

Scientific argumentation of biology students on genetic recombination: Insights from conceptual understanding analysis

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Abstract: Undergraduates still struggle to make high-quality scientific arguments on complex biological topics such as genetic recombination. To construct a scientific argument, students must use evidence and reasoning grounded in scientific concepts. However, research on how well an argument's structure represents the accuracy of a student's conceptual understanding remains limited. This study looked at the structure of students' scientific arguments, their conceptual understanding of genetic recombination, and the relationship between these aspects. A convergent mixed-methods design with 123 undergraduate biology students used in this study. We combined the results obtained from analyzing the written answers to the two tasks using Toulmin's Argumentation Pattern (TAP) and the conceptual understanding categories. The students' arguments were at level 2 (64%), which shows a relatively low-level of argumentation, and conceptual understanding was mainly based on misconceptions (60%). Students with conceptual understanding reached argumentation Levels 3–5, whereas those with partial understanding or misconceptions did not reach Levels 4–5. However, some students with misconceptions also achieved Level 3. Conceptual accuracy thus appears to enable high-level argumentation, yet well-structured arguments can still rest on misconceptions, so argument structure should be complemented by direct verification of conceptual understanding.

Keywords: Genetic recombination, Toulmin's argumentation pattern, misconceptions

Abstrak: Mahasiswa masih kesulitan membuat argumen ilmiah berkualitas tinggi tentang topik biologi kompleks seperti rekombinasi genetik. Untuk membangun argumen ilmiah, mahasiswa harus menggunakan bukti dan penalaran yang berlandaskan konsep ilmiah. Namun, penelitian tentang seberapa baik struktur argumen mewakili keakuratan pemahaman konseptual mahasiswa masih terbatas. Studi ini meneliti struktur argumen ilmiah mahasiswa, pemahaman konseptual mereka tentang rekombinasi genetik, dan hubungan antara aspek-aspek tersebut. Penelitian ini menggunakan desain metode campuran konvergen dengan 123 mahasiswa sarjana biologi. Kami menggabungkan hasil yang diperoleh dari analisis jawaban tertulis untuk dua tugas menggunakan pola argumentasi Toulmin (TAP) dan kategori pemahaman konseptual. Argumen mahasiswa berada pada level 2 (64%), yang menunjukkan tingkat argumentasi yang relatif rendah, dan pemahaman konseptual sebagian besar didasarkan pada kesalahpahaman (60%). Mahasiswa dengan pemahaman konseptual mencapai tingkat argumentasi 3–5, sedangkan mereka yang memiliki pemahaman parsial atau kesalahpahaman tidak mencapai level 4–5. Namun, beberapa siswa dengan kesalahpahaman juga mencapai Level 3. Dengan demikian, akurasi konseptual tampaknya memungkinkan argumentasi tingkat tinggi, namun argumen yang terstruktur dengan baik masih dapat bertumpu pada miskonsepsi, sehingga struktur argumen harus dilengkapi dengan verifikasi langsung terhadap pemahaman konseptual.

Kata kunci: Rekombinasi genetik, pola argumentasi Toulmin, miskonsepsi

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INTRODUCTION

Scientific argumentation skills have become one of the key competencies that need to be developed in college-level biology education. Through scientific argumentation, students must not only present a claim but also evaluate evidence, connect it to scientific concepts, and construct logical reasoning to explain a biological phenomenon (Huang et al., 2016; Ma

et al., 2025). Scientific argumentation skills are crucial for fostering scientific reasoning, critical thinking, and the capacity to assess alternative scientific explanations, essential learning outcomes for students of biology (Giri & Paily, 2020). Furthermore, constructing and refuting arguments enables students to hone the analytical and evaluative skills essential for understanding complex biological concepts (Rawe et al., 2025). Thus, the scientific argumentation skills are increasingly viewed as essential competencies to be developed in different biology courses, especially in topics that require conceptual understanding and scientific reasoning (Anwar et al., 2019).

To understand genetic phenomena, students need to link different concepts, provide explanations of biological phenomena and justify claims with scientific evidence. Scientific argumentation supports this process because it encourages students to build and evaluate explanations for abstract concepts in science, such as genetic phenomena (Green et al., 2015; Jewaru et al., 2023). Abstract concepts typically remain inert unless students actively apply and argue about them. Argumentation helps to bridge the gap between theoretical knowledge and practical understanding, making abstract ideas more accessible and meaningful to students (Fauziah et al., 2024). Consequently, learning genetics requires students to have a conceptual understanding of genetics but also the ability to construct scientific arguments to explain biological phenomena (Anisa et al., 2019).

Among the most complex topics in genetics is genetic recombination. This is the process of exchanging genetic material to produce new combinations of genetic information (Perveen et al., 2025). Genetic recombination occurs in a variety of contexts in the cell, such as during meiosis and in somatic cells. Each of these different contexts for genetic recombination has a variety of different mechanisms and biological functions (Carroll, 2013). For example, crossing over during meiosis results in new combinations of alleles, but genetic recombination in somatic cells plays a role in DNA repair processes (Raina et al., 2025). Thus, genetic recombination involves more than just crossing over during meiosis. Additionally, because of the complexity of the topic, genetic recombination requires students to understand concepts at a variety of different levels (Wright et al., 2022). Explaining these concepts scientifically requires students to construct arguments supported by evidence and logical reasoning (Fakhriyah et al., 2022; Osborne et al., 2004). Therefore, this topic provides a relevant context for exploring the quality of scientific arguments based on students' conceptual understanding.

