attractive, and useful school that values education for national progress and youth development and seeks to adapt the Moroccan education system to facilitate the direct integration of graduates into working life, particularly in the global professions chosen by Morocco (CSEFRS, 2024). In this sense, integrating advanced technologies such as ChatGPT into education could represent a significant opportunity, and the success of its integration into education depends on several factors (Adnani & Haounani, 2024).

Numerous studies indeed show that applying these technologies in schools faces many obstacles. The application of these technologies to the educational field remains one of the major challenges faced by educational systems, not only in African countries but also in some American and European countries. These obstacles are not solely financial, which hinder the acquisition of technological resources, but also involve other political, economic, technological, and cultural factors that play a role in the integration of ICT in education (Karsenti, 2009).

THEORETICAL FRAMEWORK

Importance of the Study

This study is particularly relevant both in the field of science education and for society as a whole. In academic terms, it contributes to current research into pedagogical innovation, particularly through the integration of AI into teaching practices. In this context, genetics occupies a central place, its teaching at secondary and university level is considered a strategic priority, as it provides students with the fundamental knowledge needed to pursue careers in critical sectors such as medicine, agriculture, biotechnology and environmental sciences. These fields play a decisive role in economic development, public health and global sustainability (Hogan & O'Flaherty, 2021).

Despite its importance, genetics remains a difficult subject for many learners. Research into science education has shown that students encounter significant difficulties, particularly in understanding the process of meiosis, which is essential for understanding the mechanisms of heredity (Knippel et al., 2005). In response to these challenges, the use of innovative educational technologies appears to be a promising approach to improving conceptual understanding. In this context, AI tools such as ChatGPT offer new pedagogical opportunities. Thanks to its ability to interact dynamically with learners, ChatGPT facilitates more personalized learning, stimulates critical thinking and enhances digital skills. It therefore represents a relevant lever to help students master complex concepts such as those related to genetics.

From a societal point of view, this research addresses major issues linked to equity, inclusion and the preparation of younger generations for a world in constant technological evolution. By facilitating access to quality educational resources, including in contexts where educational infrastructures are limited, AI can help reduce educational inequalities and promote more equitable and inclusive education (Holmes et al., 2019). Furthermore, by enabling learners to better understand contemporary scientific and technological challenges, this study contributes to the formation of citizens capable of thoughtfully engaging in public debates on critical issues such as genetics, public health and environmental sustainability (Choden & Kijkuakul, 2020). As a result, it aligns closely with current priorities related to human development, social justice and the transition to a knowledge-based society.

Fundamental Concepts

Meiosis: A key process in genetics

Meiosis is a fundamental process of cell division that leads to the formation of genetically unique gametes, it ensures the halving of the chromosome number, which is essential for sexual reproduction and the stability of the karyotype across generations. Meiosis involves complex mechanisms such as the pairing of homologous chromosomes, genetic recombination (crossing-over), and the independent assortment of chromosomes (Alberts et al., 2002). These three mechanisms are interdependent and essential for ensuring the genetic variability of the sex cells produced through meiosis. They guarantee that each gamete carries a unique combination of alleles, which is fundamental to evolution, individual diversity, and the stability of the genetic heritage from one generation to the next (Jones et al., 2024). Although these concepts are crucial, they remain abstract and difficult for secondary school students to grasp, particularly due to the lack of integration between the molecular, chromosomal, and informational levels of biological understanding. (Brown, 1990). These challenges often give rise to misconceptions, thereby hindering students' comprehension of genetic inheritance and biological diversity.

Educational challenges linked to conceptual abstraction

In Moroccan secondary education, meiosis is introduced as a core topic in the LES curriculum due to its biological importance. Despite the use of standard textbooks and established educational resources, students still face difficulties with the conceptual complexity of meiosis. Many students struggle to visualize the underlying mechanisms and to connect the different organizational levels of biological processes (Bahar et al., 1999). It is therefore essential to explore new teaching approaches that can facilitate students' understanding of this concept. Meiosis must be taught innovatively, integrating pedagogical methods that make abstract processes more concrete and accessible. Technology plays a key role in this approach: the use of digital tools and AI promote a better understanding of complex phenomena and increase student engagement (Danielsson & Linder, 2009; Lin, 2024). Moreover, AI tools offer new perspectives for teaching biology (Kumar, 2023). AI-powered personalized learning platforms can adapt content according to the pace and specific needs of each student, allowing for progressive and targeted understanding (Akhtar et al., 2024). Additionally, educational chatbots can answer students' questions in real time, clarify difficult concepts, and provide supplementary explanations tailored to their level of comprehension (Tong & Zhang, 2023). AI can also analyze students' recurrent mistakes and help teachers design targeted activities to correct misconceptions (Nguyen et al., 2023). By fostering a better integration of the different levels of biological understanding, these methods help strengthen students' analytical skills and critical thinking about genetic diversity and heredity.

ChatGPT as an educational innovation for deeper understanding

In this context, generative AI, particularly ChatGPT, emerges as an innovative pedagogical tool. This language model developed by OpenAI can generate contextualized explanations, simplify complex topics, and interact with learners in a personalized manner. In the framework of this study, a web interface allowed students to engage with ChatGPT by submitting written questions. The responses generated were expressed in accessible language, making the learning experience more engaging and stimulating student curiosity (Adiguzel et al., 2023; Dergaa et al., 2023). ChatGPT can play an important role as a solution to the difficulties students face with meiosis, a biological concept that is often abstract and hard to grasp. By providing clear explanations tailored to each student's level, it helps clarify complex mechanisms such as crossing-over, chromosomal reduction, and gamete formation. Thus, while it does not replace the teacher, ChatGPT effectively complements traditional instruction by offering personalized and interactive support (Bitzenbauer, 2023). It opens new possibilities for deeper and more accessible learning of genetics and cell biology.

Foundations of the Study

Our study is based on the situated cognition theory (SCT), which serves as the central theoretical framework for our research. This theory was proposed by Brown et al. (1989), is based on fundamental principles that emphasize a constructivist approach to learning, where students do not simply consume information but actively construct their knowledge. ChatGPT can play a key role in this process by offering a tool that enables students to create, synthesize, and generate new knowledge, rather than simply receiving information (Abramson, 2023).

Within the SCT framework, collaborative learning and peer interactions are at the core of the educational process (Lave & Wenger, 1991). By facilitating discussions about scientific concepts, especially in biology, ChatGPT fosters a learning environment where students can collaborate, share ideas, and engage in collective reflection on complex topics. For example, ChatGPT can support discussions on topics such as cell division, cell signaling, or gene expression regulation, while encouraging students to apply these concepts to real-world problems (Usak, 2024) and help design meaningful learning activities based on students' real-

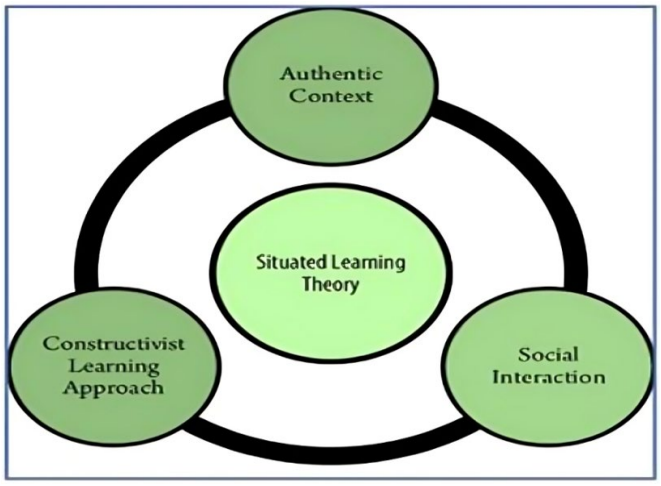

Figure 1. The key element of SCT (Green et al., 2018)

world experiences, thereby maximizing their engagement and motivation to learn (Danielsson & Linder, 2009; Lin, 2024).

