European Journal of Education Studies
ISSN: 2501 - 1111
ISSN-L: 2501 - 1111
Available online at: www.oapub.org/edu

DOI: 10.46827/ejes.v13i7.6875 Volume 13 | Issue 7 | 2026

GENETICS MISCONCEPTIONS IN MOROCCAN SECONDARY CLASSROOMS: A MIXED-METHODS STUDY POST-INSTRUCTION

Samir Laouina[i]
Provincial Directorate,
Mohammedia Regional Academy of Education and Training,
Casablanca–Settat Region,
Ministry of National Education,
Morocco

Abstract:
Genetics education remains challenging, and limited research has examined the profile of misconceptions present after curriculum-aligned instruction in the Moroccan secondary context. This descriptive cross-sectional study examined the conceptual understanding and misconceptions of 71 second-year Baccalaureate students following completion of a 34-hour formal genetics unit. Data were collected using a questionnaire assessing gene function, hereditary transmission, and genotype–phenotype relationships. Quantitative analysis used descriptive statistics and independent samples t-tests, while qualitative responses were analyzed through inductive thematic analysis. Results showed a moderate mean score of 4.06/6 ($SD = 1.19$). Hereditary transmission was the most challenging concept (40.8%), and conceptual difficulties represented 84.5% of reported challenges. A significant difference between classes was observed ($t(69) = -2.15$, $p = 0.036$, $d = 0.50$), indicating variability in conceptual understanding. Qualitative responses revealed deterministic reasoning and confusion between genotype and phenotype. These findings provide classroom-based evidence of students' conceptual understanding following curriculum instruction and highlight the persistence of conceptual difficulties even after formal teaching. The results underscore the need for instructional strategies that explicitly address misconceptions, promote mechanistic reasoning, and improve genetics learning outcomes. This study contributes to the growing body of evidence on genetics misconceptions in non-Western educational contexts and provides a basis for future interventions aimed at improving genetics education in Moroccan secondary schools.

Keywords: genetics education; misconceptions; conceptual understanding; secondary education; biology education; Morocco

[i] Correspondence: email samir.laouina@taalim.ma, samirlaouina@gmail.com

1. Introduction

Genetics is a fundamental discipline of biology, with broad applications in fields such as medicine, agriculture, and biotechnology (Nussbaum, McInnes, & Willard, 2015). A solid understanding of genetic principles is essential for enabling students to interpret major contemporary scientific and societal issues, including genetic diseases, gene therapy, and genome sequencing (Silar, 2020). However, genetics has been widely recognized as one of the most challenging domains for students in both secondary and higher education (Chapel & Marzin, 2009; Freidenreich, Duncan, & Shea, 2011). The abstract nature of genetic mechanisms and the need to integrate multiple levels of biological organization pose significant challenges for learners in developing a coherent conceptual understanding.

Numerous studies have documented that students develop misconceptions related to fundamental genetic concepts, including the nature of genes, the mechanisms of heredity, and the relationship between genotype and phenotype (Alouah, Zaibout, Madrane, Idrissi, & Tolaimate, 2025; Ojo, 2023; Osman, BouJaoude, & Hamdan, 2017). For example, students frequently confuse fundamental concepts such as gene, chromosome, and DNA, and may mistakenly assume deterministic relationships between genes and traits (Donovan, 2022; Osman *et al.*, 2017). Similarly, studies conducted in different educational contexts have shown that learners often struggle to understand the mechanisms underlying genetic transmission and variation (Agorram, Zaki, Selmaoui, & Khzami, 2017; Ojo, 2023).

Notably, several studies have reported that such misconceptions remain evident even after formal instruction. Studies involving secondary school students have demonstrated that misconceptions related to gene function and genetic mechanisms may persist despite targeted instruction (Haskel-Ittah & Yarden, 2018; Osman *et al.*, 2017). Furthermore, both longitudinal and cross-sectional studies have reported that students may retain incomplete or incorrect understandings of genetic concepts over time, suggesting that traditional instructional approaches may not always result in lasting conceptual change (Alouah *et al.*, 2025; Todd & Romine, 2018).

Evidence from diverse educational contexts further documents the persistence of misconceptions in genetics. Agorram *et al.* (2017) reported that university biology students continued to exhibit significant misconceptions related to meiosis and genetic transmission, despite having completed several genetics courses. Similarly, Ojo (2023) found that more than half of secondary school students demonstrated misconceptions in genetics, particularly concerning heredity and chromosome behavior. Collectively, these findings suggest that misconceptions in genetics may constitute a widespread and persistent educational challenge across different educational systems.