The ability to construct scientific arguments depends upon both the completeness of the argument's structure and the accuracy of the concepts used within that argument. (Sadler & Fowler, 2006). Toulmin's Argumentation Pattern (TAP) states that the claim, grounds, warrant, backing, qualifier, and rebuttal are parts of scientific arguments. To construct a scientifically accurate argument each of these components requires a correct conceptual understanding of the scientific concepts involved in the argument (Li et al., 2022; von Aufschnaiter et al., 2008). Students' ability to participate in a scientific argumentation is also highly dependent on their prior knowledge of the topic (Acar, 2014). Their skills are strengthened when they are able to organize information and evidence before synthesizing them into a clear argument (Zahra et al., 2021). Generally, students who have a better grasp of these concepts demonstrate a higher level of competence in formulating, explaining, and critiquing arguments with relevant evidence (Liu et al., 2019). Therefore, the evaluation of

the quality of scientific argumentation should consider both the structural elements of the argument and the adequacy of the conceptual framework on which it is based.

Both scientific argumentation and students' conceptual understanding have been the subject of extensive research in science education, but these areas are frequently studied separately (Krell et al., 2024; Mi et al., 2020). In particular, most of the studies in argumentation use the TAP to assess the completeness of students' reasoning. The results frequently reveal that Indonesian students struggle to construct sophisticated arguments and their answers are restricted to basic assertions and corresponding evidence (Gazali et al., 2024; Rahayu et al., 2022; Ramadhan et al., 2026). In these structural analyses, the conceptual accuracy underlying argument construction receives relatively little attention. On the other hand, research on conceptual understanding in genetics has used various diagnostic instruments to identify students' misconceptions about genetic recombination (Azzahra & Kartikawati, 2023; Choirunisa' et al., 2024; Waluyo & Rahardjanto, 2022). Research findings indicate that students still struggle to distinguish the stages and outcomes of mitosis and meiosis. Students find it difficult to understand the mechanisms of meiosis and crossing over that underlie recombination and tend to confuse recombination with other genetic phenomena (Myers et al., 2014; Rusmana et al., 2021). As a result, students' understanding varies from correct conceptual understanding to misconceptions. However, these studies generally identify levels of understanding without examining how this variation is reflected in students' scientific arguments.

Although Amin et al. (2022) examined the relationship between conceptual understanding and scientific argumentation in biology education, their study focused on animal physiology, so research on how conceptual understanding is related to the quality of scientific argumentation on genetic recombination remains limited. This study integrates an analysis of scientific argumentation skills using the TAP framework with an analysis of conceptual understanding based on students' argumentative responses to the topic of genetic recombination, as assessed through open-ended essay questions. Integrating these two analyses provides a more comprehensive profile of students' scientific reasoning. Therefore, this study aims to (1) describe the quality of scientific argumentation among biology students on the topic of genetic recombination, (2) identify students' levels of conceptual understanding, and (3) analyze the characteristics of scientific argumentation within each category of conceptual understanding. The findings of this study are expected to provide empirical contributions to the development of genetics learning strategies that not only improve the quality of scientific reasoning but also strengthen students' conceptual understanding.

METHOD

Research design

A convergent mixed-methods research design was used to explore the quality of scientific reasoning and conceptual understanding of the biology students about genetic recombination. This research design was chosen because data about students' scientific argumentation and conceptual understanding were collected from the same written responses, but analyzed in two different ways. The quantitative approach described the distribution of the quality of the arguments and categories of conceptual understanding. The qualitative approach identified the structure of their arguments, key concepts and

patterns of understanding and misconceptions emerged in their responses. The results of both analyzes were pooled to give a clearer, more complete picture of how students approach scientific reasoning.

Participants

The sample of this research was the undergraduate students of Biology Program at Universitas Negeri Malang who took the Genetics course. Students were considered suitable because their learning experiences were relevant to the aims of the research and they could engage in the study. In total, 123 students participated. Each group responded to one of two argumentative questions to provide research data. The students' answers were the main data. All responses were coded and anonymized before analysis to protect privacy.

Instrument

Before the main study, the instrument with the two open-ended tasks about genetic recombination was validated by two experts in genetics education. The experts rated the scientific accuracy, fit to the intended constructs, and clarity of language in numerical scores and written comments. Feedback from them was used to revise the instrument. Inter-rater reliability was then performed using the responses of 29 undergraduate biology students who were not part of the main sample. Two independent raters rated responses to each task. Reliability was calculated separately for scientific argumentation and conceptual understanding for each task using the intraclass correlation coefficient (ICC). The ICCs were 0.920 and 0.879 for scientific argumentation on Task 1 and 2, respectively, and 0.814 and 0.872 for conceptual understanding on Task 1 and 2, respectively. The questions were written as statements to be evaluated by the students, so students are required not only to say whether a statement is true or false, but also to give reasons and scientific evidence to support their position. We opted for an open-ended question approach because it allows students to better show the structure of their arguments and the conceptual knowledge behind their responses.

The two questions used focused on students' understanding of the relationship between genetic recombination and cell division. Task 1 presented the statement that recombination occurs only through meiosis, while Task 2 presented the statement that in eukaryotes, recombination occurs only through mitosis. In both tasks, students were asked to state their position regarding the given statements and provide examples or scientific evidence to support their opinions.

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Task 1

"Recombination occurs only through meiosis." Do you agree with this statement? Provide an example or scientific evidence to support your opinion!

Task 2

“In eukaryotes, recombination occurs only through mitosis.” Do you agree with this statement? Provide scientific evidence to support your opinion!

Data collection procedure

Before data collection, students were briefed on the purpose of the assessment and asked to provide individual responses based on their existing understanding. During the assessment, each student completed one of two prepared argumentative tasks without using any learning resources or external assistance. After collecting all responses, the students' answers were compiled as written data and anonymized by replacing students' identities with specific codes. All responses were then used as units of analysis to assess the quality of scientific argumentation and students' level of conceptual understanding.