In the context of the socio-cultural theory of learning (SCTL), ChatGPT can be considered an effective mediator that facilitates interaction between students and learning content. It provides instant access to a vast range of information and creates opportunities for more personalized and collaborative learning. By allowing students to explore concepts independently while fostering discussions around these concepts, ChatGPT becomes a catalyst for collective thinking and reflection (Ayemele et al., 2024). Thus, ChatGPT is not only a tool for individual learning; it also contributes to the expansion of social and collaborative interactions between students and teachers. By offering a space to ask questions, clarify doubts, and discuss complex concepts, it aligns perfectly with the principles of SCTL. This type of social and intellectual engagement enriches the learning process and allows students to develop beyond their individual capabilities with the support of external resources like ChatGPT. According to the SCTL, the use of innovative tools in education can be seen as a facilitator of interaction between students and knowledge, in line with the principles of social collaboration, guided learning, and cognitive development (Lent, 2008). According to Vygotsky's SCTL, learning occurs through social interaction, with the help of tools and resources, such as language, culture, and external aids, as shown in **Figure 1**.

ChatGPT can thus serve as an external resource that supports the learning process by providing students with instant access to a vast range of information, facilitating the construction of knowledge through interaction with the tool itself and with peers.

However, the study of ChatGPT's potential in education also highlights several limitations that align with concerns raised by SCT. For instance, the accuracy and reliability issues pointed out by Malinka et al. (2023) and Kumar (2023) highlight a challenge in the effectiveness of ChatGPT as a knowledge mediator. In SCT, tools and resources should enhance and scaffold learning; however, inconsistent or incorrect information provided by ChatGPT could disrupt the learning process, especially if students rely solely on this tool as their primary source of knowledge. The variability in responses and the lack of concrete examples can prevent students from engaging in authentic, real-world learning experiences, which is central to Vygotsky's idea of proximal development, where learners are encouraged to interact with content and concepts that challenge them within their zone of development. Moreover, ChatGPT's role as an impersonal mediator may fall short in fostering meaningful social and emotional interactions that are crucial to SCT.

As Bitzenbauer (2023) mentions, AI cannot replace the dynamic interpersonal exchanges between students and teachers, nor replicate the emotional support and contextual understanding provided by human interactions. The absence of this human element limits ChatGPT's ability to fully support the social and emotional aspects of learning, which are integral to the SCT framework. Thus, while ChatGPT can enrich students' cognitive experiences, its use must be thoughtfully integrated into a broader educational context that emphasizes collaborative learning and guided interaction. The suggestion by Sijing and Lan (2018) that ChatGPT should be considered a complementary tool reflects SCTL's emphasis on the teacher's role as a guide and facilitator of learning. Teachers can use ChatGPT to support students' learning journeys while still fostering the necessary social interactions that SCT advocates. In this sense, ChatGPT becomes one of the many tools within a learning environment that relies on human mediation and interaction, ensuring a balance between cognitive development and social learning.

THE CURRENT STATE OF LITERATURE

The Impact of ChatGPT on Student Learning

Given the importance of keeping up with technological evolution, the study of ChatGPT has attracted significant attention recently. In this regard, several research studies have been conducted on the potential abilities of ChatGPT in education, as well as their evaluations and risks. According to Agathokleous et al. (2023), ChatGPT can be a suitable and favorable tool to enhance biology teaching and learning. This technological tool can significantly improve students' understanding by simplifying complex and abstract concepts and facilitating knowledge in general (Jmoula, 2023). It provides pedagogical support for students, enabling them to participate in self-paced learning and effectively meet their educational needs (Holmes & Tuomi, 2022; Qureshi, 2023). In this regard, Gregorcic and Pendrill (2023), and Santos (2023), point out that

students have the opportunity to engage in meaningful discussions about biology using ChatGPT, which elicits a sense of motivation and active participation in the construction of their knowledge, this participation can be beneficial as it encourages the development of critical and constructive thinking of ideas presented by their peers.

Several recent studies have suggested the role of ChatGPT in Vietnamese education, highlighting its strengths, and its potential contribution to educational actors: administrators, teachers, and students (Cao et al., 2023; Truong, 2023; Truong et al., 2023). In this context, a series of studies by Dao et al. (2023) assessed the performance of ChatGPT on the Vietnamese national secondary school graduation exam, which covers subjects such as mathematics, literature, English, physics, chemistry, biology, history, geography, and civic education. The results of these studies indicate that ChatGPT demonstrated general competence in the exam, with an average score of 6-7 for the natural and social science combinations. More specifically, scores were medium in mathematics, physics, chemistry, and biology, while higher scores were achieved in literature, history, geography, and civic education.

In this context, Dao and Le (2023) conducted an in-depth analysis of the effectiveness of LLMs ("ChatGPT, BingChat, and Bard") in the field of education, specifically in biology, to reveal their strengths and limitations. These LLMs analyze massive linguistic datasets and then generate human-form text, thus providing valuable information for their successful integration into educational platforms. The significance of this study lies in its assessment of the LLMs' proficiency at different levels of questioning, namely knowledge, comprehension, application, and higher-level application.

The results of this study reveal that ChatGPT's role is crucial, as it shows potential at multiple levels; the results reveal that the role of ChatGPT is crucial, as it has multi-level potential, but low consistency and reliability in responding to complex application requests, but low consistency and reliability in responses to complex application queries. Bing Chat and Bard perform well, but only in tasks related to memorization and comprehension, which indicates their effectiveness in facilitating basic learning but, on the other hand, they cannot support higher-level cognitive abilities, particularly analysis, synthesis, and application. However, these higher-level cognitive abilities, as established by Bloom, require contextualized activities and active, innovative learning situations that place the student at the center of the teaching-learning process, which appears to positively influence student engagement, as emphasized by Gérard and Rubio (2020).

The Impact of ChatGPT on Students' Academic Performance and Creativity

Currently, concerns have been raised about the impact of ChatGPT on students' academic results and creativity. According to researchers, ChatGPT offers exciting aspects for education by giving quick answers to any questions posed by users, but at the same time challenges to overcome before it can be put into practice in schools. Among these challenges, the tool can generate inaccurate or misleading information, potentially hindering learning (Bitzenbauer, 2023). These assertions corroborate a study by Kumar (2023) on the potential of ChatGPT in the biomedical field, which reveals that the errors observed in students could worsen with the answers provided by ChatGPT. Indeed, significant errors, such as referencing problems, lack of in-depth knowledge, and inappropriate contextualization of the subject, will continue to affect the answers generated by tools such as ChatGPT.

ChatGPT provides explanations on a wide range of topics related to different disciplines and answers students' questions, facilitating access to diverse knowledge compared to the traditional classroom, this availability of enriched resources can stimulate curiosity and actively test their understanding of concepts (Rudolph & Tan, 2023). However, an analysis using ChatGPT to examine future trends in synthetic biology revealed that this model can anticipate these developments, and influence future scientific advances. As a result, ChatGPT could play a key role in guiding research and innovation in this field for years to come (Tong & Zhang, 2023). In summary, when used wisely and ethically, ChatGPT can potentially serve as a valuable cognitive tool in education, enriching knowledge and improving quality of life (Jmoula, 2023).

The Limits of ChatGPT

ChatGPT indeed has strengths in the field of education, but also significant limitations. Some researchers note that excessive use of these tools could undermine the social comprehension of knowledge and learning, and compromise students' critical thinking and creativity, as well as, that continuous use of ChatGPT for studies can develop laziness in students and weaken their cognitive competencies (Yilmaz & Yilmaz, 2023). With this in mind, Chan et al. (2023) reported that this innovative tool can reduce students' cognitive efforts to complete academic tasks, leading to memory loss and reduce levels of procrastination (Abbas et al., 2024). Another concern raised by researchers is that not all schools have the necessary resources for ChatGPT; limited access to the Internet, computers, and servers could create a digital divide and demotivate students, so for successful integration, schools need the necessary infrastructure and equitable access to technology. According to a study by Kumar (2023), instead of being

concerned about its inappropriate use, it would be better to consider how this new technology can help in training and learning and to focus on how these technologies are integrated into teaching. As Russell (1999) notes, it is not the technology itself that is problematic, but its use. If teachers adopt pedagogical methods that encourage interaction, reflection, and creativity, ChatGPT can enrich learning rather than hinder it.

