

Development of Punnett square electronic media on human heredity to improve students' understanding of concepts

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Abstract: School-level instruction on heredity covers genetics topics such as DNA, RNA, alleles, phenotypes, genotypes, and more. This study aimed to develop electronic Punnett square media to enhance students' understanding of genetic concepts. The ADDIE development model was employed to create the media. Trials were conducted with Grade XII students, involving 15 students for the formative assessment and 60 students for the summative assessment. Data were analyzed to determine validation and practicality percentages, while an independent t-test was used to assess the media's effectiveness. The findings indicate that the Punnett square electronic media is valid (according to experts), practical (based on student and teacher feedback), and effective in improving students' conceptual understanding. Classes that used electronic media for the Punnett square demonstrated a better understanding of the concepts than those that did not ($\text{sig} < 0.05$). The significant difference in post-test results between the experimental and control classes suggests that the electronic Punnett square supports a more meaningful learning process. Consequently, this media serves as a viable alternative for biology instruction, helping students grasp abstract concepts in heredity.

Keywords: Electronic media, genetic concept, learning difficulties, visual representation

Abstrak: Pembelajaran mengenai hereditas di tingkat sekolah mencakup topik-topik genetika seperti DNA, RNA, alel, fenotipe, genotipe, dan sebagainya. Penelitian ini bertujuan untuk mengembangkan media elektronik *Punnett square* guna meningkatkan pemahaman siswa terhadap konsep-konsep genetika. Model pengembangan ADDIE digunakan dalam pembuatan media tersebut. Uji coba dilakukan terhadap siswa kelas XII, yang melibatkan 15 siswa untuk penilaian formatif dan 60 siswa untuk penilaian sumatif. Data dianalisis untuk menentukan persentase validitas dan kepraktisan, sementara uji-t independen digunakan untuk menilai efektivitas media. Hasil penelitian menunjukkan bahwa media elektronik *Punnett square* tersebut valid (menurut para ahli), praktis (berdasarkan umpan balik siswa dan guru), serta efektif dalam meningkatkan pemahaman konseptual siswa. Kelas yang menggunakan media elektronik *Punnett square* menunjukkan pemahaman konsep yang lebih baik dibandingkan kelas yang tidak menggunakannya ($\text{sig} < 0,05$). Perbedaan signifikan pada hasil *post-test* antara kelas eksperimen dan kelas kontrol mengindikasikan bahwa media elektronik *Punnett square* mendukung proses pembelajaran yang lebih bermakna. Dengan demikian, media ini dapat menjadi alternatif yang layak untuk pembelajaran biologi, serta membantu siswa memahami konsep-konsep abstrak dalam hereditas.

Kata kunci: Media elektronik, konsep genetik, kesulitan belajar, representasi visual

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INTRODUCTION

Genetics is a key topic in biology education. It plays a fundamental role in understanding the mechanisms of heredity; the structure and function of DNA, genes, and chromosomes; gene expression; and the relationship between genetic information and an organism's characteristics. A grasp of genetic concepts serves as the foundation for advancements in modern fields such as biotechnology, medicine, agriculture, and genetic engineering. Consequently, mastering these concepts is a crucial competency for students,

enabling them to better understand the broader scope of biological science (Duncan et al., 2016; Haskel-Ittah & Yarden, 2018; Rusmana et al., 2021).

Genetic material is a biological topic that most students find hard to understand because it is vague and complicated and involves biological processes that can't be observed directly (Fitriana et al., 2022; Mussard & Reiss, 2022). To fully grasp ideas like DNA replication, transcription, translation, the connections between genes, DNA, and chromosomes, and how traits are passed down, students need to be able to picture them very clearly. Students often get the wrong ideas about genetics because they are having so much trouble. Genetic information often makes it hard for students to learn because they can't connect ideas about tiny things to biological processes in living things (Tsui & Treagust, 2010). Other things that can make it hard for students to understand genetics information are boring learning materials (Saputra et al., 2021).

When taught in schools, genetics is generally covered through standard means like classes, workbooks, and simple PowerPoint slideshows. These forms of media help spread information, but they don't offer a fully interactive learning experience or help learners understand abstract ideas well. Researchers have found issues with the way teachers used rendering tools and the range of learning materials they used to teach genetics. Many lessons are based on textbooks and a few other resources, which makes it hard for students to picture microscopic ideas (Jannah, 2023-52). Students also don't understand genetic concepts because they lack sufficient teaching materials and use new learning tools incorrectly (Arifin et al., 2019). To make digital media more interactive and relevant, researchers have found that teachers struggle to find materials that help students understand abstract biological ideas like genetics (Paramitha et al., 2026).