One explanation for this persistence may lie in the abstract and multi-level nature of genetic concepts, which requires students to integrate knowledge across molecular, cellular, and organismal levels. In addition, traditional instructional approaches may not explicitly address students' pre-existing conceptions, thereby limiting opportunities for conceptual change (Donovan, 2022; Liang *et al.*, 2023). As a result, students may acquire factual knowledge while retaining inaccurate underlying mental models.

Given the importance of genetics education and the documented persistence of misconceptions, further investigation is warranted to examine students' conceptual understanding following formal instruction. Identifying misconceptions that remain present after teaching may provide valuable insights for improving instructional practices.

Despite extensive international research on genetics misconceptions, limited studies have examined students' conceptual understanding following completion of a full instructional unit in the Moroccan secondary education context. In particular, little is known about the profile of misconceptions that remain after formal instruction aligned with the national curriculum. Addressing this gap provides context-specific insight into instructional outcomes in authentic classroom settings. Accordingly, the present study aimed to examine secondary school students' conceptual understanding of genetics following completion of a formal instructional unit. Specifically, the study sought to assess students' conceptual understanding, identify the most challenging genetic concepts, and examine the nature of the difficulties reported by students.

2. Methods

2.1 Study design

This study employed a descriptive cross-sectional design conducted in an authentic classroom setting. The objective was to examine students' conceptual understanding and misconceptions related to genetics among Life and Earth Sciences (SVT) students following formal instruction on this topic. This design enabled the assessment of students' conceptual understanding under natural classroom conditions without modifying the instructional environment. A descriptive cross-sectional approach was selected to provide an ecologically valid snapshot of students' conceptual understanding following completion of formal instruction. While a pre–post design would allow direct assessment of conceptual change, the present design was intended to document the profile of student understanding after instruction rather than to evaluate instructional effectiveness.

2.2 Study setting and participants

The study was conducted in a public high school during the 2025–2026 academic year. The sample consisted of 71 second-year Baccalaureate students (2nd Bac), distributed across two classes (2bac SP5, n = 39; 2bac SP6, n = 32).

All participants followed the same official curriculum and were taught by the same teacher, which helped ensure consistency in instructional delivery across groups.

2.3 Instructional context

The genetics unit had been fully completed prior to data collection. This instructional unit comprised 34 hours and addressed key genetics concepts, including genetic information and genes, chromosomes, genotype–phenotype relationships, hereditary transmission, and genetic diseases.

The questionnaire was administered after completion of the instructional unit, ensuring that students had been exposed to formal instruction on the targeted concepts.

2.4 Data collection tool

The data collection instrument was a paper-based questionnaire developed specifically for this study based on the scientific literature addressing misconceptions and learning difficulties in secondary-level genetics.

Content validity was supported through alignment with the official secondary school curriculum and through review by an expert in science education. In addition, the questionnaire was informed by prior empirical studies on genetic misconceptions, which supports its construct validity and relevance for assessing conceptual understanding in this domain.

The questionnaire comprised both closed-ended and open-ended items. Multiple-choice questions were used to assess students' conceptual understanding of genetics, while open-ended questions allowed students to articulate their reasoning in their own words.

The items targeted fundamental genetics concepts commonly taught at the secondary level, including the nature of genes, genotype–phenotype relationships, and mechanisms of hereditary transmission. For example, some items required students to identify the correct definition of a gene, whereas others assessed their understanding of trait transmission mechanisms or the distinction between genotype and phenotype. These items were designed to identify common misconceptions documented in the literature.

2.5 Data collection procedure

The questionnaire was administered during a regular classroom session. Students were informed that participation was voluntary and that their responses would not affect their academic evaluation. No personally identifiable information was collected. Students were given 45 minutes to complete the questionnaire.

2.6 Instrument reliability

The internal consistency of the multiple-choice items was assessed using Cronbach's alpha coefficient. The obtained value ($\alpha = 0.72$) indicates acceptable internal consistency according to commonly accepted standards in educational research. This suggests that the questionnaire was sufficiently reliable for assessing students' conceptual understanding of genetics.

The instructional unit followed the national curriculum guidelines and consisted primarily of teacher-led explanations, whole-class discussions, and textbook-based exercises. Instruction emphasized conceptual definitions, inheritance patterns, and problem-solving activities. No laboratory activities were conducted, which is typical in public secondary schools due to resource constraints.

