Educational Needs and Difficulties of High School Students in Learning Genetics: A Systematic Review

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ABSTRACT

Genetics is a foundational area of biology and scientific literacy, yet high school students frequently experience difficulty understanding its abstract mechanisms, specialized terminology, probabilistic reasoning, and links across molecular, cellular, organismal, and population levels. This systematic review examined the educational needs and learning difficulties of high school students in genetics and synthesized evidence from studies finally included in the review. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. A literature search was conducted using Google Scholar, Scopus, PubMed, ScienceDirect, and Crossref. Search results were imported into Zotero for deduplication, with additional manual verification of near-duplicate records. Of the 959 identified records, 8 duplicates were removed, leaving 951 unique records for title and abstract screening. After screening and full-text eligibility assessment, 21 studies were included. Findings show that students' difficulties cluster around five recurring areas: weak prior knowledge and retention, misconceptions and fragmented conceptual understanding, difficulty visualizing abstract and molecular processes, problems with genetics terminology and scientific articulation, and low engagement with traditional instruction. The educational needs reported across the studies include contextualized and localized learning materials, visual and simulation-based resources, strategic intervention materials, inquiry-based and problem-based learning, scaffolding, conceptual change strategies, and teacher professional development. The review indicates that genetics instruction should move beyond rote memorization and isolated problem solving toward multimodal, learner-centered, evidence-based, and conceptually connected instruction. These findings may guide teachers, curriculum developers, and education researchers in designing interventions that improve students' conceptual understanding, engagement, and scientific literacy in genetics.

Keywords— Genetics Education; PRISMA; Learning Difficulties; Educational Needs; Misconceptions

INTRODUCTION

Genetics occupies a central position in biology education because it explains heredity, variation, gene expression, inheritance patterns, mutation, biotechnology, and many socioscientific issues that learners encounter in everyday life. A basic understanding of genetics enables students to interpret information about genetic diseases, genetically modified organisms, cloning, forensic identification, family inheritance, and emerging biotechnologies. For this reason, genetics is commonly included in secondary biology curricula and is considered an important component of scientific literacy [1], [20].

Despite its importance, genetics remains one of the most difficult biology topics for students [1], [6]. The reviewed studies consistently describe genetics as abstract, terminology-heavy, and cognitively demanding. Students are often expected to reason across several biological levels, from DNA and genes to chromosomes, cells, organisms, populations, and inherited traits [10],[13]. They must also interpret invisible molecular processes, use symbolic representations such as Punnett squares, apply probability, and connect genotype to phenotype. These requirements make genetics difficult to learn through lecture-based instruction alone [14],[15].

At the classroom level, these difficulties create a need for instructional materials and teaching strategies that make abstract concepts visible, meaningful, and connected to students' experiences [3],[5]. The reviewed studies examined a range of responses to this need, including video lessons, contextualized modules, digital interactive comics, strategic intervention materials, learning activity sheets, problem-based learning, simulations, scaffolding, conceptual change strategies, and engineering design process activities [3],[8],[20]. Synthesizing these studies is useful for identifying the dominant learning difficulties in genetics and the types of educational support most frequently recommended or tested.

This systematic review aimed to examine the educational needs and difficulties of high school students in learning genetics. Specifically, it sought to answer the following questions: (1) What learning difficulties in genetics are reported among high school students? (2) What educational needs are identified to address these difficulties? (3) What instructional implications can be drawn from the included studies?

MATERIALS AND METHODS

Review Design and Framework

This study employed a systematic review design to synthesize evidence on the educational needs and difficulties of high school students in learning genetics. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure a transparent and replicable process of identifying, screening, assessing, and including relevant studies. The review focused on studies that reported genetics learning difficulties, misconceptions, least mastered competencies, instructional needs, or evaluated interventions intended to improve genetics learning.

Information Sources and Search Strategy

The electronic databases searched, the standardized search strings, and the filters applied during the literature search are summarized in Table I.

Table I. Electronic databases searched, standardized search strings, and applied filters used in the literature search.

