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Meiosis in Basic Education: Analysis of Teachers' Conceptions and Implications for Teaching

Meiose na Educação Básica: Análise de Concepções Docentes e Implicações para o Ensino

La Meiosis en la Educación Básica: Análisis de las Concepciones Docentes e Implicaciones para la Enseñanza

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Abstract

This study aims to investigate teachers' conceptions regarding the topic of meiosis, with the goal of contributing to the field of science education research by providing insights that support the understanding and overcoming of difficulties related to the appropriation of genetic knowledge. Additionally, it seeks to address a gap in the literature on genetics education, particularly the lack of studies focused on in-service teachers. For data collection, the Meiosis Concept Inventory (MCI) was used—a tool previously developed and validated by American researchers. Our research group adapted and employed the MCI for the first time in Brazil, with the purpose of identifying alternative conceptions held by both students and teachers. The conceptions of 318 in-service teachers were analyzed. The results include a comparative analysis with undergraduate students in Biological Sciences, based on data from a previous study that used the same instrument. Overall, the in-service teachers performed worse than the undergraduates, although both groups exhibited a significant prevalence of alternative conceptions concerning basic genetic concepts related to meiosis. These findings reveal a limited understanding of this biological process among participants, which poses a challenge for effectively teaching this topic in basic education and highlights a critical area of concern for teacher training programs.

Keywords: genetics education, teacher conceptions, alternative conceptions, conceptual learning, cell division

Resumo

O presente estudo tem como objetivo investigar as concepções docentes acerca do tema meiose, visando contribuir para o campo de investigação em Ensino de Ciências, fornecendo subsídios que promovam a compreensão bem como a superação de dificuldades associadas à apropriação de conhecimentos genéticos. Ademais, busca-se suprir a escassez existente na literatura da área Ensino de Genética quanto a investigações que tenham como foco principal professores em efetivo exercício da docência. Para a coleta de dados, foi utilizado o Inventário Conceitual de Meiose (ICM), instrumento previamente publicado e validado por pesquisadores norte-americanos. O ICM foi empregado pela primeira vez no Brasil, por nosso grupo de pesquisa, em uma adaptação destinada a identificar concepções alternativas entre estudantes e professores. Foram analisadas as concepções de 318 professores em exercício. Os resultados incluem uma análise comparativa com licenciandos em Ciências Biológicas, provenientes de uma pesquisa anterior com dados gerados pelo mesmo instrumento. Os docentes tiveram um desempenho geral inferior ao dos graduandos, embora ambos os grupos tenham demonstrado uma prevalência significativa de concepções alternativas sobre conceitos genéticos elementares relacionados à meiose. Os resultados revelam uma compreensão limitada desse processo biológico por parte dos pesquisados, o que representa um obstáculo para a concretização do ensino desse tema na educação básica e configura um ponto importante de atenção para os programas de formação docente.

Palavras-chave: ensino de genética, concepções de professores, concepções alternativas, aprendizagem conceitual, divisão celular

Resumen

El presente estudio tiene como objetivo investigar las concepciones docentes sobre el tema de la meiosis, con miras a contribuir al campo de investigación en la Enseñanza de las Ciencias, proporcionando insumos que favorezcan la comprensión y la superación de dificultades asociadas a la apropiación de conocimientos genéticos. Asimismo, se busca subsanar la escasez existente en la literatura del área de Enseñanza de la Genética en lo que respecta a investigaciones cuyo foco principal sean docentes en ejercicio activo. Para la recolección de datos, se utilizó el Inventario Conceptual de Meiosis (ICM), un instrumento previamente publicado y validado por investigadores estadounidenses. El ICM fue empleado por primera vez en Brasil por nuestro grupo de investigación, en una adaptación cuyo objetivo fue identificar concepciones alternativas entre estudiantes y docentes. Se analizaron las concepciones de 318 profesores en ejercicio. Los resultados incluyen un análisis comparativo con estudiantes de grado en Ciencias Biológicas, provenientes de una investigación anterior basada en datos generados con el mismo instrumento. Los docentes obtuvieron un desempeño general inferior al de los estudiantes de grado, aunque ambos grupos mostraron una prevalencia significativa de concepciones alternativas sobre conceptos genéticos elementales relacionados con la meiosis. Los resultados revelan una comprensión limitada de este proceso biológico por parte de los encuestados, lo cual representa un obstáculo para la enseñanza efectiva de este tema en la educación básica, y constituye un punto crítico de atención para los programas de formación docente.

Palabras clave: enseñanza de genética, concepciones de los profesores, concepciones alternativas, aprendizaje conceptual, división celular

Introduction

Scientific literacy (SL) is a complex and multifaceted concept, which is presented in a pluralistic manner in both linguistics and semantics. However, the different approaches are not seen as mutually exclusive, but rather complementary (Silva & Sasseron, 2021). The central idea of a more modern view of literacy, which keeps pace with the demands of the 21st century, is that students' scientific education must go beyond the simple accumulation of concepts, phenomena, and processes. The central idea of a more modern view of literacy, which keeps pace with the demands of the 21st century, is that students' scientific education must go beyond the simple accumulation of concepts, phenomena, and processes.

The role of teachers in achieving scientific literacy is to promote access to and facilitate understanding of scientific concepts, which are often restricted to the scientific community, as something hidden, beyond human comprehension (Chassot, 2003). Silva and Sasseron (2021) outline three structural axes that underpin SL: (1)

understanding scientific concepts, (2) understanding the nature and practices of science, and (3) recognizing the interconnections between science, technology, society, and the environment. Although this study emphasizes the structural axis of conceptual learning, it is understood that this should not be worked on exclusively to the detriment of the others, as all dimensions of scientific literacy are interdependent and essential. The development of skills to understand and apply scientific concepts is an integral part of a broader training process to promote greater social activism and civic engagement (Valladares, 2021).

The appropriation of scientific language is one of the greatest challenges of scientific literacy, as it differs from everyday language in several aspects, such as objectivity, precision, absence of a subject, and its formal and technical nature, contrasting with the contextualized, narrative, and linear language of everyday life (Mortimer et al., 1998). In the context of this specialized language, scientific concepts are human constructs used to interpret and explain the natural world and, as such, can be fallible and changeable over time—as is the case with the concept of the gene (Joaquim & El-Hani, 2010).

In the structural axis of conceptual learning in scientific literacy, students already have prior knowledge built from their daily and school experiences. This pre-existing knowledge forms a conceptual network that is constantly being restructured as new concepts are learned and integrated (Carvalho et al., 2020). For this learning to be effective, teachers need to create teaching situations that favor the acquisition of new concepts, connecting them with what students already know. This requires teachers not only to master specific content, but also to have a deep understanding of the teaching-learning process and the pedagogical practices appropriate to each context.

However, especially in Genetics, the development of the conceptual axis is a challenge due to the plasticity found in the definition of scientific concepts, conceptual density, the complexity of terms that define abstract entities, and structures and processes that are difficult to visualize. The importance of abstraction skills in this area stems from the fact that understanding the macroscopic or phenotypic level requires moving through biological levels that are not directly accessible to students' senses, such as the microscopic and molecular levels—in addition to the need to manipulate numerical and statistical data applied to the study of phenotypes (Carvalho & Santiago, 2020; Wright et al., 2022; Wright et al., 2017).

In genetics education, meiosis is a fundamental topic for understanding biological phenomena such as species evolution, genetic inheritance, and the life cycle of organisms, as well as being a topic that encompasses all of the above-mentioned difficulties. The literature on teaching meiosis reveals that alternative conceptions (AC) are deeply rooted and maintain the same pattern in relation to certain concepts in particular, persisting after formal schooling and found among students from different cultures and educational systems (Carvalho & Santiago, 2020; Gil et al., 2018; Guerra et al., 2022; Wright et al., 2020).

AC refers to conceptions developed by students that differ significantly from scientifically accepted conceptions and academic discussions (Dove, 1998). It is important to note that these AC, although they do not represent scientific knowledge, can coexist with it consciously (Mortimer, 1996) or interfere with the teaching-learning process when they are clearly conflicting (Dove, 1998). The spread of these misconceptions can be facilitated by methodologies that do not take into account students' conceptual difficulties, by the use of textbooks that do not address certain concepts clearly and accurately, or by teachers who lack conceptual mastery.

However, in our research, we did not find any studies in the literature on teachers' conceptions of genetic concepts related to meiosis. Despite the fundamental role of teachers in learning processes, research in science education has focused more on analyzing the AC shared by students, whether in primary or higher education. Frequent reports of the persistence of these remarkably stable and deeply rooted conceptions, together with the difficulty of understanding scientific concepts, encourage research that seeks to understand the underlying causes.