2.7 Data analysis

Data analysis was primarily based on descriptive statistics. Responses to closed-ended questions were analyzed using frequencies and percentages.

Responses to open-ended questions were analyzed using inductive thematic content analysis. Following an initial reading of the responses, thematic categories were identified and progressively refined during the analysis to ensure the coherence and transparency of the analytical process. All responses were reviewed multiple times to ensure consistency of thematic classification. The analysis followed an inductive approach, allowing themes to emerge directly from students' responses rather than being predefined.

Mean scores between the two classes were compared using an independent samples *t-test* to examine differences in performance between groups. The level of statistical significance was set at $p < 0.05$.

2.8 Ethical considerations

Student anonymity was strictly ensured, and no personally identifiable information was collected. Participation was voluntary, and students were informed about the pedagogical and research objectives of the study prior to data collection. The study was conducted in accordance with the ethical principles governing educational research in school settings.

3. Results

3.1 Sample characteristics and overall performance (Table 1)

The study included 71 secondary school students enrolled in the second year of the scientific baccalaureate program. Among them, 39 students (54.9%) were from class 2bac SP5, and 32 students (45.1%) were from class 2bac SP6.

Following completion of the 34-hour genetics instructional unit, students obtained a mean score of 4.06 (95% CI [3.78, 4.34]) out of a maximum of 6 on the misconceptions questionnaire ($SD = 1.19$), with scores ranging from 1 to 6.

An independent samples t-test was conducted to compare mean scores between the two classes. The results revealed a statistically significant difference between the groups, $t(69) = -2.15$, $p = 0.036$. Students in class 2bac SP6 achieved a higher mean score ($M = 4.38$, $SD = 0.98$, 95% CI [4.03, 4.73]) than students in class 2bac SP5 ($M = 3.79$, $SD = 1.30$, 95% CI [3.37, 4.21]).

Table 1: Sample characteristics and overall performance

Variable	n (%)	Mean ± *SD*	Min	Max
Total sample	71(100%)	4.06 ± 1.19	1	6
Class 2bac SP5	39 (54.9%)	3.79 ± 1.30	1	6
Class 2bac SP6	32 (45.1%)	4.38 ± 0.98	2	6
Comparison between classes	$t = -2.15$; $p = 0.036$; $d = 0.50$			

Note: QCM score represents the total number of correct answers across the six multiple-choice items (Q1–Q6), with higher scores indicating better conceptual understanding. Percentages represent the proportion of students within each class. An independent samples *t*-test was conducted to compare mean scores between classes. Cohen's d was calculated to estimate the effect size.

3.2 Item-level analysis of misconceptions (Table 2)

The analysis of individual questionnaire items revealed variation in student performance across the genetic concepts assessed. Question 4 had the highest proportion of incorrect responses (36.6%), followed by Question 5 (33.8%) and Question 2 (29.6%). In contrast, Question 3 showed the highest proportion of correct responses (88.7%). Questions 1 and 6 also demonstrated relatively high correct response rates, at 81.7% and 83.1%, respectively.

Analysis of incorrect response patterns suggests that students frequently selected distractors reflecting simplified interpretations of gene–trait relationships. In particular, responses to Questions 4 and 5 indicate difficulties in understanding the mechanisms of hereditary transmission and the functional role of genes. These patterns suggest that some students conceptualize genes as direct determinants of observable traits rather than as informational units involved in complex biological processes regulated across multiple levels of organization. This finding is consistent with the deterministic and entity-based misconceptions identified in students' qualitative responses.

Table 2: Percentage of correct and incorrect responses by question

Question	% Correct	% Incorrect	Rank (Difficulty)
Q4	63.4	36.6	1 (Most difficult)
Q5	66.2	33.8	2
Q2	70.4	29.6	3
Q1	81.7	18.3	4
Q6	83.1	16.9	5
Q3	88.7	11.3	6 (Easiest)

Note: Incorrect responses indicate misconceptions.

3.3 Self-reported difficult concepts (Table 3)

When asked to identify the genetics concept they found most difficult, students most frequently cited transmission (40.8%, n = 29), followed by the concept of gene (25.4%, n = 18). DNA (12.7%, n = 9) and genotype (11.3%, n = 8) were reported less frequently, while chromosome and phenotype were each identified by 4.2% of students (n = 3).