Students who are taught by the teacher are more likely to be quiet and have few chances to think about ideas on their own (Saprudin and Pratama, 2021). The fact that students did so poorly on this subject also shows how hard it is to teach genetics. Because the ideas of genes, DNA, and chromosomes are hard for students to understand, they have not met the standards for mastery. Several studies show that many students don't meet the minimum requirements for mastery in genetics because they don't understand the big ideas and struggle to link the structures and functions of genetic components (Nurwendah & Sari, 2025; Rupilele, 2025; Soamole, 2025). Genetics concepts need to be made more interesting, visual, and interactive for students to better understand them. This can be done with the help of instructional media.

Instructional media can also make learning fun and interesting (Dita et al., 2024; Sinambela et al., 2021). Multimedia programs that combine text, images, animations, videos, and interactive tests can help students better understand abstract ideas. Digital instructional media are an option because they make abstract ideas easier to understand by showing them instead of just talking about them (Mayer, 2021). Creating digital learning materials is one of the best ways that the progress of digital technology can help make biology education better (Damopolii, 2021). Dita et al. (2023) say that using digital media lets students get to materials, study on their own, and learn in a variety of multimedia ways.

Some studies show that using Punnett square media can help students who are having trouble learning genetics. Punnett squares make it easier to do genetic calculations, especially for students who have trouble with math (Williams et al., 2021). The media helps make getting ideas in population genetics easier on the brain. A study by Akpan and Ekpo

(2025) found that students who are taught genetics using Punnett squares do better than those who are taught without the media. Development results suggest that a game-based approach that incorporates Punnett squares can boost student engagement and provide a more interactive learning experience in genetics (Low & Ellefson, 2024). Punnett square simulations are made to help students understand how meiosis, chromosomes, and inheritance work together in a logical way (Strand & Boes, 2019).

It is important to create digital learning materials about human genetics because technology needs to be used in both teaching and learning in the 21st century. Students today should have learning materials that are flexible, visually appealing, interactive, and easy to get to because they are part of the digital generation. Better learning outcomes in genetics are also important because a good understanding of genetic concepts is the basis for a lot of progress in modern biology. It is hoped that the new digital learning materials will help students understand concepts better and do better in school.

METHOD

Research and Development (R&D) based on the ADDIE model was used in this study (Branch, 2009). The study took place at SMA Negeri 1 Suwawa in Bone Bolango Regency, Gorontalo Province. The study site was chosen because it had the right technology for using electronic media, the school agreed to help with the research, and there weren't any other schools using electronic media for teaching around the area. During the trial phase, 15 students and one teacher took part. During the effectiveness test, 60 students and one teacher did. Three experts in the subject and three experts in the media did the validation. There were evaluation sheets for the experts, surveys for teachers and students to fill out, and a concept understanding test as research instruments. The concept comprehension test had 20 questions with multiple choices for a right answer.

Experts in the subject matter checked to see if the media content was in line with learning goals, if genetic ideas were correct, and if the information was full. Experts in the media looked at how it looked, how it was navigated, how it was programmed, and how easy it was to use. At the same time, validation by education professionals looked at how well the media met the needs of school learning and how easy it was to use in teaching and learning activities.

We used feasibility rates to look at the validation process data and figure out the media's validity category (Table 1 shows the validation categories). The product was revised and improved based on feedback from subject matter experts, media experts, and education professionals. This led to media that can be used in learning activities. After teachers and students watched media about human genetics, they were given surveys to fill out. This was done to see how useful the information was (Table 2). The answers showed how users felt about how easy it was to use, how clear the display was, how easy it was to understand the material, how well the features worked, and how useful the media was for supporting teaching and learning activities. Concept comprehension tests were given to students before and after using the learning media to find out how well it worked. The test scores were used to see how well students understood different ideas and whether their knowledge improved after using the electronic Punnett square media in the classroom. To find out how well the media worked, normality tests, N-gain analysis, and independent sample t-tests were used. The N-gain categories were based on Hake (1998).