In this study, we understand the importance of investigating teachers' understanding of meiosis in basic education as a continuation of the work carried out by our group in higher education with trainee teachers (Sousa et al., 2023). The practicing teacher, a key player in the development of scientific literacy, can make important contributions to research in science education, providing insights that lead to understanding and overcoming problems that exist in the acquisition of genetic knowledge. Work such as this can guide the development and application of teaching and learning strategies and resources, promote improvements in teacher training and practice, raise awareness among university professors, guide curriculum reforms, and encourage self-reflection and professional development, thereby preventing the spread of unscientific information.

Considering that teachers play a key role in the internalization of concepts, competencies, and skills that are mobilized by students in practical situations of everyday life, the objective of this study is to investigate whether there are AC in the understanding of science or biology teachers about the process of meiosis and, if so, to identify the nature of these conceptions. In addition, we sought to analyze whether the possible AC present among teachers coincide with those shared by biology education students previously identified (Sousa et al., 2023), in order to verify a possible cycle of AC propagation among teachers, which persists from initial training to teaching practice and is well documented in the literature among students.

Research focused on teachers is essential, since the consolidation of non-scientific conceptions represents an obstacle to the development of scientific literacy. This challenge manifests itself from the development of the conceptual axis of literacy, its contextualization and understanding of more complex processes, to the application of scientific knowledge in everyday life, society, the environment, and sociocultural interactions. The persistence of AC not only hinders the constant updating of knowledge derived from scientific and technological advances in the field of genetics, but also favors the predominance of traditional approaches in teaching practices, compromising the implementation of educational innovations capable of overcoming weaknesses in the teaching of topics in this area, such as the process of meiosis.

Methodological Approach

This article presents an excerpt from doctoral research begun in 2023 at a Brazilian university. A quantitative approach is used, based on the application of a specific data collection instrument. The sample population, which was the subject of the study, consists of teachers from a Brazilian state, and the data were collected in the first semester of 2023 using this instrument, whose initial purpose is to provide statistical descriptions of the AC prevalent among respondents regarding the topic of meiosis. This is an intersectional *survey*, whose data were obtained at a given moment from parallel samples: 318 basic education teachers working in the Science or Biology curriculum components and 45 Biological Sciences undergraduates, both groups relevant to the research problem.

The study used the adapted version of the Conceptual Inventory of Meiosis (CIM) as a data collection tool[1]. It should be noted that the CIM was introduced in Brazil by our research group in a previous study that marked the first application of an inventory in the country in the field of biology, aimed at investigating AC. The CIM was originally developed by Kalas et al. (2013) at the University of British Columbia. Concept inventories (CI) are used to diagnose students' understanding of topics in which AC persists. Although they resemble multiple-choice tests, CI differ in that they include distractors based on extensive research to represent common AC. These tools allow us to assess students' level of conceptual understanding and identify where their reasoning has stagnated. The development of CI involves a systematic process, which includes literature review, pilot testing, and interviews with experts and students (Adams & Wieman, 2011).

The CIM covers the following conceptual categories: ploidy; relationships between DNA quantity, chromosome number, and ploidy; chronology of key events during meiosis; pictorial representation of chromosomes; purpose and outcome of meiosis; differences between mitosis and meiosis; and other cellular events. The CIM items are divided into conventional multiple-choice items and multiple-response items; in the latter, students can select all the alternatives they consider correct. The items are also classified according to Bloom's Taxonomy of Cognitive Domain[2], which organizes

1 Sousa, L., Tavares, M., & Vilas-Boas, A. (2025). *Inventário Conceitual de Meiose*. Zenodo. https://doi.org/10.5281/zenodo.17651626

2 Bloom's Taxonomy of the Cognitive Domain is a classic reference for the hierarchical organization of cognitive skills developed in the learning process. Proposed by Bloom et al. (1956) and revised by Anderson and Krathwohl (2001), the taxonomy structures educational objectives into increasing levels of complexity. In the CIM, items were classified into four levels: Knowledge (recall of information), Comprehension (interpretation of content), Application (use of knowledge in new situations), and Analysis (identification of relationships and conceptual structures).

learning skills in a hierarchical and cumulative manner, in increasing levels of complexity, namely: Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation (Anderson et al., 2001; Cullinane & Liston, 2016).

The CIM was administered via an online form on the Google Forms platform in order to achieve greater respondent participation. The educators who agreed to participate in this study answered additional questions, beyond those related to professional knowledge, in order to outline the profile of the respondents.

In order to forward the invitation to state-run schools, the project and the REC[3] Substantive Opinion were submitted for review by the Subsecretariat for Higher Education of the Minas Gerais State Department of Education (SEE MG). The authorization involved filling out a Term of Commitment for the use, storage, and disclosure of research data.

The email providing general information about this project, the link to the data collection tool, alongside other relevant instructions were sent to state educational institutions through the Regional Superintendents of Education (RSE) of the municipalities of Minas Gerais and directly to the institutional email addresses of the schools. The attempt to contact private schools was made through the Union of Private Schools of Minas Gerais (Sinepe MG).

When inviting schools to participate, care was taken to explain to teachers the objectives and importance of this study for the advancement of teaching and learning in genetics, with the aim of motivating them to participate. In order to ensure transparency of results, teachers were instructed to complete the instrument without consulting support materials.

Quantitative analyses were developed by distributing item scores dichotomously: one point for correct items and zero for incorrect items. No partial credit was awarded for multiple-choice (MC) items when the selected answers did not fully correspond to the correct answer key. The percentage of selection for each particular alternative or combinations thereof (a+b, a+b+d, a+c...) made it possible to identify overall performance, the percentage of correct answers for each item, patterns of incorrect answers, and items whose distribution of selected alternatives most closely approximated the scientific concept.

In order to identify preferences for specific distractors over the correct alternative(s), the items were categorized as proposed by Smith & Knight (2012) as follows: 1. No obvious difficulty: when 80% or more teachers answered a given item correctly; 2. No specific incorrect idea: when less than 80% of teachers answered an item correctly, but no distractors or specific combinations thereof were selected preferentially over other possible alternatives or combinations; 3. When less than 80% of teachers answered an item correctly and more than 20% preferentially selected a specific distractor

3 This research was approved by the Research Ethics Committee (REC) of the Federal University of Minas Gerais, under opinion number 88856618.6.0000.5149, which took into account the ethical principles of educational research, preserving the identity, privacy, safety, and well-being of the participants. The teachers agreed to the Informed Consent Form.

or a specific combination of distractors. This specific incorrect answer selected by 20% or more of teachers was named Common Alternative Concept (CAC). To analyze the proportions of correct alternative selection compared to the distractors preferentially selected by teachers in each item, the chi-square homogeneity test was applied (Agresti, 2007).

In addition to analyzing the data collected from the conducting teachers, this research also incorporated a comparative study with data from a master's thesis conducted by our group between 2019 and 2021. In that study, seventy undergraduate students in Biological Sciences at a Brazilian public university responded to 12 items of the CIM in September 2020 (Sousa et al., 2023). For comparison purposes, 45 students from this group were selected, considering that the focus of this research is on teachers—both those in training and those already working. The comparison between groups involved overall and item-by-item performance, as well as the main shared AC in relation to the genetic concepts evaluated.

To analyze the overall performance of practicing teachers and teacher trainees, the calculation considered the number of correct answers among the different numbers of items that both groups were given. The Shapiro-Wilk test was applied, under the null hypothesis that the scores follow a normal distribution (Kabacoff, 2015). Due to the non-normality, the non-parametric Mann-Whitney test was used, under the null hypothesis that there is no difference between the scores obtained by the groups (Weaver et al., 2017). The comparative analysis of the number of correct answers per item among respondents was conducted using Fisher's exact test, under the null hypothesis that the variables are independent (Agresti, 2007).

Finally, a comparative analysis was performed to assess differences in the performance of practicing teachers according to their length of experience and level of training using the Kruskal-Wallis test, under the null hypothesis that there are no significant differences in teachers' scores. Next, Dunn's post-test with Bonferroni correction was performed to identify which groups are statistically different. In all statistical tests performed, a significance level of $\alpha = 5\%$ was considered. The analyses were performed using R software (R Core Team, 2023).