Qualitative data analysis

Qualitative data analysis was conducted to interpret students' reasoning structures by coding their written responses to two argumentative questions regarding the mechanisms of genetic recombination. Each response was examined from two complementary perspectives: (1) the completeness of the argumentative structure and (2) the accuracy of the concepts underlying the argument. These two perspectives were analyzed independently using different coding schemes and then compared during the integration stage to identify patterns of relationships between the quality of argumentation and conceptual understanding.

Coding the quality of arguments

Each response was analyzed using Toulmin's Argumentation Pattern (TAP), adapted from Georgiou et al. (2020), by examining the presence of the components claim, grounds/data, warrant, backing, qualifier, and rebuttal. Based on the combination of components present, each response was classified into five levels of argumentation, as presented in Table 1.

Table 1. Rubric for scientific argumentation skills

Level	Criteria
0	There is no argument
1	Argument contains a claim
2	Argument consists of a claim, data, and/or a warrant
3	Argument consists of a claim, data, warrant, backing or qualifier
4	Argument consists of a claim, data, warrant, backing, and qualifier
5	Argument consists of a claim, data, warrant, backing, qualifier, and rebuttal

Source: Georgiou et al. (2020)

Conceptual understanding coding

The concept understanding coding scheme was developed based on the answer key and patterns identified in students' responses. Each response was carefully examined to identify the main ideas reflecting students' understanding of genetic recombination, including the mechanisms of recombination, the contexts in which the process occurs, and

the resulting genetic consequences. Students were required to differentiate between recombination that occurs in meiosis and recombination that occurs in mitosis, and to distinguish between recombination and other genetic processes. The students' answers were analyzed and scored into one of four categories: Conceptual Understanding (CU), Partial Understanding (PU), Misconception (MC), and No Understanding (NU) for each question.

Answers that show a correct and complete understanding of the mechanisms of genetic recombination and can relate those mechanisms to the cellular context and relevant genetic outcomes are awarded the CU category. The PU category is given to answers that show some understanding but where the explanation of the mechanisms, context or consequences of recombination is still incomplete. The MC category is assigned to responses that demonstrate an understanding that contradicts scientific concepts, including attributing recombination exclusively to a single context or conflating different recombination mechanisms. The NU category is assigned to answers that merely repeat the question's premise, are irrelevant, or do not answer the question. The coding schemes for each question are presented in Table 2 and Table 3.

Table 2. Conceptual understanding coding scheme for task 1

Answer key	CU	PU	MC	NU
I disagree. Recombination is not exclusive to meiosis. It also occurs in somatic cells (mitosis) for DNA repair, and in prokaryotes through horizontal gene transfer (transformation, transduction, conjugation).	Rejecting absolute claims regarding; providing accurate conceptual arguments about the existence of recombination outside of meiosis (e.g., mitosis/DNA repair in somatic cells, or gene transfer in bacteria).	Rejects the claim regarding the issue and acknowledges that there are other processes, but is unable to provide examples of biological mechanisms or specific, accurate locations (too general).	Agreeing with the claim by imposing an incorrect cross-taxonomic mechanism, or misunderstanding the basic concept of recombination (confusing it with single-gene mutations or ordinary cell division).	Answers that simply repeat the premise of the question, do not answer the question, or are irrelevant

Table 3. Conceptual understanding coding scheme for task 2

Answer key	CU	PU	MC	NU
I disagree. Genetic variation in eukaryotes is primarily generated through crossing over during meiosis I; recombination during mitosis serves only to repair DNA, not to generate variation.	Reject the claim and explain accurately that crossing over, which produces variation, occurs during meiosis, while recombination during mitosis serves to repair DNA.	Rejecting the claim, but mentioning only one of the components (e.g., only “meiosis” or only “crossing over”) without fully explaining the mechanisms or functions of both.	Agree with the claim, or explain that recombination /crossing over occurs during mitosis, or confuse eukaryotic mechanisms with prokaryotic ones.	Answers that simply repeat the premise of the question, do not answer the question, or are irrelevant

Quantitative data analysis

Quantitative data analysis was conducted by calculating the frequency and percentage of coding results across two dimensions: the level of scientific argumentation skills based on Toulmin's Argumentation Pattern (TAP, Levels 1–5) and the categories of conceptual understanding (Conceptual Understanding, Partial Understanding, Misconception, No Understanding). The calculations were performed on all students' argumentative responses to both questions, providing an overview of the distribution of students' argumentation levels and conceptual understanding categories regarding the concept of genetic recombination. In the context of argumentation, results of the analysis are presented as frequencies and percentages of students in each of the TAP levels (Level 1 to Level 5), whereas in the dimension of conceptual understanding, results of the analysis are presented as frequencies and percentages of students in each category (CU, PU, MC, NU). These two distributions provide a comprehensive picture of trends in students' argumentation skill levels and variations in their conceptual understanding of the mechanisms of genetic recombination.

To examine the relationship between conceptual understanding and the level of scientific argumentation, separate cross-tabulation analyses were conducted for Task 1 and Task 2. Pearson's chi-square (χ^2) test of independence was used because both variables are categorical: conceptual understanding was coded into four categories and scientific argumentation into TAP levels (0–5), and the aim was to test whether the distribution of argumentation levels differed across categories of conceptual understanding. The test does not require normally distributed data, and the responses were independent because each student completed only one task. Conceptual understanding categories were treated as nominal because the order between some categories is not clearly hierarchical. Because the

contingency table had low expected frequencies in a large number of cells, statistical significance was determined using a Monte Carlo approach with 10,000 samples. Moreover, Cramér's V was employed to estimate the strength of the association as an effect size. Therefore, the interpretation of the findings considered not only statistical significance but also the magnitude of the association between the variables.