Database	Search string	Applied Filters
Google Scholar	("heredity" OR "genetics") AND ("learning difficulties" OR "misconceptions") AND ("educational needs" OR "instructional needs" OR "teaching strategies")	English articles; Year: 2020–2026
PubMed	Same core string applied (limited to title, abstract, keywords)	Year: 2020–2026; Title, Abstract, Keywords
Scopus	Same core string applied	English; Full text available
ScienceDirect	Same core string applied	Article type: Journal; Year: 2020–2026
Crossref	Same core string applied	English articles

A literature search was conducted using Google Scholar, Scopus, PubMed, ScienceDirect, and Crossref. These sources were selected to provide broad coverage of science education, biology education, educational intervention, and genetics education studies. Search results from the databases were imported into Zotero for

deduplication. Zotero duplicate detection was followed by manual verification to identify near-duplicate entries with minor differences in metadata, title formatting, or publication details.

Eligibility Criteria

The predefined inclusion and exclusion criteria applied in the selection of studies are presented in Table 2.

Table II. Inclusion and exclusion criteria used in the selection of studies for the systematic review.

Inclusion Criteria	
	The study must investigate the teaching or learning of specific genetics concepts, including but not limited to: • Heredity and Inheritance: Mendelian and Non-Mendelian patterns (incomplete dominance, codominance, multiple alleles, sex-linked traits) • Molecular Biology / Central Dogma: DNA structure, RNA, replication, transcription, translation, and protein synthesis • Genetic Variation & Engineering.
	Examined educational needs, learning difficulties, misconceptions, conceptual understanding, attitudes, perceptions, academic performance, or instructional interventions related to genetics.
	Empirical studies (quantitative, qualitative, or mixed-methods studies)
	Published between 2020 and 2026
	Written in English
	Participants must be high school learners

Exclusion Criteria	
1.	Studies focused solely on the biological mechanisms of inheritance, livestock/plant breeding, clinical/medical genomics, or evolutionary genetics without examining teaching, learning, or student/teacher needs
2.	Non-empirical records such as commentaries, opinion pieces, editorials, newsletters, books, book chapters, or literature reviews (unless the review is the specific object of a meta-analysis)
3.	Published before 2020
4.	Not written in English
5.	Articles with unavailable full text.

The inclusion and exclusion criteria were established before screening to ensure that only relevant and methodologically appropriate studies were included in the review. Studies were included if they: (1) investigate the teaching or learning of specific genetics concepts; (2) examined educational needs, learning difficulties, misconceptions, conceptual understanding, attitudes, perceptions, academic performance, or instructional

interventions related to genetics; (3) were empirical studies; (4) were published from 2020-2026; and (5) were written in English and had accessible full texts.

Studies were excluded if they (1) focused solely on the biological mechanisms of inheritance, livestock/plant breeding, clinical/medical genomics, or evolutionary genetics without examining teaching, learning, or student/teacher needs; (2) were non-empirical studies such as commentaries, books, book chapters, review article, or newsletters; (3) were published before 2020; (4) were not written in English; or (5) had inaccessible full texts.