Results and Discussion

Profiles of Participating Teachers

The teachers participating in this study work in state and private educational institutions. Most respondents (91.1%) belong to the state education network. The teachers come from 166 municipalities in the state of Minas Gerais, which has a total of 853 municipalities (IBGE, 2022). The number of teachers per municipality ranged from one to nine participants. The study was conducted with teachers in the final years of elementary school and high school, since the central theme of this research is present in the curriculum of both levels of education in Minas Gerais (Minas Gerais

Reference Curriculum, 2025). Approximately 70% of teachers responded regarding their initial training course; of these, 91% hold degrees in Biological Sciences and the rest have degrees in other areas of Natural Sciences or Health Sciences, such as Physics, Chemistry, Nursing, and Nutrition. It is important to note that teachers with degrees in related fields can work in elementary education, especially in contexts where there is a shortage of teachers trained in Biological Sciences.

The group of teachers in this study was heterogeneous in terms of academic background and professional experience. The overall performance of teachers was measured by considering the average number of correct answers in the 15 items considered and the median. Considering the experience factor, there was no significant difference between the groups ($p = 0.54$). Teachers with less than ten years of experience had an average of 3.6 ± 2.8, as did teachers with more than twenty years (3.6 ± 2.8). Teachers with ten to twenty years of experience had a slightly higher average of 4.2 ± 3.5, although the median for all groups was 3.0 (Table 1). Therefore, the distribution of performance across different experience ranges suggests that experience does not directly correlate with better performance. Although most teachers with 10 to 20 years of experience achieved scores equal to or greater than 60%, the difference in relation to groups with less than 10 years and more than 20 years of experience is not sufficient to conclude that experience is a determining factor in understanding the genetic concepts evaluated.

In terms of education, 61.7% of teachers had completed higher education, 2.5% had incomplete higher education, and the remaining 35.8% had completed or were currently enrolled in postgraduate studies. Of the 34 teachers who achieved a performance equal to or greater than 60%, 76.5% have completed or are currently enrolled in postgraduate studies (master's, doctorate, and specializations), suggesting a correlation between continuing education and understanding of the concepts covered in the CIM. However, the specific area of postgraduate study was not specified in the data collection.

Table 1

Comparative Analysis of Teacher Scores According to Teacher Training and Experience

Factor	Group	N	Mean ± SD	Median	Kruskal-Wallis, p
Education	Completed postgraduate studies	85	5.2 ± 3.8	4.0	< 0.001
	Postgraduate studies in progress	29	4.9 ± 3.9	4.0	
	No postgraduate degree	204	3.1 ± 2.4	3.0	
Experience	<10 years	107	3.6 ± 2.8	3.0	0.54
	10-20 years	129	4.2 ± 3.5	3.0	
	>20 years	79	3.6 ± 2.8	3.0	

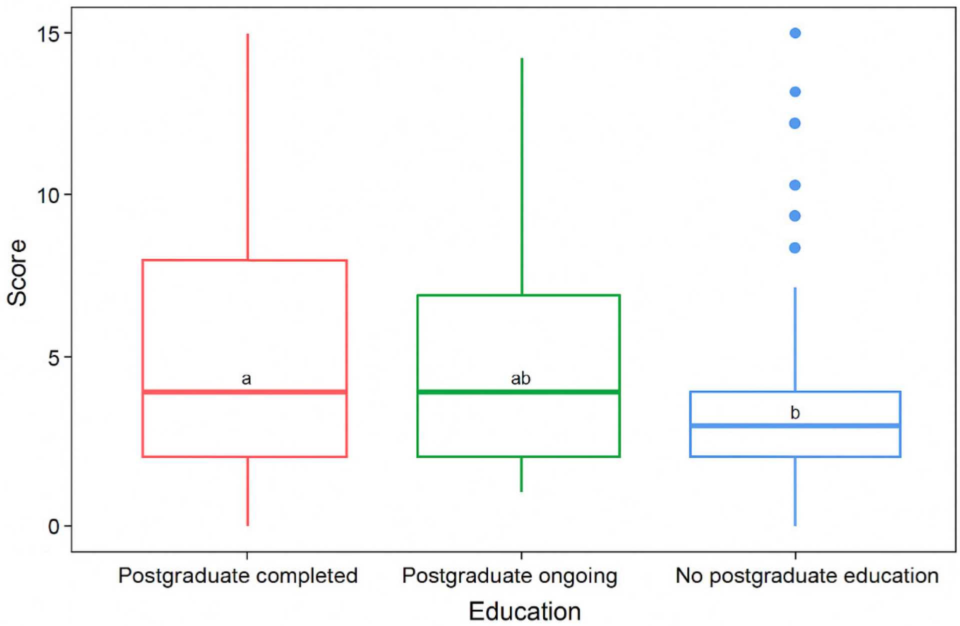
Note. N: number of observations; SD: standard deviation.

Teachers who had completed postgraduate studies had a higher average score (5.2 ± 3.8) compared to those who were currently enrolled in postgraduate courses (4.9 ± 3.9) and teachers without a postgraduate degree (3.1 ± 2.4), with a significant difference ($p < 0.001$) according to the Kruskal-Wallis test. The median was 4.0 for the first two groups and 3.0 for the last group (Table 1).

Figure 1 shows the distribution of teachers' scores according to their training and the analysis using Dunn's test with Bonferroni correction. Comparisons between groups are indicated by letters, where groups sharing the same letter do not show statistically significant differences. The data in the figure suggest that teachers with completed postgraduate degrees obtained higher scores compared to those without postgraduate degrees. Teachers currently pursuing postgraduate studies have an intermediate score, with no difference compared to the other groups.

Figure 1

Distribution of Teacher Scores by Education



Note. Groups with the same letter are not statistically different at 5% significance.

The results suggest that factors other than teaching experience influence AC persistence. These factors may include initial and continuing training, for example, where inconsistent knowledge may have been consolidated or not overcome. In related areas, however, such as Biological Evolution, professional experience proved to be fundamental for understanding concepts and identifying AC by practicing teachers in Germany (Hartelt et al., 2022b).

Regarding academic background, although the area of postgraduate study was not specified by the teachers, the superior performance of postgraduate teachers may be associated with the personal and professional development that postgraduate study provides. This advanced training process not only results in the acquisition of new technical and specialized skills, but also strengthens essential competencies such as critical thinking, analytical skills, and the ability to solve complex problems.

Filho et al. (2021) emphasize that continuing education courses in genetics—although not frequently reported in the literature—can help mitigate inefficient university education, specifically in the use of active methodologies (useful for visualizing processes that occur at the molecular and cellular levels) and overcoming difficulties in understanding topics in this area. The authors report on the enriching participation of high school biology teachers in a continuing education course in genetics. Theoretical and practical difficulties were minimized through conceptual revisions and the presentation of alternative methodologies that took into account the students' multiple intelligences.

Although continuing education courses are not necessarily associated only with teachers' self-perception of their conceptual needs, but also related to the pursuit of career advancement and salary improvement, it is undeniable that they represent an important path for the improvement of Basic Education, since they contribute to complementing and strengthening initial teacher training. However, in Genetics, reports of such courses are scarce in the literature (Filho et al., 2021; Marques et al., 2017), which highlights the importance of creating others in this area marked by constant updates.

Comparative Study Between Trainee and Practicing Teachers: Alternative Conceptions of the Process of Meiosis

A previous study conducted by our group at a Brazilian public university between 2019 and 2021 reported AC shared by freshmen and senior students majoring in Biological Sciences regarding basic concepts related to the process of meiosis. The conceptions were identified based on the application of 12 items from the CIM and cognitive interviews. Graduating students, who had already taken courses in genetics and other related subjects, performed similarly on the CIM compared to freshmen, who had not yet been exposed to this content in their undergraduate studies. Furthermore, regarding many concepts addressed in the inventory, both groups analyzed shared the same AC, such as cell ploidy, chromosome structure, and underlying molecular processes, despite the greater academic experience of the veterans (Sousa et al., 2023). This intriguing fact led to a comparative study between teacher trainees and teachers in active service, aiming to understand the persistence or overcoming of AC throughout professional experience.