Data validity and reliability

Student responses were analyzed independently by two raters using a predetermined rubric to code argumentative structure based on Toulmin's Argumentation Pattern (TAP) and categories of conceptual understanding, including CU, PU, MC, NU. The Intraclass Correlation Coefficient (ICC) was used to calculate inter-rater agreement. The results of the analysis showed a good level of reliability, ICC value for Task 1 (n = 63) was 0.844 for scientific argumentation and 0.928 for conceptual understanding, and for Task 2 (n = 60) ICC value was 0.876 for scientific argumentation and 0.938 for conceptual understanding. Differences in initial coding results between the two raters were discussed until full agreement was reached before data were integrated and further analyzed.

Integration of quantitative and qualitative data

The integration phase was performed after the qualitative and quantitative analyzes were done separately. Integration was carried out by connecting the distribution of scientific argumentation levels with the categories of conceptual understanding and patterns of reasoning as identified by the qualitative analysis. The research results provide not only the number and percent of students classified into the categories of Conceptual Understanding, Partial Understanding, Misconception and No Understanding at each level of argumentation but also elaborate on how these reasoning patterns are mirrored in the students' responses. The integration allows for a more complete interpretation of the biology students' scientific argumentation skills and conceptual understanding of genetic recombination.

RESULTS AND DISCUSSION

Students' scientific argumentation on genetic recombination

The results indicate that students' scientific arguments are mostly Level 2 (64%) which is defined by claims supported by data and/or warrants. 7% of responses were at Level 0 where no argument was present and 14% were at Level 1 where only a claim was stated. Level 3, which adds a qualifier or a backing to the basic structure, was 12%. Just 2% of students made it to Level 5, which also includes a rebuttal, and 1% of students made it to Level 4, which includes both backing and a qualifier. Most of the arguments were still at the level of claims and basic reasons, and only a small part of the arguments went to the level of backing, qualifiers and rebuttals. Figure 1 presents the percentage distribution of students' levels of scientific argumentation.

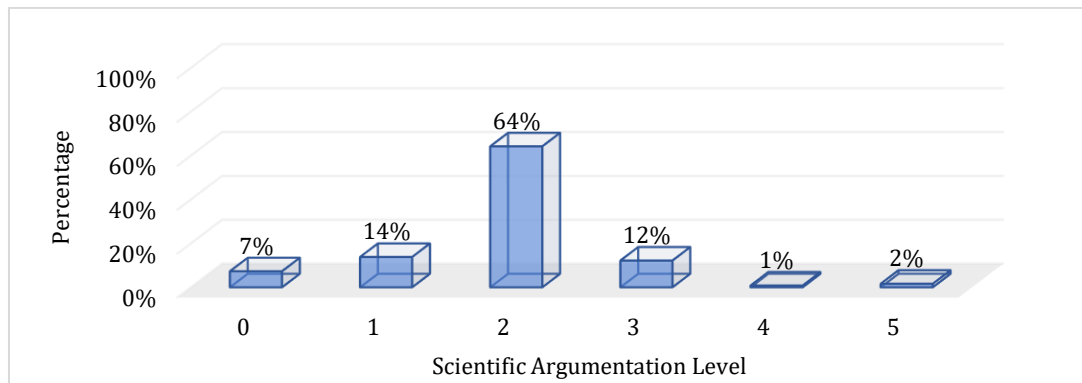


Fig. 1. Overview of students' scientific argumentation skills profiles

Analysis of argumentative components based on the TAP framework shows that claims are the most frequently found component (93% of student responses) followed by data (79%). Warrants appeared in 35% of the responses, backings in 11%. Qualifiers and rebuttals were the least common components, appearing in just 2% of responses. This distribution shows a clear decrease in frequency from the basic elements to those that require further argumentative development. Figure 2 shows the frequency of each argumentative component.

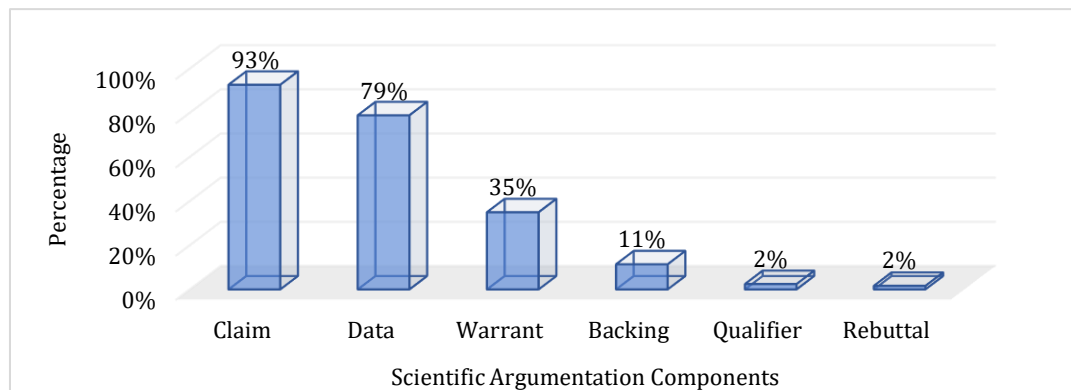


Fig. 2. Frequency of scientific argumentation components

The frequency of Level 2 and the high rate of claims and data suggest that students' argumentation skills are more developed at the stage of stating a position and providing supporting evidence than at the stage of developing and evaluating reasoning. Within the Toulmin framework, a claim is a statement that is defended, while data serve as the basis or evidence supporting that claim, and a warrant explains the basis of reasoning that connects the data to the claim (Osborne et al., 2004; Toulmin, 2003). These three components form the basic structure of an argument, whereas backings, qualifiers, and rebuttals represent advanced reasoning that does not always appear in students' arguments (Yang, 2022). Therefore, the predominance of Level 2 arguments categorized as low-level arguments can be understood in terms of students' limitations in developing argumentative components beyond the basic structure (Georgiou et al., 2020). The low frequency of warrants, backings, qualifiers, and especially rebuttals indicates that students have not consistently explained how evidence supports their claims, strengthened the basis of their reasoning, limited the applicability of their claims, or considered possible alternatives and counterarguments.