Additionally, adequate training for teachers is crucial so they can thoughtfully integrate these tools into their teaching and rethink curricula to make them realistic and adapted to new technologies (Stecher, 1991). This could not only lighten the burden of content but also allow for a more dynamic and engaging approach to learning. In sum, a deep reflection on the integration of technology and reform of pedagogical practices seems essential to make the most of these tools while preserving the quality of education. To harness the potential of ChatGPT in education, educators and policymakers must work together and address the current challenges. However, researchers have raised significant concerns regarding the accuracy and reliability of ChatGPT. A study by Malinka et al. (2023) highlighted that ChatGPT's responses exhibited considerable variability, with some being accurate and others completely incorrect, even for similar questions. It was observed that the tool tends to generate events, links, and references, which could lead to errors in the text produced. This is particularly concerning when considering the reliability and credibility of the information provided by ChatGPT. Another major worrying gap in ChatGPT's responses was the lack of practical examples or the omission of personal experiences related to the subject of the query, which is a typical feature of biological intelligence (Kumar, 2023).

Although ChatGPT is a powerful and useful tool, it can never replace the essential role of direct interaction and exchange between teacher and students, and between students themselves, which are valuable elements in providing personalized feedback, understanding of emotional and contextual gestures, and emotional support (Chen et al., 2023). AI can never fully replace this interactive and social dynamic in the classroom and the teacher's essential role in the teaching-learning process (Bitzenbauer, 2023). According to Sijing and Lan (2018), ChatGPT should be considered as a complementary tool from which teachers can benefit to enhance their activities and provide individualized support to students. Teachers will therefore play the role of guides, advisors, and mentors. They will have tools to adjust their strategies according to the issues identified, in order to offer more personalized teaching. That being said, ChatGPT cannot completely replace humans in many areas (Bisdas et al., 2021; Essel et al., 2022). For example, in fields such as medicine and healthcare, humans have a deep understanding of human physiology and psychology, as well as practical experience that cannot be replaced by a machine. Similarly, in areas such as creativity, decision-making, and solving complex problems, human expertise remains invaluable (Gutierrez, 2024; Popa et al., 2024). Moreover, ChatGPT is not credible. Although it can generate convincing responses, it can also produce inaccurate or inappropriate information. This becomes problematic in situations where accuracy and reliability are critical, such as in the field of healthcare or justice. Additionally, the use of ChatGPT raises concerns about privacy and data security. Since it processes large amounts of textual data, it could potentially be used to collect personal information, putting user confidentiality at risk. Finally, there are ethical concerns regarding the use of ChatGPT (Shangying et al., 2024). As a powerful tool capable of influencing users' opinions and behaviors, it can easily be exploited for malicious purposes, potentially causing harm to society as a whole.

The present study explores the potential of ChatGPT to help improve the learning of genetics, a crucial but often seen difficult field for students. Thus, this study aims to determine the effectiveness of ChatGPT in enhancing the understanding and mastery of essential genetics concepts among secondary school students ("meiosis", for example). It focuses on the potential of ChatGPT as a pedagogical tool to make learning genetics more accessible and attractive. Our study addresses two questions:

Q1. Does ChatGPT have a positive impact on high school student's performance in genetics?

Q2. Is there a statistically significant difference in students' performance in genetics when using ChatGPT compared to when not using this tool?

To answer these questions, two hypotheses (**H0** and **H1**) were formulated as follows:

H0. ChatGPT does not affect improving students' results.

H1. Using ChatGPT to study genetics, specifically to master the meiosis concept, can improve student performance.

MATERIALS AND METHODS

This study attempts to evaluate the effect of this innovative technological tool on improving the learning of meiosis concept and consequently improving students' academic performance. We opted for a pre-test and post-test quasi-experimental design, commonly employed in educational research. It involves assessing the knowledge and abilities of participants before (pre-test) and after (post-test) an intervention. This method included both control group (CG) and experimental group (EG), with students randomly assigned to these groups, which means that no predefined criteria, such as previous academic performance, were used for group assignments. This method ensured the initial

Table 1. Distribution of students between CG and EG

Options	Total number of learners	Groups	Numbers of learners	Female	Male
PC	45	CG	22	10	12
		EG	23	12	11
LES	37	CG	18	8	10
		EG	19	11	8
SMA	29	CG	14	7	7
		EG	15	8	7

equivalence of the groups prior to the intervention, thus guaranteeing the internal validity of the study (Cohen et al., 2007). It is descriptive and correlational in nature and is considered appropriate for comparing the average scores of the participating student groups and measuring the degree of improvement in the results of the intervention.

Sampling

Our study is based on a sample of 45 2nd year baccalaureate students in the physical sciences (PC) option, 37 students in the LES option, and 29 students in the mathematical sciences (SMA) option, studying at the qualifying high school in the regions of Marrakech, Morocco. This study population was divided into four classes; a random selection was made so that two classes were designated as the EG and two other classes were chosen as the CG. **Table 1** summarizes the distribution of the study population.

Before starting the genetics course using ChatGPT, we requested permission from the local authorities to conduct the study in the school under the right conditions. Students in the EGs used ChatGPT as a learning tool during the session; those in the control class were limited to the traditional approach, engaging in learning activities without using ChatGPT. However, the first step in using ChatGPT is to find a platform or website that allows students to access the model. ChatGPT can be used on several platforms, including the OpenAI website, transformers library, and via integrations on search engines such as Google (Dergaa et al., 2023). Once accessed, the student must enter a clear question in the field, and ChatGPT generates an answer based on its model. After receiving the answer, it is important to assess its relevance and decide whether to continue the dialogue or reformulate the request (Rahman & Watanobe, 2023).

However, ChatGPT presents limitations that should be considered for its successful implementation, in this context, our preparatory work before the class was crucial, as we were responsible for preparing the pedagogical scenario for the session, the activities and course materials, and the appropriate teaching-learning situations related to the study chapter. To achieve this, we relied on official pedagogical guidelines, the study of three national textbooks, reference frameworks, and the results of a diagnostic assessment conducted at the beginning of the year to present the topic comprehensively. To ensure the smooth running of the experiment, the classes were well equipped, connected to the Internet, and reserved exclusively for the students in the EG to facilitate their Internet access and group work. This type of work allows for the exchange of ideas among students, developing critical thinking and scientific communication.

Data Analysis

At the start of the experiment, all students in the CG and EG took a pre-test to assess the equivalence of their knowledge of meiosis. This pre-test, in line with LES pedagogical guidelines, consisted of two sections: one to evaluate the restitution of comprehension and the other to solve problems, to ensure equivalence between the groups. Subsequently, students in the EG had access to the ChatGPT application for seven sessions to study meiosis, whereas the CG followed a traditional genetics course, using textbooks, lecture notes, and teacher-guided discussions. At the end of the chapter, students in both groups were asked to answer post-test questions to compare their answers and analyze the results. The validity of two tests was confirmed by experts (teachers training centers in biology and geology and biology professors at university) and their suggestions were incorporated. The two tests included 10 questions divided into 4 levels of cognitive ability: knowledge, comprehension, analysis, and application. The tests' reliability was verified using internal consistency method expressed by Cronbach's alpha coefficient with values of 0.714 for PC, 0.78 for SMA and 0.83 for LES, exceeding the minimum threshold of 0.70 (Nunnally, 1978). The genetics program for second-year baccalaureate students incorporates meiosis as a fundamental subject. This subject was chosen because of its wide applicability and interesting nature in genetics with its different disciplines and constitutes a major role in understanding the principles and mechanisms of heredity making it a topic of interest for the ChatGPT to discuss. A web interface enabled the ChatGPT group to access the system. Students could interact with ChatGPT by typing text queries and receiving answers in a familiar language. Then, the teacher taught meiosis to the CG of students using the traditional method. The technological tool used is an independent variable, and the improvement of results and academic performance was the dependent variable in the research. Data analysis was conducted using the statistical software SPSS version 20. Basic statistics such as mean (M) and standard deviation (SD) and the comparison of means

Table 2. Pre-test scores and t-test results for average pre-test scores for LES, PC, and SMA options