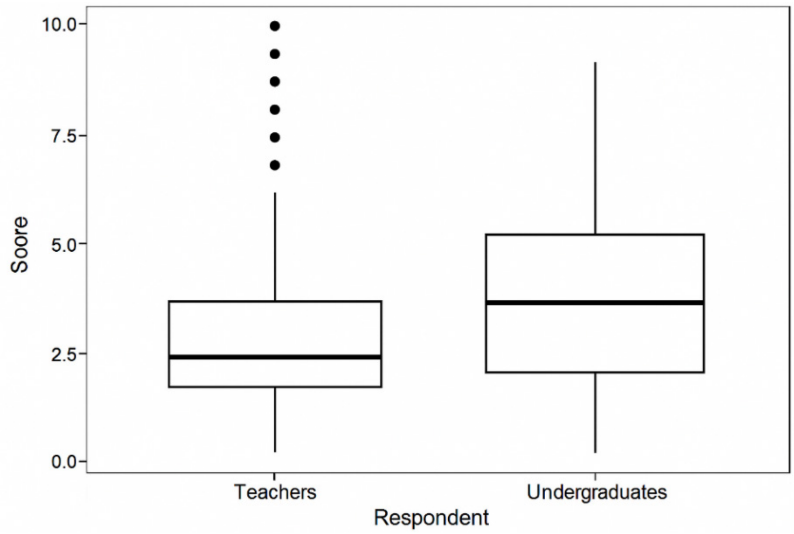
In this section, we sought to compare the understanding of the meiosis process among teacher trainees and practicing teachers based on the following criteria: overall performance and performance per item on the CIM and shared AC. Analyzing the overall performance of the licensees (N=45) and teachers (N=318) who took the CIM, it was observed that the groups obtained average scores of 3.57 (SD = 2.21) and 2.56 (SD = 2.07), with medians of 3.33 and 2.00, respectively. The p-value of the Mann-Whitney test ($p < 0.001$), comparing the values between the groups, led to the conclusion that the difference in scores between teacher trainees and teachers is significant, indicating that teacher trainees performed better than practicing teachers on the items considered.

In this study, the sample of teachers (N = 318) was substantially larger than that of undergraduate students (N = 45). This difference is due to the availability of participants and the scope of the studies, as the participating undergraduate students came from a single public university, while the teachers are part of the Minas Gerais state school system. However, the difference in sample size does not compromise the validity of the analysis, as the statistical methods used for comparison are appropriate for the data structure, considering unbalanced samples, such as Fisher's exact test and Mann-Whitney test. In addition, confidence interval analyses were performed to indicate the reliability of the estimates.

Figure 2 presents a graphical comparison of the scores obtained in the CIM by students and teachers. The median and distribution of the grades of the graduate students shifted to higher values compared to those of the teachers, suggesting that most graduate students obtained higher grades than most teachers. Despite the differences observed between the groups surveyed, the medians for both indicate a score of less than 30% of the total possible points, which suggests unsatisfactory performance for both practicing teachers and teachers in training.

Figure 2

Performance scores for students and teachers in the CIM



Note. the box plots suggest superior overall performance by trainee teachers (undergraduates). The interquartile range reveals that teachers' grades are more concentrated, while those of undergraduate students show greater dispersion. Also noteworthy is the presence of atypical values in the group of teachers, with some higher scores classified as *outliers* in relation to the rest of the group. The other scores in this group were concentrated at lower levels.

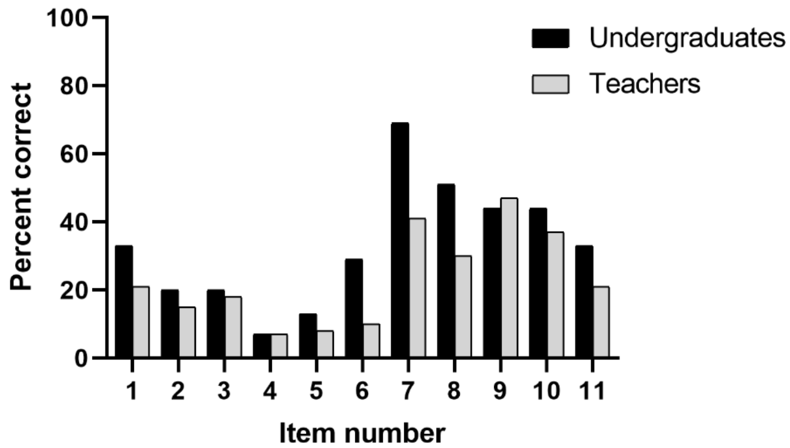
Figure 3 shows the percentage of correct answers by teacher trainees and teachers on items 1 to 11 of the Meiosis CI, which both groups were required to complete. In items 6, 7, and 8, the trainees performed better than the teachers, with significant differences according to Fisher's test; in the other items, no differences were observed at the 5% level.

The reason for the respondents' unsatisfactory performance is multifactorial and demonstrates that the impact of AC on the understanding of genetic concepts is an important factor in helping to explain the results obtained in the CIM. ACs influence the responses of undergraduate students and teachers, regardless of their level of experience.

The superior performance of graduates in some items may be related to more recent and up-to-date theoretical knowledge, reflecting their proximity to the academic content of studies and subjects related to genetics. Furthermore, genetics may not be part of the regular teaching and research activities of some practicing teachers. The trainee teachers are in the process of training and engaged in acquiring theoretical knowledge, while the other group is in the process of practical experience and approaches with theoretical content, and didactic-pedagogical updates are necessary (Marques et al., 2017).

Figure 3

Percentage of correct answers among students and teachers for each item on the CIM



However, despite the observed difference in performance, it should be noted that meiosis is a challenging topic for both trainee teachers and those already in the profession. This difficulty may be related to the intrinsic complexity of the subject, which requires an understanding of dynamic molecular and microscopic processes and involves concepts that are often confused, such as homologous chromosomes and sister chromatids, haploid and diploid cells, etc. In addition, shortcomings in initial training, lack of professional development, and ineffective teaching methodologies may contribute to this difficulty.

Common Alternative Conceptions (CACs)

Table 2 shows the items classified in category III, in which a preference for specific distractors was found, the CACs (see Methodological Approach), which are of particular interest because they point to concepts that do not aid in understanding the process of meiosis. The items of the Meiosis IC are named in this study as follows: 1 to

11 are the items that were applied in this study to practicing teachers and previously to teacher trainees (Sousa et al., 2023); items named A to D are those applied only to teachers in this study.

Table 2 shows the comparative analysis between the proportion of selection of the correct alternative and the distractor preferably selected by teachers, according to the Chi-square test. In all items in category III, except item 7 ($p = 0.63$) and item C ($p = 0.30$), teachers showed a significant tendency to choose distractors over correct alternatives ($p < 0.001$). The preferred distractors will be designated as CACs.

The other CIM items not included in Table 2 are those in which no CACs were detected, specifically in category II, in which no distractor was preferentially selected. There were no items classified in category I (>80% correct), which indicates that the concepts addressed in the CIM are challenging for the teachers surveyed.

Table 2

Comparison between the Correct Alternative and the Preferred Distractor for Teachers

Question	Correct answer	Distractor	Chi-square p
Item 1	21.5% (68)	69.4% (220)	< 0.001
Item 2	15.1% (48)	65.9% (209)	< 0.001
Item 3	17.9% (57)	57.7% (183)	< 0.001
Item 5	7.6% (24)	35.3% (112)	< 0.001
Item 7	41.5% (131)	43.9% (139)	0.63
Item 11	21.6% (67)	49.7% (154)	< 0.001
Item A	20% (63)	64.4% (203)	< 0.001
Item C	40.8% (125)	35.6% (109)	0.30
Item D	13.4% (42)	30.4% (95)	< 0.001

Figures 4 to 9 detail representative items of the main CACs identified on the following concepts: cell ploidy; pictorial representation of chromosomes and DNA replication; relationship between chromosomes and the DNA molecule; gametogenesis and chromosomal segregation; changes in the amount of DNA in the cell cycle; and chronology of events in meiosis. In the description of the items, some alternatives or combinations of these indicated by teachers were not included, as they do not represent a significant percentage of choices.

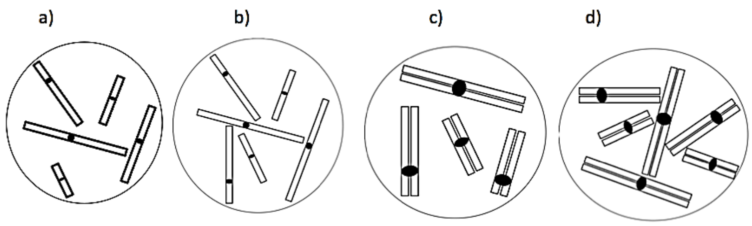
Regarding the conceptual category of *Ploidy*, undergraduates and teachers demonstrate difficulty in conceptualizing the term, a skill assessed in **item 1**[4], of lower cognitive order in Bloom's category, which requires the ability to recall the knowledge assessed. The teachers achieved a pass rate of 21.5% and the undergraduates achieved 33% ($p<0.001$). Both groups share the view that the absolute number of chromosomes determines the ploidy of a cell or organism, specifically 68.8% of teachers. This AC was also shared among 31% of the 193 undergraduates who underwent CIM in their country of origin (Kalas et al., 2013). In this reasoning, haploid cells would always have fewer chromosomes than diploid cells, regardless of the species to which they refer.