Study Selection and Screening Process

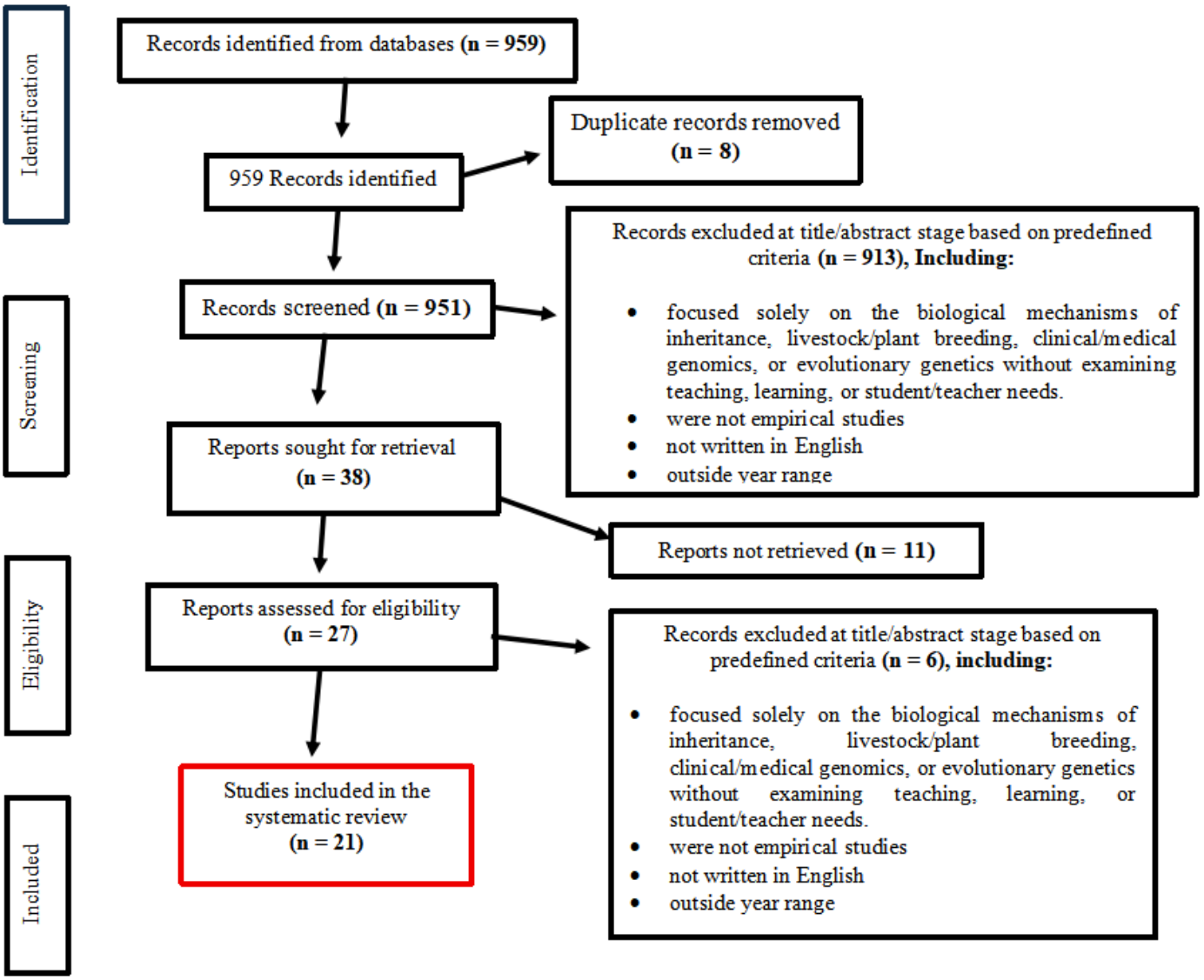

Figure 1. PRISMA flow diagram of the study selection process

A total of 959 records were identified from Google Scholar, Scopus, PubMed, ScienceDirect, and Crossref. All retrieved records were imported into Zotero for deduplication. Eight duplicate records were removed through automated and manual checking, leaving 951 unique records for title and abstract screening. Screening and study selection procedures were organized in accordance with systematic review reporting standards, while article screening decisions were facilitated through structured review practices similar to those supported by Rayyan [16].

During title and abstract screening, records were excluded when they were not related to genetics education, did not involve students or learning contexts, were not empirical, or did not address learning difficulties, educational

needs, misconceptions, or instructional interventions. Twenty-seven full-text reports were assessed for eligibility. Six reports were excluded after full-text review because they did not sufficiently address the review focus or did not meet the empirical and educational relevance requirements. Finally, 21 studies were included in the systematic review.

Data Extraction

A standardized data extraction form was used to collect comparable information from each included study. Extracted data included title, authors, publication year, research methodology, educational level, learning difficulties identified, educational needs reported, and key findings. The second sheet of the extraction form synthesized the extracted information across all included studies.

In addition, the extracted data were analyzed thematically by grouping recurring difficulties, needs, and intervention findings. Frequencies were not treated as effect sizes because the included studies varied in design, participants, topics, instruments, and outcome measures. Instead, the synthesis emphasized recurring patterns across the final set of studies. To strengthen the findings, data triangulation was employed by integrating quantitative results and qualitative themes, enabling validation and deeper interpretation of the identified learning gaps

RESULTS AND DISCUSSION

Characteristics of Included Studies

The 21 included studies covered a range of genetics topics and educational contexts. Most studies focused on junior or senior high school learners, particularly Grades 9 and 10. However, a small number of related studies involving upper secondary, Grade 12, or tertiary biology contexts were retained because they addressed genetics learning difficulties relevant to secondary preparation and progression. The studies used diverse method ologies, including descriptive surveys, mixed methods designs, quasi-experimental approaches, and action research, developmental research, qualitative case studies, and diagnostic testing.