Tabel 1. Validity criteria (Akbar, 2017)

Percentage (%)	Criteria
85.01–100	Highly Valid
70.01–85.00	Valid
50.01–70.00	Less Valid
1.00–50.00	Invalid

Tabel 2. Practicality criteria (Riduwan, 2015)

Percentage (%)	Category
81–100	Excellent
61–80	Good
41–60	Fair
21–40	Poor
0–20	Very Poor

RESULTS AND DISCUSSION

The analysis phase was conducted to identify learning needs, student characteristics, and the alignment of the material with the current curriculum. The study showed that students think the subject of human genetics is one of the hardest parts of biology. This is hard because of the general ideas involved, like genes, alleles, genotypes, traits, Mendelian laws, transfer rates, and genetic crosses.

Observations and talks with biology teachers showed that lessons and textbooks are still the most common ways to teach, which makes it hard for students to picture how traits are passed down. Also, students are still not very good at fixing problems that have to do with genetics. Because of this, there is a need for teaching materials that make ideas about heredity clearer and more concrete. The results of this needs analysis will be used to create a product that will help students with these learning problems (Ahmad et al., 2026; Yomaki et al., 2023).

Based on the needs analysis, an electronic learning media was designed to present genetics content in a structured manner. The design incorporated principles of interactivity, ease of use, and material integration. The developed product comprises eight main menus (Figure 1): (1) user instructions; (2) genetics content; (3) Punnett square simulation; (4) problem-solving exercises; (5) evaluation; (6) developer profile; (7) references; and (8) glossary. Each menu is systematically organized to enable students to engage in independent learning, progressing from conceptual understanding to the final evaluation.

The Figure 1 main menu screen is a navigation hub that leads students to all of the learning features that are available. DNA, chromosomes, cells, and genetic cross diagrams are used in the background to give the page a genetics theme that helps students immediately understand what it is about. The menu is set up vertically and uses colors that are different from each other to make it easy to find and use. The main page serves as an initial orientation tool that helps students understand how the lessons work on their own. The media has more than just information; it has lessons, games, tasks, tests, and other learning materials. This is clear from the way the menus are organized.



Fig. 1. Punnett square electronic media main menu

During the development phase, the media design was turned into a working product that could be tested. The video was made with Flutter, which lets digital devices connect with it. On the main page, there is a place to look around and a link that goes to all the work areas. The layout has a genetics theme with pictures of chromosomes, DNA, cells, and genetic crosses. This will get students interested in the subject right away, and it will also let them know how they're doing. The steps in the media are shown clearly, so students can figure out how to learn on their own. In this part, we'll talk about genes and alleles, genotypes and phenotypes, Mendel's rules and how they can be broken, and how human genes work. The writing is made better with pictures and drawings that help students understand vague ideas.

Figure 2 shows the simulation feature. This function lets students find out what the parental genotype is, do the genetic dihybrid cross, and see the results automatically as Punnett square tables. This tool helps people see how genes, phenotypes, and the chance of a child having traits are connected. The problem-solving section presents case-based questions to help you solve genetic problems in a structured way. This part will teach you how to solve genetic problems in a planned way. Students are helped to find problems, study information, choose answers, and rate how well those methods work. The review part is a list of multiple-choice questions that check how much the students know about what they've seen. So that the learner knows how well they are doing, the test result can be shown right away.

In the simulation feature (Figure 2), students can select the type of cross, define traits, view parental genotypes, generate a Punnett square table, and obtain genotype and phenotype percentages. This feature helps students visually understand the relationships between genetic symbols, offspring probabilities, and the outcomes of genetic crosses. Meanwhile, the problem-solving practice feature presents case-based questions, answer fields, guidance, and tracking of scores and progress. From a learning perspective, this feature encourages students to move beyond rote memorization of concepts and instead

apply a systematic approach to solving genetics problems. Interactivity is evident in the processes of inputting answers, checking responses, and navigating between questions.