4 For further information, see: https://doi.org/10.5281/zenodo.17651626.

The difficulty in conceptualizing cellular ploidy extends to more complex cognitive skills, such as applying knowledge to interpret new situations, in the case of item 2 (Figure 4), in diagrams (Bloom Level III — application). It is observed that 65.9% of teachers understand that haploid cells cannot have chromosomes composed of sister chromatids. Kalas et al. (2013), in the process of developing the CIM, identified the same concept among 23% of undergraduate students (n=193).

Figure 4

Information about Item 2

Summary of item 2 – MC format	
Concept evaluated: cell ploidy	
Bloom's Level: III	
[select all that apply] One or more of the cells shown below are haploid. Mark which cell(s) this/these is/are. 	%
A + B	65.9
A + C	15.1
Other alternatives or combinations	19.0

Note. the combination of correct alternatives is highlighted in green and the CAC in red. The second column shows the percentage of teachers who chose each combination of alternatives. MC: multiple-choice item.

Another possible interpretation is that there may be confusion between the concepts of sister chromatids and homologous chromosomes. Thus, if sister chromatids exist, the subjects tested may conceive of the cell as diploid. It is suggested that the different representations of chromosomes found in literature and textbooks contribute to the emergence of this concept (Newman et al., 2020). The inappropriate use of language, such as the use of images to represent abstract structures and phenomena, can distort scientific knowledge and create obstacles to learning (Bachelard, 1996). This can cause AC or reinforce it in formal education. Infante-Malachias (2010), for example, reports on the difficulty Brazilian undergraduate students from different areas of health and biology have in identifying sister chromatids in diagrams.

The difficulty in distinguishing homologous chromosomes from sister chromatids may stem from debatable representations, such as those illustrating chromosomes in the form of an "X" or as two vertical bars connected by the centromere, in addition to the absence of further clarification on the different representations.

According to Newman et al. (2021), representational competence in biology—the ability to correctly interpret and use specific visual representations—is fundamental, as biology is a field that encompasses scales ranging from the atomic to the ecosystemic level.

The confusion between a basic genomic set and two complete copies of the genome was also evident in **items 3** and **A**[5]. In item 3, participants were asked to identify diagrams representing diploid cells. It was observed that 57.7% of teachers selected only representations of cells with duplicated chromosomes, even though some were haploid. In item A, teachers were asked to choose the most appropriate ploidy notation to describe a cell illustrated in a diagram. Although the cell represented was triploid (3n=6), 64.4% of respondents indicated the notation 2n=6. These results reiterate the AC that ploidy is related to chromosome structure, rather than to the number of complete genomic sets present. In other words, the presence of duplicated chromosomes tends to be mistakenly interpreted as indicative of diploidy. This AC was also observed among 71% of the graduates, reflecting the difficulty in distinguishing and generalizing the concepts of haploid and diploid from the initial training stage to teaching practice.

Kindfield (1994), in his study conducted at the University of California, already suggested that a possible explanation for the incorrect association between cell ploidy and chromosome structure lies in the understanding that cell ploidy changes due to DNA replication. Therefore, DNA synthesis would increase the number of chromosomes, and a haploid cell would become diploid, or diploid cells would become tetraploid (Wright et al., 2017). This AC was also identified in **item 6**[6] among approximately 23% of teachers in this study and 40% of students in the study by Kalas et al. (2013), demonstrating that it is an understanding shared by individuals from different backgrounds and levels of education, highlighting the importance of emphasizing, during teaching, the clear distinctions between chromosome configurations, number of chromosomes, and ploidy.

Another factor that may contribute to this AC is the idea that sister chromatids form when non-duplicated homologous chromosomes from haploid cells unite, giving rise to a diploid cell, as in the case of the zygote (Kindfield, 1994; Wright & Newman, 2011). Wright et al. (2017) attribute a simpler explanation to this AC, the idea that the prefix "di" signals two of something and there are two visible chromatids—which explains why students describe a post-meiosis I cell as diploid.

The same ACs on ploidy are observed in recent literature among Brazilian teacher trainees (Guerra et al., 2022) and among biology students from various courses at a university in the United States (Wright et al., 2017). These misconceptions persist, in part, due to the complexity of the concept, which requires connection to other genetic terms within a conceptual network, such as homologous chromosomes, alleles, sister chromatids, among others. Furthermore, it is possible that the concept of ploidy is not given due emphasis in training courses, being treated only superficially, since it is addressed as basic content in high school. As a result, many teachers end up simply revisiting the topic in a simplified form in higher education courses (Guerra et al., 2022).

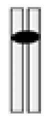
5 For further information, see: https://doi.org/10.5281/zenodo.17651626.
6 For further information, see: https://doi.org/10.5281/zenodo.17651626.

Consolidated ACs among practicing teachers can be disseminated among students and hinder understanding of meiosis and related topics. This scenario highlights the need to rethink the teaching strategies employed so that this concept can be addressed more effectively, considering that the concept of ploidy needs to be examined and explained at the chromosomal and molecular levels of DNA, giving it the emphasis and detailed attention it requires.

In the conceptual category *Relationship between DNA and Chromosomes*, there is a difficulty in articulating the fields of Genetics and Molecular Biology, both among undergraduate students and teachers. In Figure 5, relating to item 5, it is clear that teachers find it difficult to correlate the pictorial representation of a duplicated chromosome with the process of genetic material replication. Only 7.6% of teachers and 13.3% of undergraduates can identify a chromosome that has undergone DNA replication, correctly associating this process with the presence of sister chromatids.

Figure 5

Information about Item 5

Summary of item 5 – MC format	
Knowledge assessed: representation of chromosomes, relationship between chromosome structure (sister chromatids or not) and DNA replication	
Bloom's Level: II-III	
[select all that apply] Sometimes chromosomes are represented as "Xs" or as in the image on the right. This image represents a 	**%**
a) chromosome composed of two sister chromatids.	35.3
b) chromosome that has undergone DNA replication.	5.4
c) chromosome in its diploid state.	10.7
d) pair of homologous chromosomes.	19.5
A+B	7.6
Other combinations of alternatives	21.5

Note. the combination of correct alternatives is highlighted in green and the CAC in red. The second column shows the percentage of teachers who chose each combination of alternatives. MC: multiple-choice item.

The AC observed in item 5 corroborates findings documented in the literature among students. Guerra et al. (2020) observed difficulties in different aspects of genetic material replication in meiosis diagrams produced by Brazilian undergraduate students, which were also observed among British primary school students in a model-building activity (Brown, 1990). ACs include representations of chromosomes that are not duplicated after interphase and chromosomes with different sister chromatids, highlighting the difficulty in relating chromosome structure to the underlying DNA replication process.

Wright et al. (2020) discuss the DNA Triangle Model, which integrates three different scales on which DNA can be considered: chromosomal (C), molecular (M), and informational (I) levels. Level C describes the structure of chromosomes, including their count; it is the scale at which DNA is visible under a microscope. Level I describes how DNA encodes genetic information, such as protein-coding regions or regulatory information. Level M describes the chemistry and nucleotide sequence of DNA, which is crucial for molecular interactions. This study highlights the difficulty teachers have in articulating the three scales, focusing on level C.

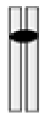
The duplication of genetic material is a crucial molecular process for understanding how DNA is transmitted from one generation to another, and is fundamental to the continuity of the species. In this sense, it is important that teachers emphasize the inseparability between molecular processes and cellular structures and incorporate a more interdisciplinary approach into their teaching practices in genetics courses. In this area, the lack of association between the molecular mechanisms underlying genetic concepts, such as genes and gene expression, is observed, for example, among biological science students in the United States (Newman et al., 2021).

Item 5 also assesses understanding of the pictorial representation of chromosomes. Once again, it is observed that approximately 20% of teachers confuse the representations of sister chromatids and homologous chromosomes. The AC identified in the interpretation of the two-dimensional model of the item may stem from the difficulty in establishing a consensus on the conformation of chromosomes: whether they are X-shaped (the usual representation, as described in textbooks) or whether the sister chromatids are arranged in parallel, connected by the centromere (a less common representation) (Mendonça et al., 2022).

Figure 6 shows item 7 of the conceptual category *Relationship between DNA Quantity and Number of Chromosomes*. The item requires respondents to understand one of the different chromosomal representations and recognize the material that makes up these structures. However, the difficulty of coordination between Genetics and Molecular Biology is corroborated. The teachers (~44%) confirmed the concept that each duplicated chromosome is composed of a DNA molecule, therefore, each chromatid would represent one of the DNA strands, which are complementary and represented by the attached bars. Among the undergraduates, however, no obvious difficulties were detected in the same item.