Options	Total numbers of learners	Groups	Number	M	SD	t	DDL	p-value
PC	45	CG	22	8.63	2.21	1.01	43	0.31
		EG	23	9.31	2.26			
LES	37	CG	18	9.61	2.38	1.73	35	0.83
		EG	19	9.40	2.24			
SMA	29	CG	14	10.32	3.02	1.22	27	0.23
		EG	15	11.56	1.86			

Note. DDL: Data definition language

Table 3. t-test results for the average pre-test scores according to cognitive abilities for LES

Statistics of the groups							
LES	Group	Number	M	SD	t	DDL	p-value
Pre-test	CG	18	9.61	3.11	0.21	35	0.83
	EG	19	9.40	2.63			
Knowledge	CG	18	3.30	0.97	0.82	35	0.41
	EG	19	3.02	1.08			
Comprehension	CG	18	2.80	1.03	0.11	35	0.91
	EG	19	2.76	1.26			
Analysis	CG	18	2.02	0.91	0.00	35	0.99
	EG	19	2.02	0.67			
Application	CG	18	1.44	0.74	1.40	35	0.16
	EG	19	1.76	0.63			

Note. DDL: Data definition language

between the CG and EG were performed using the Student's t-test. To verify the effect of ChatGPT compared with the traditional method, we calculated each student's learning level by calculating the students' learning gain in various cognitive abilities and the learning gain of groups of size N (N-gain).

RESULTS

Pre-Test Results

To measure the positive impact on genetics performance, a statistical analysis using an independent samples t-test was conducted to assess the initial similarity between the two groups (CG and EG) from the three options: LES, PC, and SMA. **Table 2** summarizes the descriptive statistics of Ms and SDs obtained by students from both groups in the pre-test for the three options. To determine whether the difference between the means of the two groups is statistically significant to reject the null hypothesis (**H0**), we used the student's t-test to compare the means of the two independent samples, assuming they follow a normal distribution (based on the Shapiro-Wilk p-value). The results of the comparison are presented in **Table 2**.

The analyses of the pre-test results showed that for students in the LES, the variances appear homogeneous ($F = 1.60$), $t(43) = 1.01$ and the p-value is 0.31, is higher than the chosen alpha level ($p < 0.05$), the same situation is observed for students in the PC ($F = 4.85$), and mathematical sciences ($F = 3.11$), where the variances are also homogeneous and a p-value is higher than the chosen alpha level. Consequently, we cannot reject the null hypothesis **H0**, This suggests that students in both groups could be considered comparable in knowledge and comprehension of the concept of meiosis, as shown in **Table 2**. In other words, students in both groups, whatever their options, show similar levels of comprehension, qualified as low, indicating a superficial acquisition of concepts due to a traditional teaching method, focused on knowledge restitution and memorization.

Analysis of the results in **Table 3**, **Table 4**, and **Table 5** showed low performance in Bloom's cognitive skills (knowledge, comprehension, analysis, and application), which were treated as independent variables in the statistical analyses.

Table 4. t-test results for the average pre-test scores according to cognitive abilities for PC

Statistics of the groups							
LES	Group	Number	M	SD	t	DDL	p-value
Pre-test	CG	23	8.63	1.73	1.06	43	0.29
	EG	22	9.31	2.55			
Knowledge	CG	23	2.69	0.77	0.95	43	0.34
	EG	22	2.93	0.87			
Comprehension	CG	23	2.45	0.54	1.41	43	0.16
	EG	22	2.75	0.82			

Note. DDL: Data definition language

Table 4 (Continued). t-test results for the average pre-test scores according to cognitive abilities for PC

Statistics of the groups							
LES	Group	Number	M	SD	t	DDL	p-value
Analysis	CG	23	1.97	0.69	0.82	43	0.41
	EG	22	1.81	0.58			
Application	CG	23	1.10	0.87	2.02	43	0.04
	EG	22	1.54	0.50			

Note. DDL: Data definition language

Table 5. t-test results for the average pre-test scores according to cognitive abilities for SMA

Statistics of the groups							
LES	Group	Number	M	SD	t	DDL	p-value
Pre-test	CG	14	10.32	2.95	1.367	27	0.183
	EG	15	11.56	1.86			
Knowledge	CG	14	3.53	1.00	2.272	27	0.031
	EG	15	4.30	0.79			
Comprehension	CG	14	2.42	0.95	2.842	27	0.008
	EG	15	3.56	1.17			
Analysis	CG	14	2.28	0.69	-1.079	27	0.290
	EG	15	1.96	0.87			
Application	CG	14	1.92	1.08	-0.804	27	0.429
	EG	15	1.66	0.61			

Note. DDL: Data definition language

Table 6. t-test results for average post-test scores for PC, LES, and SMA options

Options	Total numbers of learners	Groups	Number	M	SD	t	DDL	p-value
PC	45	CG	22	12.47	2.25	5.85	43	0.00
		EG	23	16.55	2.54			
LES	37	CG	18	9.97	2.01	8.30	35	0.00
		EG	19	15.60	2.10			
SMA	29	CG	14	11.96	2.69	7.32	27	0.00
		EG	15	17.50	1.11			

Note. DDL: Data definition language

Furthermore, according to the quasi-experimental design, no significant difference was found between the performance of the CG and EG (Cohen et al., 2007).

Post-Test Results

Table 6 presents the results of descriptive statistics of mean scores obtained by students in the post-test for three PC, LES, and MATH options.

The results of the student's scores in the LES option during the post-test show that the average score for the EG is (M = 15.60, SD = 2.10), while the average for the CG is only (M = 9.97, SD = 2.01), with a difference of 5.63 between the two means. Regarding PC, the average score for the EG is (M = 16.55, SD = 2.54), while the CG's average is (M = 12.47, SD = 2.25), with a difference of 4.08 between the two means. For mathematical sciences, the average score for the EG is (M = 17.50, SD = 1.11), while the CG's average is (M = 11.96, SD = 2.69), with a difference of 5.54 between the two means. These scores are higher than those in the pre-test. The effects on knowledge gains were calculated to examine the impact of ChatGPT on improving students' knowledge. To determine if this difference was significant, and to reject the null hypothesis (**H0**) that ChatGPT, as an innovative learning tool, had no impact on student results, we used Student's t-test. This test compares the means of two independent samples according to a normal distribution. The results of this comparison are presented in **Table 6**. According to **Table 6**, we can see that the p-values for both groups are 0.000, which is below the chosen alpha level ($p < 0.05$). A p-value of 0.00 (if $p < 0.05$, the null hypothesis **H0**, which suggests equality of means, should be rejected). We can deduce that the difference in the means of the pre- and post-test scores is statistically significant. This indicates that the performance of students in the EG has significantly exceeded that of students in the CG for the three options (PC, LES, and SMA), allowing us to accept the alternative hypothesis **H1**. Therefore, we conclude that the use of ChatGPT in teaching and learning LES, particularly in genetics, has a significantly positive impact that far exceeds that of the traditional approach, which is limited to lectures and exercises. Bloom classified educational objectives into specific categories (knowledge, understanding, analysis, and application). Based on Bloom's cognitive abilities, we analyzed the results to determine to what extent ChatGPT could improve the abilities of our students to evaluate students' performance. The results below present the performance of the four abilities (knowledge, understanding, analysis, and application) in the post-test for students in the three options: LES, PC, and SMA.