Table III. Distribution of the included studies according to educational level, main topic, reported learning difficulty, and educational need/intervention focus

Category	Subcategory	Number of Studies
Educational Level	Grade 8	1
	Grade 9	4
	Grade 10	6
	Grade 11	1
	Grade 12	2
	Secondary mixed/upper secondary	5
	Tertiary/transition-related genetics learning	2
Main Topic	General heredity/genetics or least mastered biology competencies	4
	Mendelian or non-Mendelian inheritance learning challenges	6
	Mutation/genetic engineering/conceptual understanding	3

	Central dogma/molecular genetics/learning difficulty	4
	Genetics misconceptions/conceptual understanding/intuitive reasoning	4
Reported Learning Difficulty	Weak prior knowledge and poor retention	7
	Misconceptions and fragmented conceptual understanding	8
	Abstract, microscopic, and molecular processes	6
	Terminology, scientific language, and articulation	5
	Low engagement, low interest, and traditional instruction	7
	Contextualized and localized learning materials	4
	Visual, simulation-based, and multimodal resources	6
	Strategic Intervention Materials and remedial instruction	6
Educational Need/Intervention Focus	Inquiry-based, problem-based, and design-oriented learning	4
	Scaffolding, articulation, and conceptual change strategies	5
	Teacher professional development, textbooks, and curriculum support	4

*Some studies reported more than one difficulty or educational need; therefore, these frequencies overlap and do not total 21.

The distribution (Table 3) shows that the evidence base is concentrated on inheritance, heredity, mutation, and molecular genetics. Many Philippine studies examined least mastered competencies and intervention materials, while international studies provided a stronger emphasis on misconceptions, conceptual understanding, genetic terminology, and the origins of misunderstanding [6],[15].

Learning Difficulties Identified in Genetics

The extracted data indicate that students experience several overlapping difficulties in learning genetics. Weak prior knowledge and poor retention appeared in 7 studies, showing that many learners entered genetics lessons with limited mastery of prerequisite concepts such as inheritance patterns, genes in chromosomes, meiosis, cell division, Mendelian inheritance, genotype, phenotype, alleles, probability, DNA replication, transcription, and translation. Misconceptions and fragmented conceptual understanding appeared in 8 studies and were the most frequently reported difficulty. Accordingly, students often confuse genes, alleles, DNA, and chromosomes, use genotype and phenotype inconsistently, misunderstand gene expression, mutation, genetic engineering, meiosis, and inheritance patterns, and sometimes view genes as tangible particles or assume that traits are simply blended from parents [18],[19]. Difficulty with abstract, microscopic, and molecular processes appeared in 6 studies. Students struggled to visualize invisible processes such as DNA replication, transcription, translation, mutation, chromosome behavior during meiosis, and the molecular basis of trait expression [13].

Furthermore, terminology, scientific language, and articulation problems appeared in 5 studies, with learners confusing terms such as gene and chromosome, allele and alleles, genotype and phenotype, chromatid and chromatin, and mitosis and meiosis, which limited their ability to explain genetic concepts clearly in discussion

and writing. Low engagement, low interest, and traditional instruction appeared in 7 studies, indicating that students often perceived genetics as difficult, abstract, boring, or disconnected from everyday life, while lecture-based or module-based instruction was insufficient for topics requiring visualization, reasoning, problem solving, and conceptual change. These findings suggest that genetic learning difficulties are cumulative, conceptual, linguistic, and instructional, and that students need learning experiences that connect prior knowledge, correct misconceptions, visualize invisible processes, support scientific language, and increase meaningful engagement [6],[12],[17].