Table 3: Genetics concepts identified by students as most difficult (N = 71)

Concept	Frequency (n)	Percentage (%)	Rank
Transmission	29	40.8	1
Gene	18	25.4	2
DNA	9	12.7	3
Genotype	8	11.3	4
Chromosome	3	4.2	5
Phenotype	3	4.2	5
Other	1	1.4	7

Note: Students were asked to identify the genetics concept they found most difficult.

3.4 Nature of reported difficulties

Thematic analysis revealed several recurring patterns in students' reasoning, including deterministic interpretations of genetic processes, confusion between genotype and phenotype, and simplified representations of hereditary transmission. For example, one student stated that "*the gene is the trait itself*," reflecting confusion between genetic information and phenotypic expression. Another indicated that "*genotype and phenotype are the same thing*," illustrating conceptual conflation. These responses highlight the presence of simplified mental models of genetic mechanisms.

Additional responses further illustrated deterministic reasoning patterns. For example, one student stated that "*if you have the gene, you will definitely have the trait*," reflecting a deterministic interpretation of gene function. Another response indicated that "*genes decide everything about a person*," suggesting an oversimplified causal model of biological traits. Similarly, statements such as "*a person's character is determined by their genes" and "if your family has a disease, you will definitely get it*" reflect essentialist and deterministic interpretations of genetic inheritance. These examples reinforce the presence of deterministic and entity-based reasoning patterns in students' conceptual understanding. These statements reflect essentialist reasoning patterns in which genes are perceived as fixed and deterministic causal agents, rather than probabilistic contributors interacting with environmental and developmental factors.

Table 4: Types of difficulties reported by students (N = 71)

Type of Difficulty	Frequency (n)	Percentage (%)
Conceptual difficulty	60	84.5
Comprehension difficulty	9	12.7
Vocabulary difficulty	2	2.8

Note: Students classified the nature of their difficulty after completing the questionnaire.

4. Discussion

The present study examined secondary school students' conceptual understanding and misconceptions in genetics following completion of formal classroom instruction. Despite completing a 34-hour instructional unit, students demonstrated only a moderate level of conceptual understanding, with a mean score of 4.06 out of 6 and substantial variability in performance. The presence of misconceptions after completion of the instructional unit indicates that alternative conceptions coexisted with scientific explanations in students' understanding at the time of assessment.

Furthermore, the predominance of conceptual difficulties (84.5%) suggests that students' difficulties primarily reflect conceptual misunderstandings rather than linguistic or vocabulary-related issues.

A statistically significant difference was observed between the two classes, despite identical curricular exposure. This difference indicates that conceptual understanding may vary between classroom groups. However, the present study was not designed to identify the factors responsible for this variability. Future research involving larger samples and multiple classrooms is needed to examine how contextual and learner-related factors may influence conceptual understanding.

These findings are consistent with previous studies that have documented the persistence of genetic misconceptions despite formal instruction. For example, Haskel-Ittah and Yarden (2018) reported that approximately one-third of secondary school students retained non-mechanistic conceptions of genes even after targeted instruction, viewing genes as traits themselves rather than as causal agents underlying phenotypic expression. Such misconceptions represent fundamental cognitive obstacles that hinder the integration of mechanistic explanations. This interpretation is consistent with the profile of understanding documented in the present study, where conceptual misunderstandings were found to be present after formal and structured instruction.

Similarly, Osman *et al.* (2017) reported that misconceptions related to gene–trait relationships, genetic determinism, and confusion between fundamental genetic concepts persisted across grades 7 through 12, suggesting limited conceptual progression despite several years of biology instruction. This pattern mirrors the results observed in the present study, in which a substantial proportion of students demonstrated difficulties with core concepts of heredity, particularly genetic transmission and gene function.

Our findings are further supported by Ojo (2023), who reported that 51% of upper secondary school students demonstrated persistent misconceptions, particularly regarding the mechanisms of heredity and chromosome behavior. Notably, the highest misconception rates in that study were also associated with concepts related to genetic transmission, which is consistent with the present finding that transmission was the concept most frequently identified as difficult by students (40.8%). This convergence across different educational contexts suggests that the mechanisms of heredity may represent a particularly challenging conceptual domain in genetics education.

Evidence from the Moroccan educational context further supports the consistency of the present findings. Agorram *et al.* (2017) demonstrated that even university students majoring in biology continued to exhibit significant misconceptions related to meiosis and genetic transmission, despite having completed several semesters of genetics instruction. Similarly, Alouah *et al.* (2025) reported widespread conceptual misunderstandings among both secondary school and university students, including confusion between genotype and phenotype, gene and chromosome, and mitosis and meiosis. These findings are particularly relevant given the shared educational context and suggest that the types of misconceptions identified in the present study at the secondary level are also observed at the university level, indicating they may represent enduring conceptual challenges across educational stages.