Table 7. t-test results for the average post-test scores according to cognitive abilities for LES

	Statistics of the groups							
LES	Group	Number	M	SD	t	N-gain	Criteria	p-value
Post-test	CG	18	9.97	2.01	8.30	0.03	Low	0.00
	EG	19	15.60	2.10		0.58	Medium	
Knowledge	CG	18	3.33	0.98	5.35	0.01	Low	0.00
	EG	19	4.68	0.47		0.83	High	
Comprehension	CG	18	3.22	0.89	5.57	0.19	Low	0.00
	EG	19	4.60	0.59		0.82	High	
Analysis	CG	18	2.11	0.76	5.84	0.03	Low	0.00
	EG	19	3.86	0.98		0.61	Medium	
Application	CG	18	1.30	0.66	4.44	-0.03	Low	0.00
	EG	19	2.44	0.96		0.20	Low	

Table 8. t-test results for the average post-test scores according to cognitive abilities for PC

	Statistics of the groups							
LES	Group	Number	M	SD	t	N-gain	Criteria	p-value
Post-test	CG	23	12.47	2.43	5.85	0.23	Low	0.00
	EG	22	16.55	2.22		0.67	Medium	
Knowledge	CG	23	3.33	0.83	4.98	0.27	Low	0.00
	EG	22	4.68	0.39		0.84	High	
Comprehension	CG	23	3.22	0.99	4.92	0.30	Medium	0.00
	EG	22	4.60	0.64		0.82	High	
Analysis	CG	23	2.16	0.83	6.03	0.06	Low	0.00
	EG	22	3.86	0.93		0.64	Medium	
Application	CG	23	1.25	0.66	2.29	0.03	Low	0.00
	EG	22	2.44	1.00		0.26	Low	

Table 9. t-test results for the average post-test scores according to cognitive abilities for MATH

	Statistics of the groups							
LES	Group	Number	M	SD	t	N-gain	Criteria	p-value
Post-test	CG	14	11.96	2.69	7.32	0.16	Low	0.00
	EG	15	17.50	1.11		0.70	High	
Knowledge	CG	14	4.00	1.01	2.85	0.31	Medium	0.00
	EG	15	4.80	0.36		0.71	High	
Comprehension	CG	14	3.28	1.01	6.55	0.33	Medium	0.00
	EG	15	5.00	0.00		1.00	High	
Analysis	CG	14	2.39	0.52	8.66	0.04	Low	0.00
	EG	15	4.60	0.80		0.86	High	
Application	CG	14	2.07	1.14	3.37	0.04	Low	0.00
	EG	15	3.20	0.59		0.46	Medium	

Table 10. Interpretation of N-gain score

N-gain score	Criteria
$0.0 \leq$ N-gain < 0.3	Low
$0.3 \leq$ N-gain < 0.7	Medium
N-gain > 0.7	High

According to the results obtained in **Table 7**, **Table 8**, and **Table 9**, we observed an improvement in many cognitive abilities through teaching using the innovative pedagogical tool ChatGPT. To identify precisely which abilities were improved by this tool, we calculated and then interpreted the conceptual gain (N-gain) for each CG and EG in the three options studied, using **Table 10** from Hake (2002).

We then performed a t-test to determine the statistical significance of differences between the N-gains of the CG and EG, as shown in **Figure 2** and the **Table 7**, **Table 8**, and **Table 9** presented.

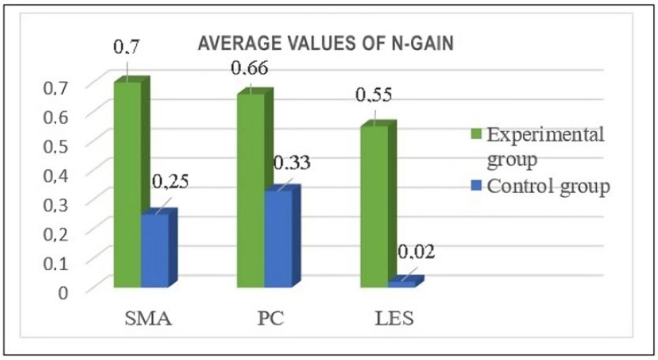

Figure 2. Averages values of N-gain calculated using SPSS, based on Hake's (2002) formula

Based on the mean T test scores and the results of the learning gain calculation for each cognitive ability in the post-test, a significant difference was observed between the cognitive ability levels of the CG and EG in the post-test for the three options: LES, PC, and SMA. The EGs in the LES option achieved a high average score of 4.68/5 for knowledge level, a similar result for PC, whereas SMA obtained 4.80/5.

For comprehension, LES and PC achieved an average of 4.60/5, whereas SMA registered a perfect score of 5.00/5. For the analysis level, SMA showed the highest average with 4.60/5, while LES and PC scored 3.86/5.

Finally, regarding the application level, the scores of PC and LES options failed to achieve the mean, whereas SMA presented a relatively high mean of 3.20/5. These scores were significantly higher than those of the CG, which did not exceed 2.50/5. In other words, the students in the CG answered correctly, especially on the questions related to comprehension and analysis/synthesis abilities. It was also revealed that the students understood and assimilated the concepts of genetics very well after studying the subject using GPT Chat, in contrast to the CGs, which were limited to knowledge and superficial comprehension, without acquiring abilities such as comprehension, analysis, and application. In other words, the experimental students performed better than the control students, which can be explained by the reason that the CGs did not benefit from the intervention such as the activities organized by the teacher to successfully integrate the Chat GPT, which the EG benefited. Therefore, we can conclude that the ChatGPT-based learning environment significantly improved the students' understanding of the meiosis concept, whereas traditional teaching had a mediocre impact on our students' comprehension.

DISCUSSION

This study aimed to determine the impact of integrating ChatGPT on improving students' understanding and cognitive performance in learning meiosis, a fundamental concept in genetics. The results of the comparison between the pre- and post-tests, as well as the students' feedback, provide valuable and encouraging insights into the usefulness of ChatGPT as an educational learning technology. The comparison of test results before and after the use of ChatGPT shows a statistically significant difference in cognitive performance, indicating that the tool improved students' understanding of meiosis.

In a ChatGPT-based learning environment, students in the LES, PC, and SMA options became more engaged in the course. They actively built their knowledge, facilitating the development of higher-order cognitive skills. These results are consistent with Qureshi (2023), who confirms that ChatGPT enhances student participation in virtual dialogues, offering quick feedback and guidance that strengthens the development of essential abilities such as critical thinking and problem-solving. However, it will be difficult to achieve these objectives without a fundamental understanding of scientific concepts in genetics, such as the meiosis concept. Therefore, ChatGPT is an effective and essential tool for teaching genetics, a subject characterized by a dense curriculum, many complex and abstract scientific concepts, and especially the insufficient amount of time available to cover all its branches (Baroud et al., 2022; Choden & Kijkuakul, 2020).

According to Eden (2024), the use of AI, particularly ChatGPT, in biology represents a promising and alternative solution, offering positive effects by considering the individual differences of learners, their learning pace, as well as feedback and engagement from all students. The ChatGPT-based approach considers students' prerequisites, abilities, and preferences, which increases the chances of achieving positive outcomes by the end of the biology course (Tiwari, 2023). Furthermore, this tool can even assist teachers in addressing various topics in biology. The main goal is to provide effective learning that is tailored to the specific needs of students.

As noted by Jmoula (2023), ChatGPT helps reduce content load, diversify learning methods, and make lessons more interactive, especially by allowing more classroom time to be dedicated to developing students' higher-order cognitive skills, thereby preparing them to become active citizens capable of thinking critically and solving problems. It also allows for a more targeted approach to meet the needs of each learner by analyzing their prompts and queries, providing answers suited to their level, and offering personalized content such as exercises, definitions of difficult concepts, grammar rule reminders, recommendations for additional sources of information, etc. For instance, students struggling to understand a specific idea should be provided with knowledge and resources, whereas academically proficient students could be tasked with more complex assignments. This study aims to implement a personalized methodology that effectively addresses the heterogeneous learning needs of students and fosters inclusive educational practices (Alarabi et al., 2024). Our study aligns with the one conducted by Rudolph and Tan (2023), which emphasizes that ChatGPT can direct learners to supplementary resources such as books or online courses, helping them improve their understanding of a given topic. Other studies reveal that students in ChatGPT groups are highly engaged in collaborative learning activities and participate in meaningful interactions with their peers. According to Firat (2023), and Lin (2023) ChatGPT is an online educational tool that provides pedagogical support by helping students solve problems and encouraging collaborative dialogue between peers. Furthermore, it

creates collaborative learning that facilitates knowledge acquisition and the exchange of opinions and ideas among students, leading to the collective construction of knowledge.