Figure 6

Information about Item 7

Summary of item 7 – SC format	
Knowledge assessed: representation of chromosomes and the relationship between chromosomes and DNA	
Bloom's Level: II-III	
[select all that apply] The object shown on the right is composed of 	**%**
a) four single-stranded DNA molecules.	<5%
b) a double-stranded DNA molecule.	43.9
c) two double-stranded DNA molecules.	41.5
d) two single-stranded DNA molecules.	10.1

Note. the combination of correct alternatives is highlighted in green and the CAC in red. The second column shows the percentage of teachers who chose each combination of alternatives. SC: single-choice item.

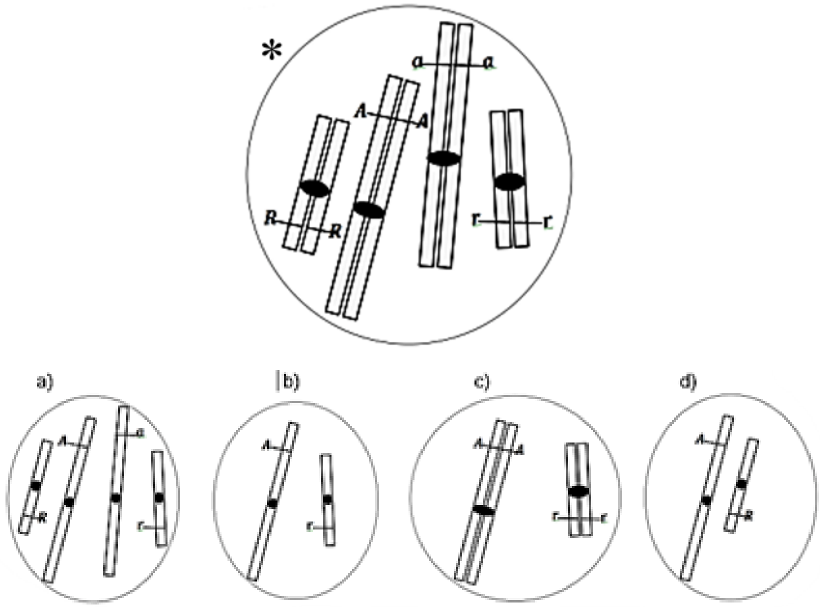
This AC suggests that teachers have difficulty connecting and using knowledge about DNA at the chromosomal, molecular, and informational levels simultaneously (Wright et al., 2020). It is plausible that the conceptual construction regarding these aspects in initial training was flawed at some level. Furthermore, it is possible that elementary school biology textbooks, which are essential support material for teachers, do not emphasize the relationship between concepts that span different biological scales. Thus, the process of meiosis is presented on a chromosomal scale rather than a molecular scale, favoring the separation between levels.

The study by Saka et al. (2006) explores the understanding of three fundamental genetic concepts—gene, DNA, and chromosome—among students of different age groups and among teachers-in-training in the fields of science and biology in Turkey. According to the authors, one of the sources of AC in students' minds is the teachers' own AC. The study found that the undergraduates did not establish a relationship between the concepts of genes, chromosomes, and DNA in diagrams requested from the research participants, demonstrating simplified and inaccurate conceptions. Only 20% of future biology teachers drew all the concepts correctly, which demonstrates the difficulty of connecting the genetic concepts covered. Similarly, high school students from Brazilian public and private schools demonstrate that the correlation between DNA and chromosomes is a constant challenge (Lima et al., 2007).

Half of the teachers in this study also demonstrated difficulty in distinguishing cells resulting from meiosis, maintaining the notion that, genetically, a gamete resembles a post-mitotic cell. This perception was also observed among undergraduate students in the same proportion. Item 11, shown in Figure 7, comprises levels III (application) and IV (analysis) of Bloom's cognitive skills, requiring teachers to be able to relate key concepts and events of meiosis, such as segregation of homologues and sister chromatids, ploidy, chromosome structure, and gene allele arrangement, in order to understand the end products of meiosis through diagrams.

Figure 7

Information about Item 11

Summary of item 11 – MC format	
Knowledge assessed: assess understanding of gametogenesis and chromosome segregation	
Bloom’s Level: III-IV	
[select all that apply] The parent cell (*) shown below undergoes normal meiosis I and meiosis II and produces four daughter cells. Which of these cells could it be? 	%
A	49.7
C	10.6
B+D	21.6
Other alternatives or combinations	18.1

Note. the combination of correct alternatives is highlighted in green and the CAC in red. The second column shows the percentage of teachers who chose each combination of alternatives. MC: multiple-choice item.

Sometimes, the terms mitosis and meiosis cause confusion, as they are similar and both processes refer to the behavior of chromosomes and cytokinesis. In item 11, it is difficult to distinguish the outcomes of both types of cell division. Although many students know what the final products of meiosis should look like, they make several mistakes in their models of the process as a whole (Guerra et al., 2022; Kindfield, 1994; Wright & Newman, 2011; Newman et al., 2012). This is because they do not consider the molecular structure and behavior of DNA during cell division, such as the pairing of homologues based on homology at the DNA sequence level, which allows chromosomes to interact and guides accurate segregation, ensuring chromosomal stability in daughter cells. The absence of a more in-depth approach, at the molecular and informational level, contributes to the lack of understanding of this process (Wright et al., 2017).

The difficulty in distinguishing between mitosis and meiosis is observed in other items, in which teachers did not show a preference for specific distractors, such as in items 9 and 10[7]. Item 9 addresses a typical process of meiosis, crossing-over, by asking the respondent to identify the type of cell division represented in a diagram of a cell in anaphase II with sister chromatids containing different alleles. About 23% of teachers associated the pictorial representation with the process of mitosis. In item 10, teachers were asked to identify the type of cell division represented in a diagram containing homologous chromosomes aligned in the equatorial region of the cell. Some teachers (23%) confused the representation with the process of mitosis, while others (~21%) were uncertain about the type of cell division. In the study by Kalas et al. (2013), no specific misconceptions were identified in items 10 and 11, whereas in this study, teachers clearly had difficulty recognizing processes inherent to meiosis, suggesting that many of them interpret such events as characteristics common to any cell division.

Item C assesses the cognitive ability to apply knowledge about variations in the amount of DNA in a cell, relating it to the chronology of cell division events in order to interpret these variations at each stage of the process (Bloom's level III — application). The main AC identified in this item is the understanding, present among 35.6% of respondents (Figure 8), that DNA replication occurs during meiosis, specifically in prophase I. This same AC was reported in the study by Kalas et al. (2013), among 33% of students participating in the development of the CIM.

Figure 8

This same AC was reported in the study by Kalas et al. (2013), among 33% of students participating in the development of the CIM

Summary of item C – SC format	
Knowledge assessed: changes in the amount of DNA in a cell during the events of meiosis	
Bloom's Level: III	
[select the best alternative] The amount of DNA in a woman's skin cell before DNA replication is the same as the amount of DNA in	%
a) germ cells in metaphase of meiosis I.	9.8
b) germ cells in the prophase of meiosis I.	35.6
c) germ cells that have completed meiosis I but have not yet started meiosis II.	40.8
d) mature gametes (germ cells that have completed meiosis II).	13.7

Note. the combination of correct alternatives is highlighted in green and the CAC in red. The second column shows the percentage of teachers who chose each combination of alternatives. SC: single-choice item.

7 For further information, see: https://doi.org/10.5281/zenodo.17651626.

Lack of knowledge about the chronology of DNA replication reflects a lack of understanding of interphase and the integral S-phase, including the control of DNA replication through checkpoints, such as the critical point at which the cell only initiates the division process if the replicated DNA is intact.

Although interphase accounts for about 90% of the cell cycle and cell division accounts for the smallest part of this process, teachers may have a simplistic and generalist view of this phase of the cell cycle, defining it as a stage of preparation for cell division or rest after division. Excessive generalization obscures important events in interphase, such as DNA replication and other cellular and metabolic activities (Karatas, 2021).

Molecular processes are particularly challenging because they cannot be directly observed, and DNA is at the heart of these discussions. In cell cycle diagrams, chromosomes are depicted in a more relaxed state during interphase. Since individual chromosomes are not represented at this stage, DNA replication is a hidden process. The duplicated chromosome becomes visible and is represented in prophase, which may have influenced teachers' choice of the preferred distractor in item C (Figure 8).

Still in the conceptual category of the chronology of meiosis events, another elementary concept for understanding this process of cell division is *crossing-over*, a key event for genetic variability. However, there is incomplete knowledge about the behavior of chromosomes during the process, as demonstrated in item D (Figure 9), which sought to assess the cognitive ability to retrieve information, i.e., recall (Bloom's level I). Incomplete understanding of *crossing-over* negatively influences comprehension of related topics, such as gene linkage, genetic mapping, genetic syndromes, and evolution, for example. However, it is a challenging concept even among undergraduate students from different courses (Carvalho & Santiago, 2020).