Table 4. Representative examples of student arguments at various TAP levels

TAP Level	Source	Representative Student Response
Level 1	Task 1 (S63)	"I agree, recombination occurs only during meiosis (claim)"
Level 2	Task 2 (S43)	"I disagree (claim), because mitotic division is not the only mechanism of recombination in eukaryotes (data/grounds). Meiosis also contributes to the mechanism of recombination in eukaryotes (data/grounds)."
Level 3	Task 1 (S36)	Yes, because recombination is the separation of genes and the formation of new genes that originally came from the same chromosome [Claim]. The scientific example is a flower that has a purple color and long pollen, and a white color with pollen that comes from the same chromosome [Data]. So during meiotic division, genes can undergo recombination, which then separate and form new genes [Warrant]. This is based on the chromosomal principle, where genes that were initially linked or originated from the same chromosome can break apart and then rejoin to create new genes [Backing]."
	Task 2 (S2)	"I disagree. (Claim) In addition to recombination during mitosis, which is marked by the presence of twin spots in <i>Drosophila</i> , recombination also occurs during meiosis. For example, during crossing over in <i>Drosophila melanogaster</i> (data/grounds). Crossing over occurs during Prophase I when homologous chromosomes pair up and DNA segments are exchanged, resulting in different combinations of alleles. (warrant). This is supported by the results of crosses between <i>Drosophila</i> strains BCL and normal, which produced black and clot recombinant offspring (backing)."
Level 4	Task 1 (S43)	"I Disagree (claim). Although most recombination is indeed observed during meiosis (qualifier), recombination may also occur during mitosis because somatic cells possess this capability (data/grounds). For example, in somatic cells that make up the immune system, specific recombination (V(D)J recombination) occurs, which rearranges gene segments to produce millions of different antibody variations (backing)."
Level 5	Task 2 (S22)	"I disagree with that statement (claim). Recombination can occur during meiosis through crossing over in Prophase I, which results in the exchange of segments of homologous chromosomes (data). This exchange produces new combinations of alleles, thereby increasing genetic variation in the offspring (warrant). This demonstrates that meiosis is one of the key mechanisms for generating genetic variation (backing). Nevertheless, recombination can also occur during mitosis under certain conditions (qualifier). However, mitotic recombination is more closely associated with DNA repair rather than the generation of genetic variation through gametes (rebuttal)."

To provide a concrete picture of the characteristics of argumentative structures at each level, this study presents examples of authentic student responses representing the basic, dominant, and highest levels achieved in this research. These examples illustrate how the completeness of argumentative components from claims to arguments that include rebuttals is reflected in students' responses, as shown in Table 4. Low-level responses generally contain only claims with little supporting information. In contrast, high-level responses explicitly integrate warrants and are supplemented with backing, qualifiers, and rebuttals in highly developed arguments.

The students' argumentation patterns indicate that evidence in an argument is not always followed by reasoning that explicitly links the evidence to the claim. This was seen in some students' responses containing information related to genetic recombination such as the concepts of crossing over, meiosis and mitosis but did not fully explain how this information supported their claims. This result is in line with the finding that students are more likely to cite scientific evidence without explicitly stating how the evidence supports their claims. Rather, responses in Levels 3-5 display a more developed structure as students begin to connect data with warrants and incorporate supporting elements such as backing, qualifiers, or rebuttals. This capacity shows a high degree of maturity in the reasoning process, not just the presentation of claims and data (Kundariati et al., 2024; Naovalia et al., 2021). For example, in Table 4 a Level 3 response connects the concept of "crossing over" in Prophase I to the swapping of DNA segments and creating new allele combinations. This argument is then supported with supporting data from *Drosophila* crosses. These findings indicate that an argument's complexity is not solely determined by the amount of information, but by how that information constructs coherent reasoning (Berkle et al., 2023).

These findings are consistent with earlier studies that reported that basic components like claims and data are more easily integrated into arguments, while components that need further explanation of reasoning, such as warrants, backings, qualifiers, and rebuttals, are more restricted (Gazali et al., 2024; Rahayu et al., 2022; Setiono et al., 2021). But it was the opposite in this study which shows that it is not enough to judge argument quality based on structural completeness. Table 4 Task 1 S36 Students' biological content may be scientifically inaccurate even if it satisfies the structural criteria of a Level 3 argument. Thus, the quality of scientific argumentation depends not only on the structure of the argument, but also on the accuracy of conceptual understanding. Therefore, such a finding guides the need for further investigation which is conducted in the following section to analyze students' conceptual understanding and its relationship with their argumentation levels.

Students' conceptual understanding of genetic recombination

Analysis of student responses revealed variation in conceptual understanding for both the argumentation tasks. As shown in Figure 3, misconceptions (MC) predominated, making up 60% of all student responses. Conversely, a small percentage of students (6%) exhibited scientifically sound conceptual understanding (CU). The high incidence of misconceptions suggests that students' difficulties are not only due to a lack of knowledge but also to the possession of knowledge that does not fully correspond to the scientific explanations of genetic recombination. These difficulties are related to the complexity of

genetic recombination mechanisms, including understanding of crossing over, homologous chromosome pairs and chromosome segregation (Wright et al., 2022). Besides crossing over during meiosis, recombination is also mediated by a broader range of mechanisms related to the maintenance of chromosome integrity and segregation (Arter & Keeney, 2024). Students can recognize the processes commonly associated with recombination but have difficulty in distinguishing the mechanisms, cellular contexts and genetic consequences of recombination.