Educational Needs Reported Across the Included Studies

The reviewed studies identified several educational needs to address the learning difficulties in genetics. Visual, simulation-based, and multimodal resources appeared in 6 studies, while providing critical visual scaffolding for abstract and microscopic mechanisms—such as the central dogma and meiosis—that are otherwise "invisible and inaccessible" to the human senses. These tools enable students to move beyond rote memorization by allowing them to visualize and "experience" molecular interactions inside the cell rather than relying solely on imagination [1]. Strategic Intervention Materials (SIMs) and remedial instruction appeared in 6 studies, while serving as effective re-teaching tools designed to target "least mastered competencies" through structured, story-guided activities. These materials support independent and self-paced learning, allowing low-performing students to bridge learning gaps in complex topics like mutations and non-Mendelian inheritance without the pressure of regular classroom timing [2],[13],[14]. Scaffolding, articulation, and conceptual change strategies appeared in 5 studies. Strategies such as the Predict-Observe-Explain (POEAE) model and HOTS-driven questioning help students restructure their mental models and build the technical vocabulary necessary to communicate complex biological ideas [8],[9],[20].

In addition, contextualized and localized learning materials appeared in 4 studies. These findings suggest that connecting lessons to socio-scientific issues like food biotechnology or local genetic disorders significantly enhances student motivation and the practical application of scientific knowledge [4],[10]. Inquiry-based, problem-based, and design-oriented learning appeared in 4 studies. These suggest that Frameworks like the Engineering Design Process (EDP) and Problem-Based Learning (PBL) encourage students to synthesize information, collaborate in teams, and build evidence-based explanations for complex genetic phenomena [9],[11].

Lastly, teacher professional development, improved textbooks, and curriculum support appeared in 4 studies, while strengthening the foundational alignment of the science curriculum to ensure logical sequencing and the prevention of cumulative learning gaps. These studies emphasize that addressing teacher competence and textbook errors is essential for correctly navigating the spiral progression of genetics and providing students with reliable, visually-enriched instructional resources [15],[17],[18].

Integrated Framework of Genetics Learning Needs

Across the 21 included studies, the learning difficulties and educational needs can be organized into an integrated framework. Students first need strong prerequisite knowledge of cells, chromosomes, meiosis, alleles, and inheritance [6]. They then need visual and conceptual supports that connect molecular processes to observable traits [1]. They also need language scaffolds to use genetics terminology accurately and explain mechanisms [20]. Instruction should diagnose misconceptions early and use conceptual change strategies to restructure incorrect ideas [8]. Finally, learning should be contextualized, interactive, and linked to real-life problems so that students experience genetics as meaningful rather than as isolated terminology and calculations [7],[10]. This framework suggests that genetics instruction should be sequential, connected, and multimodal. Teachers should not teach Mendelian inheritance, non-Mendelian inheritance, mutation, and the central dogma as separate topics only [15]. Instead, instruction should repeatedly connect DNA, genes, chromosomes, proteins, traits, reproduction, and variation. These connections can reduce fragmentation and help students understand genetics as a coherent explanatory system [15],[17].

CONCLUSION

This systematic review examined the educational needs and difficulties of high school students in learning genetics using evidence from 21 included studies selected through a PRISMA-guided process. The review found that students' Genetic learning difficulties are multidimensional. They include weak prior knowledge, poor retention, misconceptions, difficulty visualizing abstract molecular processes, confusion with terminology, weak scientific articulation, low engagement, and dependence on rote memorization. These difficulties are especially evident in topics such as heredity, Mendelian and non-Mendelian inheritance, mutation, central dogma, meiosis, gene expression, and genetic engineering.

In addition, the educational needs identified across the studies include contextualized learning materials, visual and simulation-based resources, strategic intervention materials, scaffolding, problem-based and inquiry-based learning, conceptual change strategies, improved textbooks, diagnostic assessment, and teacher professional development. The evidence suggests that genetics instruction should be learner-centered, multimodal, and explicitly focused on connecting concepts across biological levels. Instructional interventions are most useful when they are based on diagnosed learning gaps, support visualization, promote explanation-building, and provide opportunities for students to challenge and revise misconceptions.

Overall, the findings support that genetics needs a more dynamic explanatory framework rather than as a collection of isolated terms, formulas, and inheritance problems. Strengthening genetics education requires better alignment among curriculum, teaching materials, assessment, teacher preparation, and classroom pedagogy. Future research should employ stronger experimental designs, larger and more diverse samples, delayed posttests, and cross-context comparisons to determine which interventions produce durable conceptual understanding in genetics.

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