Figure 9

Information about Item D

Summary of item D – MC format	
Knowledge assessed: chronology of events in the cell cycle and meiosis	
Bloom's Level: I	
[select all that apply] Which of the following events occur during the prophase of meiosis I?	%
a) Crossing-over of homologous chromosomes.	30.4
b) Alignment of homologous chromosomes in the center of the cell	5.8
c) Pairing of homologous chromosomes.	12.8
d) Replication of most of the chromosomal DNA (formation of sister chromatids).	15.7
A+C	13.4
Other combinations of alternatives	21.9

Note. the combination of correct alternatives is highlighted in green and the CAC in red. The second column shows the percentage of teachers who chose each combination of alternatives. MC: multiple-choice item.

Approximately 30% of teachers recall that *crossing-over* occurs in prophase I, however, only 13% associate this event with the pairing of homologous chromosomes. This view stems from the fact that respondents do not consider the correct alignment of homologous pairs to be a prerequisite for recombination. This process is driven by sequence homology and is also essential for accurate chromosome segregation (Wright et al., 2020).

Thinking about the underlying molecular processes would help teachers understand the behavior of chromosomes during cell division, as the process remains implicit when the emphasis is on the end result, i.e., the representation of paternal and maternal chromosomes with exchanged parts and the designations "A" and "a" for alleles (Wright et al., 2022). With this knowledge, they could, in turn, guide their students to discover and learn about these processes that are not directly visible (Newman et al., 2021).

In **item 4**, as well as in items **6**, **8**, **10**, **11** and **B**[8], no preferred AC were identified, i.e., the choice of distractors was relatively balanced from a quantitative point of view. Item 4 assessed the concepts of ploidy, chromosome structure, alleles, and genotypes, asking teachers to identify the correct representation of a diploid plant cell containing two pairs of chromosomes and genotype AaBbDd. The main difficulties observed were concentrated in understanding the structure of chromosomes: approximately 25% of teachers indicated that the most appropriate configuration of a chromosome would be its duplicated form; similarly, in Kalas et al. (2013), 25% of undergraduate students (n=193) understand that real or normal chromosomes have sister chromatids. On the same item, 23% of teachers in this study misinterpreted sister chromatids as two distinct chromosomes. It should also be noted that item B, which addressed the relationship between the DNA molecule and chromosomes, achieved the best performance among participants, with a correct answer rate of around 57%. In item 8, which dealt with identifying the number of chromosomes in diagrams, no specific ACs were found.

It is clear that difficulties in understanding the process of meiosis are not limited to teachers in training or currently teaching, but are also shared by students at different levels of education, including elementary school. Previous studies conducted by our group identified the presence of AC among freshmen in the Biological Sciences course—recent graduates of basic education—evidencing that these conceptions are perpetuated among individuals with different levels of education (Sousa et al., 2023). This suggests that such conceptions are not naturally overcome with progression through the levels of education; on the contrary, they may become consolidated throughout the academic career. This phenomenon can be explained by several factors, such as the inherent complexity of the meiosis process, the traditional teaching approach, and the difficulty students have in establishing connections between cellular and molecular events.

Considering that, as outlined by Silva and Sasseron (2021), scientific literacy is structured around three interdependent axes—the comprehension of scientific concepts, the understanding of nature and scientific practices, and the recognition of

8 For further information, see: https://doi.org/10.5281/zenodo.17651626.

the interrelationships between science, technology, society, and the environment—it is essential to overcome the ACs identified among teachers. The persistence of these concepts in teaching not only compromises students’ conceptual learning, but also interferes with other aspects of literacy, limiting the development of critical, reflective, and socially engaged education. Furthermore, knowledge of poorly developed content is an obstacle to pedagogical knowledge—defined as knowledge about student understanding and instructional strategies that aim to identify and overcome ACs. Action-oriented knowledge, in other words, the validation of information, diagnostic activities, methods that make content understandable, and addressing specific learning difficulties, depend on theoretical knowledge (Fischer et al., 2021).

Conclusion

The main objective of this study was to investigate the understanding of concepts related to the process of meiosis among practicing elementary school teachers, given that this topic involves concepts that are central to the understanding of various topics in genetics and biology, such as genetic variability, chromosomal mutations, the life cycle of living beings, sexual reproduction, speciation processes, and others. It is understood that knowledge of the content, combined with the pedagogical knowledge of teachers, is an essential aspect for the development of scientific literacy in these areas.

The research reinforced evidence from previous studies on the teaching of genetics in basic education and higher education, showing that teachers maintain ACs similar to those observed among students at different levels of education, as documented in the literature, especially on ploidy, chromosome structure, distinctions between mitosis and meiosis, and the molecular basis of cell division. Therefore, it is important to raise awareness among both trainee teachers and those already in the profession, as well as university lecturers, about the ACs that persist after the stages of teaching and professional experience.

The observed reality suggests that professional experience alone is not a determining factor in understanding genetic concepts. Instead, aspects such as initial training, participation in continuing education courses, and the adoption of alternative teaching methodologies can play a significant role in building knowledge about meiosis.

Furthermore, although a considerable majority of teachers have higher education, this does not translate into solid knowledge about genetics. The correlation between higher academic education and performance suggests the need to strengthen initial and continuing education in the field of genetics in order to mitigate difficulties in understanding concepts that directly affect teaching practice and the ability to comprehend related content.

The results obtained not only reveal difficulties in university teacher training, but also indicate specific situations that need to be addressed in order to transform knowledge of content into actions and procedures. New strategies can enable teachers to understand and confront their own ACs, preventing its spread in basic education. Teachers who are aware of their own conceptions and familiar with those of their students will be able to diagnose and deal with the issue more appropriately. It is therefore clear that future research should focus on investigating teachers' knowledge of content in order to plan teaching activities based on the training needs identified.

Finally, the use of the Conceptual Inventory of Meiosis is recommended for elementary school teachers and university professors. The instrument proved to be an effective tool for assessing conceptual understanding among students and professionals, accurately identifying problematic concepts described in the specialized literature on the process of meiosis. AC detection drives the development of innovative teaching methodologies and the creation of teaching materials aligned with conceptual needs. In addition, CIM can be used for a variety of purposes, such as providing instant feedback during teaching, supporting curriculum reforms, and evaluating the effectiveness of alternative teaching strategies.

Research Limitations

This is a cross-sectional study involving teachers of different age groups, professional experience, and educational levels, so it cannot be assumed that the individuals are directly comparable. Furthermore, in the comparative study between graduates and practicing teachers, these differences between the groups analyzed are even more pronounced.

This research is limited to a specific context. Although Minas Gerais is a representative state on the national scene, being the second most populous and fourth largest in terms of land area (IBGE, 2023), the sample does not reflect the total number of teachers in the state, as most participants are from public schools, since there was not the expected response from private school teachers, who were contacted through the union. The generalization of the results of this study to the local context, as well as to teachers from other states and countries, depends on more comprehensive research. However, in our investigations, we did not find any studies that investigated teachers' conceptions of genetic concepts associated with the process of meiosis, which reinforces the relevance of this work, which makes important contributions to research in Genetics Education and can be extrapolated to other contexts.

With regard to the Conceptual Inventory of Meiosis, although this instrument has undergone a validation process in terms of reliability and content, there is a recognized need for specific validation of the translation stage, in order to ensure semantic equivalence in relation to the Portuguese language spoken in Brazil, as well as to guarantee the accuracy of the test.

Outlook

The next steps in this study include investigating the reasoning adopted by teachers in solving CIM items through cognitive interviews. In addition, semi-structured interviews will be conducted in order to understand the main difficulties faced in teaching meiosis. The research will also involve a qualitative analysis of participants' verbalizations and observations in the school environment, aiming to explore teachers' pedagogical knowledge in the context of teaching genetics.

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References

Adams, W. K., & Wieman, C. E. (2011). Development and validation of instruments to measure learning of expert-like thinking. *International Journal of Science Education*, *33*(9), 1289–1312. https://doi.org/10.1080/09500693.2010.512369

Agresti, A. (2018). *An introduction to categorical data analysis* (3rd ed.). Wiley.

Anderson, L. W., Krathwohl, D. R., & Bloom, B. S. (2001). A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives. Addison Wesley Longman.

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

Bloom, B. S., Engelhart, M. D., Furst, E. J., Hill, W. H., & Krathwohl, D. R. (1956). The classification of educational goals: Taxonomy of educational objectives (Vol. 1). David McKay.