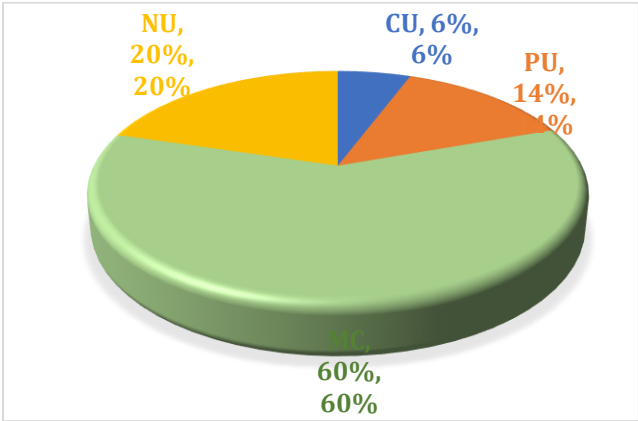


Fig. 3. Profile of students' conceptual understanding of genetic recombination

Additional analysis examined the conceptual codes underlying each understanding category for Task 1 and Task 2. Analysis of the conceptual codes in Task 1 indicated that the misconception category was mainly characterized by “Meiotic Exclusivity,” 37%. This trend indicates a tendency for students to see meiosis as the only setting for genetic recombination. This misconception was also associated with other weaknesses such as Logical Fallacy/Conceptual Contradiction (11%) and Misconception on Meiotic Recombination (8%). The full distribution of codes is in Table 5.

Table 5. Distribution of concept understanding codes in task 1

Category	Code	Percentage
Conceptual Understanding	DNA repair recombination	2%
	horizontal gene transfer	2%
	mitotic recombination	3%
	rekombinasi somatik	2%
	site specific recombination	2%
Partial Understanding	Incomplete Understanding of Meiotic Recombination	5%
	Incomplete Understanding of Mitotic Recombination	3%
Misconception	Meiotic Exclusivity	37%
	Logical Fallacy / Conceptual Contradiction	11%
	Misconception on Meiotic Recombination	8%
	Conceptual Blending	6%
	Misconception on Mitotic Recombination	5%
No Understanding	Circular Reasoning	9%
	Irrelevant or No Response	8%

Task 2 conceptual coding patterns had different trends in conceptual difficulties. The misconceptions in this task were mainly dominated by issues related to Conceptual Blending (17%) and Misconceptions about Mitotic Recombination (16%). Also, among the PU category, the code “Incomplete Understanding of Meiotic Recombination” was significantly overrepresented (14%). The results of Task 2 suggest that the main difficulties students have are related to inappropriate conceptual blending and the inability to distinguish between different recombination mechanisms in different cellular contexts. Full code distributions are presented in Table 6.

Table 6. Distribution of concept understanding codes in task 2

Category	Code	Percentage
Conceptual Understanding	Crossing over concept	5%
	DNA repair concept	3%
	mitotic recombination	2%
Partial Understanding	Incomplete Understanding of Meiotic Recombination	14%
	Incomplete Understanding of Mitotic Recombination	5%
Misconception	Conceptual Blending	17%
	Misconception on Mitotic Recombination	16%
	Misconception on Meiotic Recombination	10%
	Logical Fallacy / Conceptual Contradiction	6%
No Understanding	Circular Reasoning	11%
	Irrelevant or No Response	11%

The main misconception patterns that emerged were related to students' understanding of the context and mechanisms of genetic recombination. In Task 1, the most common misconception code was “Meiotic Exclusivity” (37%), suggesting that students tend to think of meiosis as the only situation in which genetic recombination occurs. This is in line with findings that students frequently have difficulties in differentiating the processes and products of mitosis and meiosis and have a more limited understanding of recombination restricted to the context of meiosis (Chattopadhyay, 2005; Kalas et al., 2013; Ozcan et al., 2012). Meanwhile, the most dominant code in Task 2 was “Conceptual Blending” (17%) followed by “Misconception on Mitotic Recombination” (16%). The pattern suggests that it is difficult to work out the recombination mechanisms from the context of cell division. To be able to accurately combine several concepts related to genetic recombination. These challenges are consistent with findings that some fundamental genetics ideas can be conceptual barriers even after formal instruction as pre-instruction ideas can influence newly acquired scientific ideas (Smith & Knight, 2012). Thus, the misconceptions in both tasks were not only errors in one concept but also reflected difficulties in accurately distinguishing and relating recombination, cell division and genetic variation.

These findings support studies on the understanding of genetic concepts that indicate that misconceptions are still a significant problem in genetics teaching. Misconceptions were found as a dominant category in the understanding of genetic concepts and accurate conceptual understanding in a lower proportion in various studies (Menendez et al., 2024;

Ojo, 2024; Rodríguez Gil et al., 2019). Other findings also suggest that misconceptions in genetics can be persistent, as students build their understanding on erroneous relationships between concepts, especially when genetic concepts have complex interrelated concepts (Machová & Ehler, 2023). In this work, this pattern appears more specific to genetic recombination, in particular for discriminating recombination mechanisms, the context in which cells divide and their genetic consequences. Thus, the prevalence of misconceptions in this study not only indicates low accuracy in understanding recombination but also points to difficulties in constructing a coherent conceptual representation of the relationships among the components of this process. To provide a more concrete picture of these patterns of understanding, Table 7 presents several student responses representing the CU, PU, MC, and NU categories.