Furthermore, Baroud *et al.* (2025) reported that students receiving traditional instruction often demonstrated superficial understanding and persistent conceptual difficulties, particularly regarding abstract genetic processes such as meiosis and genetic variation. These findings raise important questions about how different instructional approaches support conceptual understanding in genetics and highlight the need for further research examining the effectiveness of alternative pedagogical strategies.

The profile of misconceptions observed in this study is consistent with broader theoretical and empirical research. Donovan (2022), in a comprehensive literature review, concluded that conventional genetics instruction often fails to correct deterministic and essentialist misconceptions, and may even inadvertently reinforce them when mechanistic explanations are not explicitly addressed. Similarly, Todd and Romine (2018) demonstrated that although students may initially acquire factual genetic knowledge, a substantial portion of this knowledge may be lost over time, particularly when instruction does not promote deep mechanistic understanding.

From a pedagogical perspective, Liang *et al.* (2023) showed that traditional lecture-based instruction was less effective in fostering understanding of genotype–phenotype relationships compared to experiential instructional approaches, suggesting that teaching methods play a critical role in conceptual development. These findings highlight the importance of examining instructional and contextual factors in future studies designed to evaluate their influence on conceptual understanding, although the present study does not allow direct examination of causal relationships.

These findings further suggest that many students experience difficulties related to conceptual understanding rather than purely linguistic or vocabulary-related issues. Genetic concepts are inherently abstract, involving multiple levels of biological organization, probabilistic reasoning, and invisible molecular mechanisms. Students must integrate knowledge across molecular, cellular, and organismal levels, which imposes substantial cognitive demands on learners and thereby increases the likelihood of alternative conceptions.

Qualitative responses further illustrated the nature of these conceptual difficulties. Students' explanations revealed deterministic interpretations of genetic processes and confusion between key concepts such as gene, genotype, and phenotype. For example, some students described genes as being equivalent to observable traits, reflecting entity-based reasoning rather than mechanistic understanding. These findings highlight the persistence of simplified mental models that may hinder deeper conceptual integration.

Taken together, the findings of the present study, combined with prior research conducted across diverse educational systems, provide converging evidence that misconceptions in genetics have been repeatedly documented across different educational levels and contexts. The consistency of these findings across secondary and university levels, as well as across different educational contexts, suggests that these misconceptions may represent significant conceptual challenges rather than isolated learning gaps.

These findings carry important implications for genetics education. Addressing these conceptual difficulties may require pedagogical approaches that explicitly target conceptual change, promote mechanistic reasoning, and actively engage students in the reconstruction of their mental models. Future research is needed to examine the effectiveness of alternative instructional strategies — such as inquiry-based learning, model-based teaching, and conceptual change interventions — in reducing genetic misconceptions and improving long-term conceptual understanding.

4.1 Limitations

This study has several limitations that should be acknowledged. First, the sample was drawn from a single school, which may limit the generalizability of the findings to other educational contexts. Second, the cross-sectional and descriptive design does not allow for causal inferences regarding the relationship between instruction and students' conceptual understanding. In particular, the absence of a pre-instruction assessment limits the ability to determine the extent to which misconceptions changed over time. Third, although the questionnaire was developed based on the scientific literature and aligned with the official curriculum, questionnaire-based assessments may not fully capture the complexity of students' mental models. Additionally, the qualitative analysis was based on brief written responses and did not involve multiple independent coders, which may limit interpretive depth and reliability of thematic interpretation. Furthermore, instructional practices were not systematically observed, which limits the ability to characterize how genetics concepts were taught and prevents examination of relationships between teaching approaches and student understanding. Finally, although the instrument demonstrated acceptable internal consistency, the limited number of questionnaire items may restrict the breadth of conceptual domains assessed. Future studies should employ more comprehensive instruments to capture the multidimensional nature of genetics understanding.

Despite these limitations, the present study provides meaningful insight into students' conceptual understanding and misconceptions following formal instruction in an authentic classroom context. These findings contribute to a better understanding of the nature of students' conceptual difficulties in genetics and provide a basis for future research employing longitudinal and experimental designs.

4.2 Recommendations

Based on the findings of this study, several recommendations can be made for improving genetics education in Moroccan secondary schools.