Carvalho, H. F., & Santiago, S. A. (2020). A fragilidade do ensino da meiose. *Ciência & Educação (Bauru)*, *26*, 1–15. https://doi.org/10.1590/1516-731320200025

Carvalho, Í. N. de, El-Hani, C. N., & Nunes-Neto, N. (2020). How should we select conceptual content for biology high school curricula? *Science and Education*, *29*(3), 513–547. https://doi.org/10.1007/s11191-020-00115-9

Chassot, A. (2003). Alfabetização científica: uma possibilidade para a inclusão social. *Revista Brasileira de Educação*, (22), 89–100. https://doi.org/10.1590/S1413-24782003000100009

Cullinane, A., & Liston, M. (2016). Review of the Leaving Certificate biology examination papers (1999–2008) using Bloom's taxonomy: An investigation of the cognitive demands of the examination. *Irish Educational Studies*, *35*(3), 249–267. https://doi.org/10.1080/03323315.2016.1192480

Dove, J. E. (1998). Students' alternative conceptions in Earth science: A review of research and implications for teaching and learning. *Research Papers in Education*, *13*(2), 183–201. https://doi.org/10.1080/0267152980130205

Filho, R. dos S., Alle, L. F., Cestari, M. M., & Leme, D. M. (2021). Avaliação de um curso de formação continuada como método de capacitação de professores do ensino médio em genética. *Revista de Educação Ciência e Tecnologia*, *10*(1), 1–24. https://doi.org/10.35819/tear.v10.n1.a5068

Gil, S. G. R., Fradkin, M., & Castañeda-Sortibrán, A. N. (2018). Conceptions of meiosis: Misunderstandings among university students and errors. *Journal of Biological Education*, *53*(2), 1–14. https://doi.org/10.1080/00219266.2018.1469531

Guerra, L., Tavares, M., & Vilas-Boas, A. (2022). Persistência de concepções alternativas sobre meiose no ensino de genética entre licenciandos de Ciências Biológicas. *Dynamis*, *28*(1), 1–19. https://doi.org/10.7867/1982-4866.2022v28n1p107-126

Hartelt, T., Martens, H., & Minkley, N. (2022). Teachers' ability to diagnose and deal with alternative student conceptions of evolution. *Science Education*, *106*(3), 706–738. https://doi.org/10.1002/sce.21705

Instituto Brasileiro de Geografia e Estatística (IBGE). (2022). *Censo 2022: Panorama de indicadores*. https://censo2022.ibge.gov.br/panorama/indicadores.html?localidade=BR&tema=4

Joaquim, L. M., & El-Hani, C. N. (2010). A genética em transformação: Crise e revisão do conceito de gene. *Scientiae Studia*, *8*(1), 93–128. https://doi.org/10.1590/s1678-31662010000100005

Kabacoff, R. (2015). *R in Action: Data analysis and graphics with R* (2ª ed.). Manning.

Kalas, P., O'Neill, A., Pollock, C., & Birol, G. (2013). Development of a meiosis concept inventory. *CBE Life Sciences Education*, *12*(4), 655–664. https://doi.org/10.1187/cbe.12-10-0174

Karataş, A. (2023). A Phase Overshadowed by Mitotic Division: Interphase. *Journal of Biological Education*, *57*(2), 317–330. https://doi.org/10.1080/00219266.2021.1909637

Kindfield, A. C. H. (1994). Understanding a basic biological process: Expert and novice models of meiosis. *Science Education*, *78*(3), 255–283. https://doi.org/10.1002/sce.3730780308

Lima, A. C., Pinton, M. R. G. M., & Chaves, A. C. L. (26 de novembro a 2 de dezembro, 2007). *O entendimento e a imagem de três conceitos: DNA, gene e cromossomo no ensino médio*. VI Encontro Nacional de Pesquisa em Educação em Ciências (ENPEC), Florianópolis, Santa Catarina.

Marques, K. C. D., Persich, G. D. O., & Neto, L. C. B. T. (3–6 de julho, 2017). *Formação continuada para professores de Biologia: Curso a distância sobre ensino de genética*. XI Encontro Nacional de Pesquisa em Educação de Ciências (ENPEC), Florianópolis, Santa Catarina.

Secretaria de Estado de Educação de Minas Gerais. (n.d.). *Superintendências Regionais de Ensino (SREs)*. https://www.educacao.mg.gov.br/a-secretaria/superintendencias-regionais-de-ensino-sres/

Mortimer, E. F. (1996). Construtivismo, Mudança Conceitual e Ensino De Ciências: Para Onde Vamos?. *Investigações Em Ensino De Ciências*, *1*(1), 20–39. https://ienci.if.ufrgs.br/index.php/ienci/article/view/645

Mortimer, E. F., Chagas, A. N., & Alvarenga, V. T. (1998). Linguagem Científica Versus Linguagem Comum nas Respostas Escritas De Vestibulandos. *Investigações em Ensino de Ciências*, *3*(1), 7–19. https://ienci.if.ufrgs.br/index.php/ienci/article/view/622

Newman, D. L., Coakley, A., Link, A., Mills, K., & Wright, L. K. (2021). Punnett squares or protein production? The expert–novice divide for conceptions of genes and gene expression. *CBE Life Sciences Education*, *20*(4), 1–10. https://doi.org/10.1187/CBE.21-01-0004

R Foundation for Statistical Computing. (n.d.). *R: A linguagem de programação e ambiente para computação estatística*. https://www.r-project.org/

Saka, A., Cerrah, L., Akdeniz, A. R., & Ayas, A. (2006). A cross-age study of the understanding of three genetic concepts: How do they image the gene, DNA, and chromosome? *Journal of Science Education and Technology*, *15*(2), 192–202. https://doi.org/10.1007/s10956-006-9006-6

Sasseron, L. H., & de Carvalho, A. M. P. (2011). Alfabetização Científica: Uma Revisão Bibliográfica. *Investigações em Ensino de Ciências*, *16*(1), 59–77. https://ienci.if.ufrgs.br/index.php/ienci/article/view/246

Secretaria de Estado de Educação de Minas Gerais. (n.d.). *Plano de cursos CRMG*. https://curriculoreferencia.educacao.mg.gov.br/index.php/plano-de-cursos-crmg

Silva, M. B. e., & Sasseron, L. H. (2021). Alfabetização científica e domínios do conhecimento científico: Proposições para uma perspectiva formativa comprometida com a transformação social. *Ensaio Pesquisa em Educação em Ciências*, *23*, 1–20. https://doi.org/10.1590/1983-21172021230129

Smith, M. K., & Knight, J. K. (2012). Using the Genetics Concept Assessment to document persistent conceptual difficulties in undergraduate genetics courses. *Genetics*, *191*(1), 21–32. https://doi.org/10.1534/genetics.111.137810

Sousa, L. E., Tavares, M. L., & Vilas-Boas, A. (2023). The use of a meiosis concept inventory to identify alternative conceptions among Biological Science first-year students and prospective teachers. *Ciência & Educação (Bauru)*, *29*, 1–18. https://doi.org/10.1590/1516-731320230049

Sousa, L., Tavares, M., & Vilas-Boas, A. (2025). *Inventário Conceitual de Meiose*. Zenodo. https://doi.org/10.5281/zenodo.17651626

Valladares, L. (2021). Scientific literacy and social transformation: Critical perspectives about science participation and emancipation. *Science and Education*, *30*(3), 557–587. https://doi.org/10.1007/s11191-021-00205-2

Weaver, K. F., Morales, V. C., Dunn, S. L., Godde, K., & Weaver, P. F. (2017). *An introduction to statistical analysis in research: With applications in the biological and life sciences*. Wiley.

Wright, L. K., Catavero, C. M., & Newman, D. L. (2017). The DNA triangle and its application to learning meiosis. *CBE Life Sciences Education*, *16*(3), 1–14. https://doi.org/10.1187/cbe.17-03-0046

Wright, L. K., Grace, G. E., & Newman, D. L. (2020). Undergraduate textbook representations of meiosis neglect essential elements. *American Biology Teacher*, *82*(5), 296–305. https://doi.org/10.1525/abt.2020.82.5.296

Wright, L. K., & Newman, D. L. (2011). An interactive modeling lesson increases students' understanding of ploidy during meiosis. *Biochemistry and Molecular Biology Education*, *39*(5), 344–351. https://doi.org/10.1002/bmb.20523

Wright, L. K., Wrightstone, E., Trumpore, L., Steele, J., Abid, D. M., & Newman, D. L. (2022). The DNA Landscape: Development and Application of a New Framework for Visual Communication about DNA. *CBE Life Sciences Education*, *21*(3), 1–8. https://doi.org/10.1187/cbe.22-01-0007

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