In a recent study, Williams (2023) identified over ten applications of ChatGPT to support dyslexic students in higher education, including helping with reading long texts by summarizing or reading the text aloud (text-to-speech) and assisting with note-taking during classes, which facilitates their understanding and later revision. Through its language processing capabilities, ChatGPT can help students ask questions in real time, clarify complex scientific concepts hindering their understanding, and explore topics in greater depth. By integrating this tool, teachers can create personalized activities where students collaborate, share ideas, and discuss outcomes, thereby fostering scientific curiosity and critical thinking in students–abilities that are essential in the biological sciences (Gérard & Rubio, 2020). Despite the potential benefits of ChatGPT in the field of education, concerns remain regarding the risks associated with this technology, raising significant ethical issues that require collective reflection to mitigate its dangers. The ability of ChatGPT to generate plausible and semantically correct texts is at the center of ethical and societal debates. In the educational context, the use of ChatGPT by learners to write essays or complete assignments, as well as its use by teachers to assist in their pedagogical and scientific activities, raises ethical questions related to academic integrity and honesty, thereby increasing the risks of plagiarism and cheating (Adnani & Haounani, 2024).

CONCLUSION

Genetics presents a major challenge for high school students and even university students. Our study seeks to validate the widely accepted hypothesis that high school students in LES can greatly benefit from using ChatGPT, especially in learning the meiosis concept. This fundamental process of cell reproduction is essential for genetic diversity and the transmission of hereditary traits. However, this concept is often perceived as complex and creates difficulties for many students. The results of our current study show that the integration of ChatGPT into learning not only facilitates the understanding of meiosis and improves student performance but also stimulates students' interest and engagement. This tool can provide clear and personalized explanations, allowing students to progress at their own pace and according to their needs by analyzing their prompts and queries. Thanks to its ability to provide instant responses to questions and offer interactive exercises, ChatGPT helps strengthen students' confidence and autonomy in the learning process. Furthermore, the ease of use of ChatGPT is a significant advantage for high school students, as it is accessible from any device with an Internet connection, allowing them to study at any time. However, some students encounter difficulties accessing the ChatGPT platform due to technical issues, particularly in remote areas where the Internet connectivity is limited, highlighting the importance of finding appropriate solutions and overcoming accessibility barriers. Additionally, collaboration between educators and digital education innovators is essential to create relevant content aligned with curricula and learning objectives, as well as to develop quality educational resources that will better prepare students to tackle complex subjects like genetics. To achieve this, it is also essential to provide adequate training for teachers to improve the quality of their lessons and generate creative ideas that open the way to new teaching perspectives, enabling them to master this new AI technology in the educational setting. Students must also be more aware of its ethical use and how to adapt it to science courses. Furthermore, it is recommended to engage in more collaborative research using ChatGPT as an educational tool. It is also essential to establish quality assurance procedures to ensure the reliability and accuracy of the responses provided by AI. In this context, in-depth studies on the effectiveness of AI-based education and its long-term impacts on teaching LES are needed. Researchers, educators, and decision makers should work together to integrate AI into education by identifying best practices, developing guidelines, and creating appropriate policies. This partnership could foster the creation of a learning community, facilitating the exchange of ideas, tools, and innovative experiences. Finally, it is crucial to regularly evaluate the effectiveness of this approach. Our ultimate goal is to contribute to improving science education, making the learning of genetics more accessible and engaging for all students.

Author contributions: SB: conceptualization, software, validation, investigation, resources, writing – original draft; **ME:** conceptualization, resources, writing – original draft; **RJI:** methodology, writing – review & editing; **NB:** methodology, validation, investigation; **GG:** formal analysis; **HS:** formal analysis. All authors have agreed with the results and conclusions.

Funding: No funding source is reported for this study.

Acknowledgments: The authors would like to thank the provincial director of Elkelaa des Sraghna for the administrative and technical support provided during the research process and the colleagues within the laboratory, who offered us enriching discussions. The authors would like to thank the work colleagues for their invaluable help in providing them with the materials and equipment used in the experiments, which greatly facilitated the research.

Ethical statement: The authors stated that they have obtained permission from the local authorities to conduct the study. The study was approved by the institutional ethics committee of the Provincial Directorate of Kelaa des Sraghna on July 11, 2024 (Approval code: F-2598). All the participants were informed that their participation was voluntary and that the data collected would be kept strictly confidential and anonymous.

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

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

REFERENCES

Abbas, M., Jam, F. A., & Khan, T. I. (2024). Is it harmful or helpful? Examining the causes and consequences of generative AI usage among university students. *International Journal of Educational Technology in Higher Education, 21*, Article 10. https://doi.org/10.1186/s41239-024-00444-7

Abramson, A. (2024). How to use ChatGPT as a learning tool. *American Psychological Association, 54*(3), Article 67.

Adiguzel, T., Kaya, M. H., & Cansu, F. K. (2023). Revolutionizing education with AI: Exploring the transformative potential of ChatGPT. *Contemporary Educational Technology, 15*(3), Article ep429. https://doi.org/10.30935/cedtech/13152

Adnani, E., & Haounani, A. (2024). Artificial Intelligence in Morocco: Between ethics and regulation. *International Journal of Scientific Research, 2*(3), 1234-1252. https://doi.org/10.5281/zenodo.11621028

Agathokleous, E., Saitanis, C. J., Fang, C., & Yu, Z. (2023). Use of ChatGPT: What does it mean for biology and environmental science. *Science of The Total Environment, 888*, Article 164154. https://doi.org/10.1016/j.scitotenv.2023.164154

Akhtar, N., Matloob, R., & Nawaz, R. (2024). Exploring the impact of artificial intelligence in teaching of biology at secondary level. *International Research Journal of Management and Social Sciences, 5*(3), 427-440.

AlAbidi, S., AlArabi, K. S., Alsalhi N. R., & al Mansoori, M. (2023). The dawn of ChatGPT: Transformation in science assessment. *Eurasian Journal of Educational Research, 106*(106), 321-337.

Alagui, A., El Hariri, K., Bouab, W., Rafouk, L., & Razouki, A. (2020). Transition from high school to university: Difficulties faced by first-year students at the faculty of sciences. *Le Pédagogue, 2*(5). https://doi.org/10.29333/ejedus/11400

Alarabi, K., Halaweh, M., Tairab, H., Alsalhi, N. R., Annamalai., N., & Aldarmaki, F. (2024). Making a revolution in physics learning in high schools with ChatGPT: A case study in UAE. *Eurasia Journal of Mathematics, Science and Technology Education, 20*(9), Article em2499. https://doi.org/10.29333/ejmste/14983

Alberts, B., Johnson, A., Lewis, J., Raff, M., Roberts, K., & Walter P. (2002). *Molecular biology of the cell* (4th ed.). Garland Science.

Alberts, B., Johnson, A., Lewis, J., Raff, M., Roberts, K., & Walter, P. (2007). Molecular biology of the cell (5th ed.) Garland Science. https://doi.org/10.1201/9780203833445

Alibi, I., & Boilevin, J.-M. (2021). Typology of learning difficulties related to acceleration in higher education. *Mediterranean Journal of Education, 1*(2), 158-169. https://doi.org/10.26220/mje.3852

Alnaqbi, H., Bahroun, A., &Vian, A. (2024). Enhancing work productivity through generative artificial intelligence: A comprehensive literature review. *Sustainability, 16*(3), Article 1166. https://doi.org/10.3390/su16031166

Alneyadi, S., & Wardat, Y. (2023). ChatGPT: Revolutionizing student achievement in the electronic magnetism unit for eleventh-grade students in Emirates schools. *Contemporary Educational Technology, 15*(4), Article ep448. https://doi.org/10.30935/cedtech/13417

Astolfi, J. P. (1993). Three paradigms for research in didactics. *Revue Française de Pédagogie*, (103), 5-18. https://doi.org/10.3406/rfp.1993.1293

Ayemele, S., Noubiengang, R., Agbanglanon, S., & Shamsi, M. (2024). *ChatGPT under the spotlight: Analysis, awareness, and precautions within the educational system*. ENSIM.