First, instructional strategies should explicitly address common misconceptions identified in this study, particularly those related to hereditary transmission and the relationship between genotype and phenotype. Teachers should be encouraged to use conceptual change approaches that actively engage students in confronting and revising their pre-existing conceptions.

Second, curriculum developers should consider integrating more inquiry-based and model-based activities that allow students to explore genetic concepts through concrete examples and problem-solving tasks. Such approaches may help students develop mechanistic rather than deterministic reasoning patterns.

Third, teacher professional development programs should emphasize the importance of identifying and addressing misconceptions in genetics. Teachers should be equipped with diagnostic tools and pedagogical strategies specifically designed to promote conceptual change in genetics education.

Finally, future research should employ longitudinal and experimental designs to examine the effectiveness of these instructional interventions in reducing misconceptions and improving long-term conceptual understanding across different educational contexts.

5. Conclusion

This study documents the profile of genetics misconceptions among secondary school students following formal instruction. The findings highlight the importance of developing instructional approaches that explicitly address conceptual difficulties and support mechanistic understanding. Future research should employ longitudinal and experimental designs to examine instructional strategies targeting the specific misconceptions identified in this study.

Ethics Statement

This study was conducted in accordance with ethical guidelines for educational research involving human participants. Permission to conduct the study was obtained from the school administration. Participation was voluntary, and students were informed about the purpose of the research. No personally identifiable information was collected, and all responses were treated confidentially and analyzed anonymously.

Funding

This research received no external funding.

Author Contributions

The author was responsible for the conception, design, data collection, analysis, and writing of the manuscript.

Acknowledgments

The author would like to thank the participating students and school administration for their cooperation.

Conflict of Interest Statement
The author declares no conflicts of interest.

About the Author
Samir Laouina is a Life and Earth Sciences teacher in Morocco. His research interests include science education, conceptual understanding in genetics, and student misconceptions in biology learning.

References

Agorram, B., Zaki, M., Selmaoui, S., & Khzami, S. E. (2017). Moroccan science students' understanding of meiosis and its relation to gene transmission: A cross-sectional study. *Journal of Education, Society and Behavioural Science, 21*(4), 1-8. doi:10.9734/JESBS/2017/34578

Alouah, M., Zaibout, N., Madrane, M., Idrissi, R. J., & Tolaimate, A. (2025). Identifying conceptual obstacles in genetics education: A diagnostic analysis. *International Journal on Technical and Physical Problems of Engineering, 17*(64), 296-305.

Baroud, S., El Alaoui, M., Idrissi, R. J., Boucetta, N., Ghariz, G., & Seghir, H. (2025). Improving biology learning in high school with ChatGPT: A case study in Morocco. *Eurasia Journal of Mathematics, Science and Technology Education, 21*(7), em2669.

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

Donovan, B. M. (2022). Ending genetic essentialism through genetics education. *Human Genetics and Genomics Advances, 3*(1).

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

Haskel-Ittah, M., & Yarden, A. (2018). Students' conception of genetic phenomena and its effect on their ability to understand the underlying mechanism. *CBE—Life Sciences Education, 17*(3).

Liang, L., Yan, X.-C., Cao, X.-L., He, L., Zheng, M.-H., Qin, H.-Y., & Han, H. (2023). A student experience-based teaching to improve the understanding of genotype-phenotype relationship in classroom teaching of medical genetics. *Journal of Biological Education, 57*(3), 555-565.

Nussbaum, R. L., McInnes, R. R., & Willard, H. F. (2015). *Thompson & Thompson Genetics in Medicine* (8 ed.). Philadelphia: Elsevier.

Ojo, A. (2023). Examination of secondary school students' conceptual understanding, perceptions, and misconceptions about genetics concepts. *Indonesian Journal of Multidisciplinary Research, 4*(1), 213-226. doi:10.17509/ijomr.v4i1.72125

Osman, E., BouJaoude, S., & Hamdan, H. (2017). An Investigation of Lebanese G7-12 Students' Misconceptions and Difficulties in Genetics and Their Genetics Literacy. *International Journal of Science and Mathematics Education, 15*(7), 1257-1280. doi:10.1007/s10763-016-9743-9

Silar, P. (2020). *Genetics: Basic Concepts and Advanced Notions*. France: HAL Open Sciences.

Todd, A., & Romine, W. (2018). The learning loss effect in genetics: What ideas do students retain or lose after instruction? *CBE—Life Sciences Education, 17*(4), ar55.