Table 7. The examples of students' responses across conceptual understanding categories

Category	Source	Representative Response	Conceptual Code
Conceptual Understanding	Task 2 (S22)	“I disagree. In addition to <u>recombination during mitosis, which is marked by the presence of twin spots in Drosophila</u> , recombination also occurs during meiosis. For example, during the crossing-over event in <i>Drosophila melanogaster</i> . <u>Crossing over occurs during Prophase I when homologous chromosomes pair up and DNA segments are exchanged</u> , resulting in different combinations of alleles. This is supported by the results of crosses between <i>Drosophila</i> of the BCL strain and the wild-type strain, which produced black and clot recombinant offspring.”	Mitotic recombination, Crossing over concept
Partial Understanding	Task 2 (S43)	“I disagree, because mitosis is not the only mechanism of recombination in eukaryotes. <u>Meiosis also contributes to the mechanism of recombination in eukaryotes.</u> ”	Incomplete Understanding of Meiotic Recombination
Misconception	Task 1 (S61)	“ <u>Recombination occurs only during meiosis</u> , specifically during prophase I. Prophase I consists of several subphases: leptotene, zygotene, pachytene, diplotene, and diakinesis. During leptotene, the two homologous chromosomes move closer together and align. In leptotene, two homologous chromosomes move closer to each other and cluster together. In zygotene, homologous chromosomes begin	Meiotic Exclusivity

		to move closer and form chiasmata. In pachytene, the chromosomes undergo crossing-over recombination and begin to separate. In diplotene, the chromosomes separate after recombination has occurred. In diakinesis, the chromosomes are ready to proceed to the next stage. Punnet cited other scientific evidence in his experiment.”	
	Task 2 (S47)	“That’s right, in eukaryotes, the <u>recombination mechanism occurs during mitosis</u> , in which one haploid cell produces four haploid cells. During this process, two homologous chromosomes combine (recombine) to produce four haploid cells. <u>This process includes prophase I</u> , which plays a crucial role in recombination.”	<i>Conceptual blending</i>
No Understanding	Task 1 (S18)	“Recombination occurs only during meiosis, this statement is true.”	<i>Circular Reasoning</i>

The sample responses in Table 7 illustrate differences in students’ understanding across each category. Responses in the CU category reflect a conceptual understanding consistent with the concept of genetic recombination, whereas responses in the PU category indicate that students have recognized some aspects of the concept but have not provided a complete explanation. For the MC category, students’ answers reflected an understanding that was not consistent with scientific concepts, such as the conflation of recombination characteristics in meiosis and mitosis. For the NU category, responses failed to provide relevant conceptual explanations and tended to copy sentences from the question without providing supporting logic.

Association between argumentation structure and conceptual understanding

Cross-tabulations were run separately for Task 1 and Task 2 to examine the relationship between students’ conceptual understanding and scientific reasoning skills. Four categories of conceptual understanding were mapped to levels of scientific reasoning based on the TAP. In Task 1 (N = 63), the distribution in Table 8 indicates different patterns between the categories of conceptual understanding and levels of scientific argumentation. NU responses were concentrated at lower levels of argumentation (TAP levels 0–2). CU responses, however, appeared only at higher levels of argumentation, i.e., TAP Levels 3–5. MC responses were mainly located at TAP Level 2. Meanwhile, PU responses were also concentrated at TAP Level 2. These results indicate that students’ levels of scientific argumentation are accompanied by good conceptual understanding.

Table 8. Cross-tabulation of conceptual understanding and scientific argumentation task 1

Conceptual Understanding Category	Scientific Argumentation Level						Total
	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	
NU	3	5	3	-	-	-	11
MC	-	4	33	6	-	-	43
PU	-	-	4	1	-	-	5
CU	-	-	-	2	1	1	4
Total	3	9	40	9	1	1	63

A similar pattern was observed in Task 2 (N = 60), as shown in Table 9. NU responses were primarily concentrated at TAP Levels 0–2, while all CU responses were at higher levels of argumentation. MC and PU responses were primarily concentrated at TAP Level 2, although some MC responses reached higher levels of argumentation. This pattern is consistent with the results from Task 1, namely that responses with low conceptual understanding tend to be at a low level of scientific argumentation.

Table 9. Cross-tabulation of conceptual understanding and scientific argumentation task 2

Conceptual Understanding Category	Scientific Argumentation Level						Total
	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	
NU	6	3	5	-	-	-	14
MC	-	3	26	2	-	-	31
PU	-	2	9	1	-	-	12
CU	-	-	-	2	-	1	3
Total	6	8	40	5	0	1	60

The inferential analysis in Table 10 confirms the patterns observed in the cross-tabulations for both tasks. In Task 1, the relationship between conceptual understanding and scientific reasoning was statistically significant, $\chi^2(15) = 64.672$, Monte Carlo $p < 0.001$, with a strong association indicated by a Cramer's V value of 0.585. In Task 2, a statistically significant relationship was also found, $\chi^2(12) = 59.275$, Monte Carlo $p < 0.001$, with a Cramer's V value of 0.574, indicating a strong relationship between conceptual understanding and students' level of scientific argumentation.

Table 10. Association of argumentation and conceptual understanding

Task	χ^2	df	Monte Carlo p	Cramer's V
Task 1	64.672	15	< .001	.585
Task 2	59.275	12	< .001	.574

Students with conceptual understanding are able to produce the Level 3–5 argumentative structures, while students with partial understanding and misconceptions are still able to construct arguments at an intermediate level. This pattern aligns with the threshold model of content knowledge transfer by Sadler and Fowler (2006), who found

that students with the deepest content knowledge significantly outperformed other groups in terms of both the quality and frequency of the justifications they provided. According to this model, scientific argumentation should be accompanied by conceptual understanding to argue effectively (Ogan-Bekiroglu & Eskin, 2012). Different empirical studies indicate that deep conceptual understanding leads to high-quality arguments in discussion as these arguments are more informative and coherent (Gürel & Süzük, 2017; Murphy et al., 2018; Sands & Kozelková, 2025). This supports the link between the quality of scientific argumentation and conceptual understanding, as conceptual knowledge not only serves as the content used in arguments, but also provides the foundation for developing more complex lines of reasoning.