Bahar, M., Johnstone, A. H., & Hansell, M. H. (1999). Revisiting learning difficulties in biology. *Journal of Biological Education, 33*(2), 84-86. https://doi.org/10.1080/00219266.1999.9655648

Baroud, S., El alaoui, M., Janati-idrissi, R., & Amiri, M. (2022). Difficulties of learning molecular genetics at university: Characterization and analysis of results, *American Journal of Innovative Research & Applied Sciences, 15*(1), 322-328.

Bisdas, S., Topriceanu, C. C., Zakrzewska, Z., Irimia, A. V., Shakallis, L., Subhash, J., Casapu, M. M., Leon-Rojas, J., dos Santos, D. P., Andrews, D. M., Zeicu, C., Bouhuwaish, A. M., Lestari, A. N., Abu-Ismail, L., Sadiq, A. S., Khamees, A., Mohammed, K. M. G., Williams, E., Omran, A. I., & Ebrahim, E. H. (2021). Artificial intelligence in medicine: A multinational multicenter survey on the perception of medical and dental students. *Frontiers in Public Health, 9*. https://doi.org/10.3389/fpubh.2021.795284

Bitzenbauer, P. (2023). ChatGPT in physics education: A pilot study on easy-to-implement activities. *Contemporary Educational Technology, 5*(3), Article ep430. https://doi.org/10.30935/cedtech/13176

Bouhafs, M., & Karam, S. (2020). Identification of linguistic and methodological difficulties among Moroccan science students. *International Journal of Legal, Economic and Social Sciences, 1*(1).

Brown, C. R. (1990). Some misconceptions in meiosis shown by students responding to an Advanced level practical examination question in biology.

Journal of Biological Education, 24(3), 182-186. https://doi.org/10.1080/00219266.1990.9655138

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher, 18*(1), 32-41. https://doi.org/10.3102/0013189x018001032

Cao, H. T., Huynh, C. B., & Cao, L. (2023). Integrating ChatGPT into online education system in Vietnam: Opportunities and challenges. *EdArXiv*. https://doi.org/10.35542/osf.io/hqyut

Chan, M. M. K., Wong, I. S. F., Yau, S. Y., & Lam, V. S. F. (2023). Critical reflection on the use of ChatGPT in student learning: Benefits or potential risks. *Nurse Educator, 48*(6), E200-1. https://doi.org/10.1097/NNE.0000000000001476

Chapel, G., & Marzin, P. (2009). Identification and classification of difficulties encountered by 10th grade students regarding genetic information. In *Proceedings of the 6th ARDIST Conference*.

Chen, Y., Jensen, S., Albert, L. J., Gupta, S., & Lee, T. (2023). AI student assistants in the classroom: Designing chatbots to support student success. *Information Systems Frontiers, 25*, 161-182. https://doi.org/10.1007/s10796-022-10291-4

Choden, T., & Kijkuakul, S. (2020). Blending problem based learning with scientific argumentation to enhance students' understanding of basic genetics. *International Journal of Instruction, 13*(1), 445-462. https://doi.org/10.29333/iji.2020.13129a

Chouraik, C. (2024). Sustainable AI in Morocco: A systematic review of opportunities, challenges and policy directions. *EHEI Journal of Science and Technology, 4*(1), 11-26. https://doi.org/10.34874/PRSM.ehei-jst-vol4iss1.51630

CNPEN. (2023). *Generative artificial intelligence systems: Ethical issues*. National Pilot Committee for Digital Ethics

Cohen, L., Manion, L., & Morrison, K. (2007). *Research methods in education*. Routledge. https://doi.org/10.4324/9780203029053

CSEFRS. (2024). For a school of equity, quality and promotion a strategic vision of reform 2015-2030. *Journal of Information Sciences, 22*(2), 26-40.

Danielsson A. T., & Linder, C. (2009). Learning in physics by doing laboratory work: Towards a new conceptual framework. *Gender and Education, 21*(2), 129-144. https://doi.org/10.1080/09540250802213081

Dao, X.-Q., & Le, N. B. (2023). Performance of large language models (LLMs) on the Vietnamese high school biology exam. *International Journal of Modern Education and Computer Science, 15*(6), 14-30. https://doi.org/10.5815/ijmecs.2023.06.02

Dao, X.-Q., Le, N. B., Phan, X. D., & Ngo, B. B. (2023). Evaluation of ChatGPT and Microsoft Bing AI chat performances on physics exams of Vietnamese national high school graduation examination. *arXiv*. https://doi.org/10.48550/arXiv.2306.04538

Dergaa, I., Chamari, K., Zmijewski, P., & Saad, H. B. (2023). From human writing to artificial intelligence generated text: Examining the prospects and potential threats of ChatGPT in academic writing. *Biology of Sport, 40*(2), 615-622. https://doi.org/10.5114/biolsport.2023.125623

Djarmouni, M. (2017). Structural biochemistry course. *FSNV*. https://fsnv.univsetif.dz/telecharger/EDT2017/Biochimie_structurale.pdf

Duncan, R. G., & Reiser, B. J. (2007). Reasoning across ontologically distinct levels: Students' understandings of molecular genetics. *Journal of Research in Science Teaching, 44*(7), 938-959. https://doi.org/10.1002/tea.20186

Eden, N. C. A., Adeleye, N. O. O., & Adeniyi, N. I. S. (2024). A review of AI-based pedagogical strategies for equitable access to science education. *Magna Scientia Advanced Research and Reviews, 10*(2), 44-54. https://doi.org/10.30574/msarr.2024.10.2.0043

Essel, H. B., Vlachopoulos, D., Tachie-Menson, A., Johnson, E. E., & Baah, P. K. (2022). The impact of a virtual teaching assistant (Chatbot) on student learning in Ghanaian higher education. *International Journal of Educational Technology in Higher Education, 19*, Article 57. https://doi.org/10.1186/s41239-022-00362-6

Firat, M. (2023). How ChatGPT can transform autodidactic experiences and open education? *OSF*. https://doi.org/10.31219/osf.io/9ge8m

Freidenreich, H. B., Duncan, R. G., & Shea, N. (2011). Exploring middle school students' understanding of three conceptual models in genetics. *International Journal of Science Education, 33*(17), 2323-2349. https://doi.org/10.1080/09500693.2010.536997

Gérard, L., & Rubio, A. (2020). Sources influencing student engagement in a flipped classroom setup at university. *International Journal of Higher Education Pedagogy, 36*(1). https://doi.org/10.4000/ripes.2212

Green, C., Eady, M., & Andersen, P. (2018). Preparing quality teachers: Bridging the gap between tertiary experiences and classroom realities. *Teaching and Learning Inquiry: The ISSOTL Journal, 6*(1), 104-125. https://doi.org/10.20343/teachlearninqu.6.1.10

Gregorcic, B., & Pendrill, A. M. (2023). ChatGPT and the frustrated Socrates. *Physics Education, 58*(3). https://doi.org/10.1088/1361-6552/acc299

Gutierrez, G. (2020). Artificial intelligence in the intensive care unit. *Critical Care, 24*, Article 101. https://doi.org/10.1186/s13054-020-2785-y

Hake, R. R. (2002). Relationship of individual student normalized learning gains in mechanics with gender, high-school physics, and pretest scores on mathematics and spatial visualization. In *Proceedings of the Physics Education Research Conference*.

Harabi, M., & Kilani, C. B. (2019). Analysis of university teaching practice: The case of organic chemistry. *Educational Journal of the University of Patras UNESCO Chair, 6*(1), 295-307.