Nevertheless, the cross-tabulation also shows that conceptual understanding and argumentative structure are not absolutely directly proportional. The integration of quantitative and qualitative results presented in Table 11 reveals interesting findings. A relatively well-developed argumentative structure is not always accompanied by scientifically accurate conceptual understanding. This pattern is particularly evident in responses categorized as MC. As shown in the cross-tabulations for Task 1 and Task 2 (Tables 7 and 8), MC responses are largely concentrated at TAP Level 2, but some responses also reach TAP Level 3.

Table 11. Joint display of scientific argumentation and conceptual understanding

Category	Quantitative patterns	Qualitative evidence/patterns	Integrated interpretation
CU	Concentrated on higher TAP level	Coherent and scientifically accurate conceptual reasoning	A correct conceptual understanding accompanied by a more developed argumentative structure
PU	Mainly at TAP Level 2	The conceptual explanation is incomplete	A partial understanding supports the formation of a basic argument, but has not yet led to sufficient elaboration
MC	Mainly at TAP Level 2, but some reach Level 3	Meiotic Exclusivity, Conceptual Blending, and another misconceptions	A relatively well-developed argumentative structure can emerge even if the conceptual reasoning is not scientifically accurate
NU	Concentrated on TAP Levels 0–2	Circular reasoning, The response is irrelevant or does not provide an explanation	Limitations in conceptual understanding are accompanied by limitations in the development of arguments

Interestingly, misconceptions do not entirely hinder the formation of argumentative structures. Students with misconceptions can still reach Level 3 when they are able to link

claims to evidence and reasoning, even if the concepts underlying those connections are not yet accurate. This is evident in S12's response to Task 1:

"I agree that recombination occurs during meiosis I in prophase I in the pachytene stage (claim), where homologous chromosomes undergo synapsis and form tetrads, followed by crossing over (data/grounds), in which a chromatid pairs with a non-sister chromatid to produce a new allele (warrant). This crossing over was demonstrated by Thomas Hunt in his research on fruit flies, or *Drosophila melanogaster* (backing)."

Although structurally the response meets the criteria for Level 3, conceptually, the warrant section still reveals a misconception because the student states that crossing over "produces new alleles." Scientifically, crossing over produces new combinations of alleles through the exchange of DNA segments, not new alleles (Korunes & Noor, 2017). This response demonstrates that a relatively complete argumentative structure can be constructed even though the concepts used in building that reasoning still contain misconceptions. Theoretically, this phenomenon is explained by Berkle et al. (2023) through the concept of "incongruent fallacies," whereby an argument may possess a valid deductive logical structure and appear convincing, even though it is actually very weak inductively due to the use of erroneous content. This is supported by von Aufschnaiter et al. (2008), who explain that there is no absolute relationship between the quality of an argument and conceptual understanding, so that an argumentative structure can be developed with a low level of knowledge.

In contrast, more fundamental limitations in conceptual understanding appear to be linked to increasingly limited argumentative structures. Students in the "no understanding" category primarily produced arguments at lower levels (levels 0–2), indicating that limited knowledge of the debated phenomenon can restrict the resources available for selecting evidence, establishing lines of reasoning, and defending claims (Nugroho et al., 2023). This aligns with the view that the use of evidence in scientific argumentation requires not only the ability to recognize evidence but also the knowledge that enables individuals to understand the relevance of evidence and connect it to claims (Sadler & Zeidler, 2005; von Aufschnaiter et al., 2008). According to Cahyani et al. (2024), poor scientific argumentation abilities in genetics education are linked to a conceptual understanding that is either fragmented or shallow. Students with a shallow conceptual framework tend to make descriptive arguments, rely on memorized facts, and struggle to support claims through reasoning (Herak et al., 2025). This clarifies research findings like students' answers, which frequently rephrase the question and create unrelated arguments.

The results of this study suggest that the development of scientific argumentation in genetics education should be accompanied by the consolidation of conceptual understanding. Instruction should not end with the mere giving of exercises in the formulation of claims, data, warrants and other elements of argumentation. It must also provide students opportunities to test the accuracy of the concepts used in the construction of arguments. Within the framework of genetic recombination, argumentation tasks might be driven by problems that require students to relate mechanisms of recombination, the context of cell division, and genetic consequences, and to support their arguments with evidence. The approach allows the structure of the argument and the quality of conceptual

knowledge to develop in parallel, so that the resulting arguments are structurally complete and scientifically accurate.

CONCLUSION

This study reveals that the scientific argumentation of undergraduate students on genetic recombination was at low to intermediate levels, with Level 2 as the most dominant. Data and warrants, backings, qualifiers and rebuttals were claimed and used more frequently by students. Misconceptions dominated students' conceptual understanding especially when it came to the context and mechanisms of genetic recombination. Conceptual understanding was related to the level of argumentation: students with conceptual understanding reached Levels 3–5, whereas students with partial understanding or misconceptions did not reach Levels 4–5. Nevertheless, the presence of Level 3 arguments among students with misconceptions shows that a more complete argument structure does not always reflect conceptual accuracy. Therefore the highest levels of argumentation require accurate conceptual understanding, but this cannot be deduced from argument structure alone. Scientific arguments must therefore be assessed for both structure and conceptual accuracy.

There are a number of limitations to this study. Since the analysis was based on the students' written answers to two tasks concerning genetic recombination within a single genetics learning situation, the results do not include any aspect of oral argumentation, do not deal with all the recombination mechanisms, and ought to be applied to other populations with care. Moreover, the association identified in this study does not prove that there is a causal relationship. In future research it would be possible to look at argumentation in discussion situations and combine the written responses with interviews, to extend the analysis to other genetics topics, mechanisms, and different groups of students, and to test instructional approaches which aim to improve both conceptual understanding and argumentation in order to find out whether more students are able to achieve higher levels of argumentation.

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