Hogan, D., & O'Flaherty, J. (2021). Addressing education for sustainable development in science teaching: The case of a biology teacher education program. *Sustainability, 13*(21), Article 12028. https://doi.org/10.3390/su132112028

Holmes, W., & Tuomi, I. (2022). State of the art and practice in AI in education. *European Journal of Education, 57*(4), 542-570. https://doi.org/10.1111/ejed.12533

Holmes, W., Bialik, M., & Fadel, C. (2019). Artificial intelligence in education: Promises and implications for teaching and learning. *Center for Curriculum Redesign*. http://udaeducation.com/wp-content/uploads/2019/05

Hwang, G. J., & Chang, C. Y. (2021). A review of opportunities and challenges of chatbots in education. *Interactive Learning Environments, 31*(7), 4099-4112. https://doi.org/10.1080/10494820.2021.1952615

Jmoula, L. (2023). Teaching and learning in the era of ChatGPT: Insights from a literature review. *Education Sciences, 14*(6), 1-18. https://doi.org/10.34874/IMIST.PRSM/jis-v22i2.41122

Jones, G., Kleckner, N., & Zickler, D. (2024). Meiosis through three centuries. *Chromosoma, 133*(2), 93-115. https://doi.org/10.1007/s00412-024-00822-0

Karsenti, T. (2009). Pedagogical integration of ICT in Africa: Action strategies and reflection paths. *IDRC*. http://crdi.crifpe.ca/karsenti/docs/livre.pdf

Khan, M. U. H. (2019). UAE's artificial intelligence strategies and pursuits. *Defence Journal, 23*(4).

Kirkwood, A., & Price, L. (2013). Examining some assumptions and limitations of research on the effects of emerging technologies for teaching and learning in higher education. *British Journal of Educational Technology, 44*(4), 536-543. https://doi.org/0.1111/bjet.12049

Knippel, M. C., Waarlo, A. J., & Boersma, K. T. (2005). Design criteria for learning and teaching genetics. *Journal of Biological Education, 39*(3), 108-112. https://doi.org/10.1080/00219266.2005.9655976

Kumar, A. H. S. (2023). Analysis of the ChatGPT tool to assess its potential usefulness for academic writing in the biomedical field. *BEMS Reports, 9*(1), 24-30. https://doi.org/10.5530/bems.9.1.5

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge University Press. https://doi.org/10.1017/CBO9780511815355

Lent, R. W. (2008). A social cognitive approach to career development: Theoretical and practical considerations. *O. S. P., 37*(1), 57-90. https://doi.org/10.4000/osp.1597

Lin, X. (2024). Exploring the role of ChatGPT as a facilitator for motivating self-directed learning. *Eurasia Journal of Mathematics, Science and Technology Education, 20*(9), 156-166. https://doi.org/10.1177/10451595231184928

Malinka, K., Perešíni, M., Firc, A., Hujňák, O., & Januš, F. (2023). *On the educational impact of ChatGPT: Is artificial intelligence ready to obtain a university degree?* Cornell University Press. https://doi.org/10.1145/3587102.3588827

Mathé, S., Méheut, M., & De Hasson, C. (2008). Inquiry-based learning in middle school: What are the stakes? *Didaskalia*, (32), 41-76. https://doi.org/10.4267/2042/23980

Nguyen, X. H., Nguyen, A. H., Cao, L., & Truong, H. (2023). *Potential of ChatGPT in biology teaching and learning at the Vietnamese high school*. Authorea. https://doi.org/10.22541/au.169029376.68639796/v1

Nunnally, J. C. (1978) *Psychometric theory* (2nd ed.). McGraw-Hill.

Nussbaum, R. L., McInnes, R. R., & Willard, H. F. (2015). *Thompson & Thompson genetics in medicine*. Elsevier.

Popa, S. L., Ismaiel, A., Brata, V. D., Turtoi, D. C., Barsan, M., Czako, Z., Pop, C., Muresan, L., Stanculete, M. F., Dumitrascu, D. I. (2024). Artificial intelligence and medical specialties: Support or substitution? *Medicine and Pharmacy Reports, 97*(4), 409-418. https://doi.org/10.15386/mpr-2696

Qureshi, B. (2023). Exploring the use of ChatGPT as a tool for learning and assessment in the undergraduate computer science curriculum: Opportunities and challenges. *arXiv*. https://doi.org/10.48550/arXiv.2304.11214

Rahman, M. M., & Watanobe, Y. (2023).ChatGPT for education and research: Opportunities, threats, and strategies. *Applied Sciences, 13*(9), 1-21. https://doi.org/10.3390/app13095783

Robert, A., & Rogalski, J. (2002). The complex and coherent system of mathematics teachers' practices: A dual approach. *Canadian Journal of Science, Mathematics and Technology Education, 2*(4), 505-528. https://doi.org/10.1080/14926150209556538

Rudolph, J., & Tan, S. (2023). ChatGPT: A bullshit detector or the end of traditional assessments in higher education? *Journal of Applied Learning & Teaching, 6*(1). https://doi.org/10.37074/jalt.2023.6.1.9

Russell, T. L. (1999). *The no significant difference phenomenon*. North Carolina State University Press.

Santos, R. P. D. (2023). Enhancing chemistry learning with ChatGPT and Bing Chat as agents to think with: A comparative case study. *arXiv*. https://doi.org/10.48550/arXiv.2311.00709

Séré, M. G., Journeaux, R., & Winther, J. (1997). Survey on the objectives of practical work in 10th grade, 11th grade S, and 12th grade S classes. *Bulletin of the Union of Physicists, 796*, 1377-1389.

Shangying, H., Shuangci, J., & Shengyi, J. (2024). The limitations and ethical considerations of ChatGPT. *Data Intelligence, 6*(1), 201-239. https://doi.org/10.1162/dint_a_00243

Sijing, L., & Lan, W. (2018). Ethical issues and solutions in artificial intelligence education. In *Proceedings of the IEEE 13th International Conference on Computer Science and Education* (pp. 1-5). IEEE. https://doi.org/10.1109/ICCSE.2018.8468773

Silar, P. (2020). Genetics: Basic concepts and advanced notions. *Hal Open Sciences*. https://hal.science/hal-02921475

Smutny, P., & Schreiberova, P. (2020). Chatbots for learning: A review of educational chatbots for the Facebook Messenger. *Computers & Education, 151*, Article 103862. https://doi.org/10.1016/j.compedu.2020.103862

Stecher, B. (1991). *On the road toward educational technology use: Second year research findings from California's model technology schools*. Educational Testing Service. https://doi.org/10.1002/j.2333-8504.1991.tb01413.x

Tiwari, R. (2023). The integration of AI and machine learning in education and its potential to personalize and enhance students' learning experiences. *Indian Journal of Scientific Research in Engineering and Management, 7*(2). https://doi.org/10.55041/ijsrem17645

Tong, Y., & Zhang, L. (2023). Discovering the next decade's synthetic biology research trends with ChatGPT. *Synthetic and Systems Biotechnology, 8*(2), 220-223. https://doi.org/10.1016/j.synbio.2023.02.004

Truong, H. (2023). ChatGPT in education–A global and Vietnamese research overview. *EdArXiv*. https://doi.org/10.35542/osf.io/r4uhd

Truong, H., Nguyen, P., Cao, L., Nguyen, T., & Nguyen, P. (2023). Role of ChatGPT in Vietnamese education. *EdArXiv*. https://doi.org/10.35542/osf.io/52smv

Usak, M. (2024). Artificial intelligence in biology education. *Journal of Baltic Science Education, 23*(5), 806-808. https://doi.org/10.33225/jbse/24.23.806

Welzel, M., & Haller, K. (1998). *Teachers' objectives for labwork*. Institute of Physics Education, University of Bremen.

Williams, K. (2023). Overcoming dyslexia in higher education: How ChatGPT is changing the game. *Dyslexiauk*. https://www.dyslexiauk.co.uk/overcoming-dyslexia-in-higher-education-how-chatgpt-ischanging-the-game/

Wynne, C. F., Stewart, J., & Passmore, C. (2005). High school students' use of meiosis when solving genetics problems. *International Journal of Science Education, 23*(5), 501-515. https://doi.org/10.1080/09500690175016285 6

Yilmaz, R., & Yilmaz, F.G.K. (2023). Augmented intelligence in programming learning: Examining students' perspectives on using ChatGPT for programming education. *Computers in Human Behavior: Artificial Humans, 1*(2), Article 100005. https://doi.org/10.1016/j.chbah.2023.100005

Zawacki-Richter, O., Marín, V. I., Bond, M., & Gouverneur, F. (2019). Systematic review of research on artificial intelligence applications in higher education–Where are the educators? *International Journal of Educational Technology in Higher Education, 16*(1), Article 39. https://doi.org/10.1186/s41239-019-0171-0