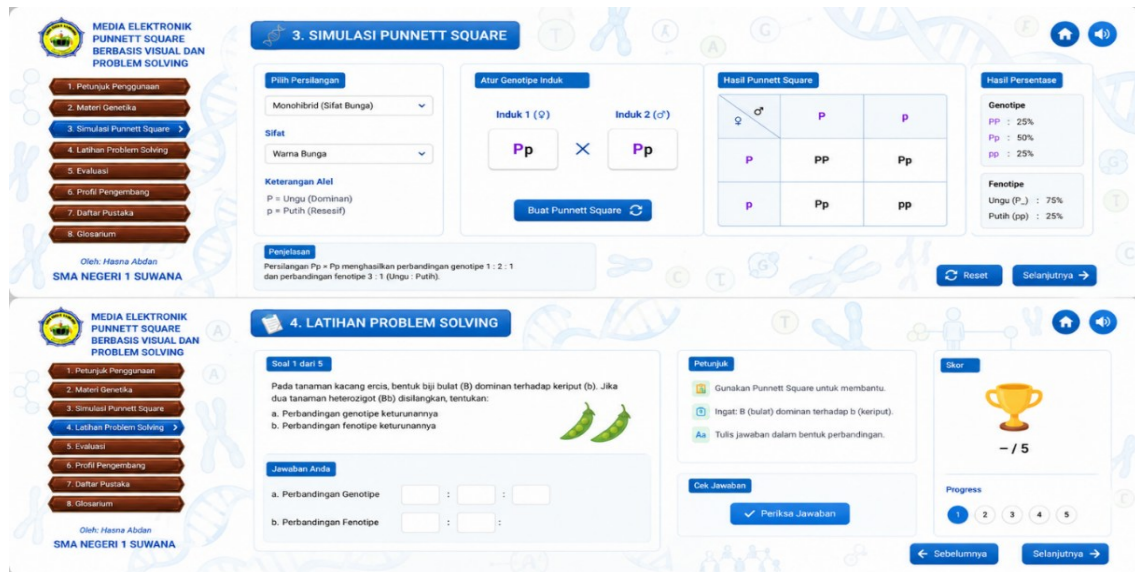


Fig. 2. Punnett square simulation feature and problem-solving exercises

Based on the research, the product developed is an electronic Punnett square learning media. The goal of this media is to help students understand complex ideas about human heredity by combining genetic visualizations, interactive Punnett square simulations, and problem-solving activities into a single digital learning platform. Some of the most important things about the media are that it is interactive, visually appealing, problem-solving-focused, encourages independent learning, and offers real-time genetic simulations and tests. These traits aren't random; they come from a learning needs analysis that showed that human heredity is one of the hardest subjects for students to understand because it involves complex concepts such as genes, alleles, genotypes, phenotypes, Mendelian laws, and the probability of trait inheritance. Not long ago, another study showed how important pictures are for teaching genetics. Menendez et al. (2024) said that using pictures to teach trait inheritance improves the way students understand concepts and makes it easier for them to see how gene and phenotype are related. Research by Newman et al. (2021) supports these results. It shows that the Punnett square is still one of the best ways to help students understand how traits are passed down and how likely it is that certain traits will show up in their children.

In addition to being based on visual representations, another distinguishing characteristic of this media is the integration of a problem-solving approach (Figure 2). With the developed media, students do not merely study genetic concepts; they are also presented with various cases requiring resolution through stages such as problem identification, information analysis, strategy determination, problem resolution, and outcome evaluation. This approach is designed to foster higher-order thinking skills while simultaneously enhancing students' problem-solving abilities. The integrated problem-solving characteristic aligns with the constructivist perspective, which positions the student at the center of the learning process. In a constructivist approach, students construct

knowledge through active learning experiences and direct engagement in solving problems. Regarding the topic of human heredity, problem-solving skills are crucial, as students must be able to interpret genetic information, determine potential genotypes, predict offspring phenotypes, and draw conclusions based on available data. These research findings are supported by the study conducted by Deep et al. (2020), which demonstrated that technology-based genetics learning environments integrating problem-solving activities can enhance students' scientific thinking skills and conceptual understanding.

The new media includes an interactive Punnett square simulation element (Figure 2). This function allows students to identify the parents genotypes , execute crosses, and examine the outcomes automatically. This process helps students better understand the connection between traits, genes, and the probability of having children. This simulation is particularly essential since in the past, students often learned the processes for solving genetic crossings without fully grasping the basic concepts behind them. Williams et al. (2021) found that utilizing the Punnett square as a visual tool may assist students grasp how gene pairs and genotype patterns are connected. Low and Ellefson (2024) also showed through the creation of Punnett Farms that adding the Punnett square to a digital game environment makes students more interested in learning genetics. As opposed to the usual way of using Punnett squares, the simulation function makes learning more active because students can try out different cross-scenarios and get instant feedback on their guesses.

It was time to do a product validity test on the Punnett square electronic media after it had been developed. The goal of this test was to see if the created media would work well before it was used in the learning process. The validity review was done with the help of subject matter experts, media experts, and education professionals' opinions. The evaluation results can be seen in Figure 3.

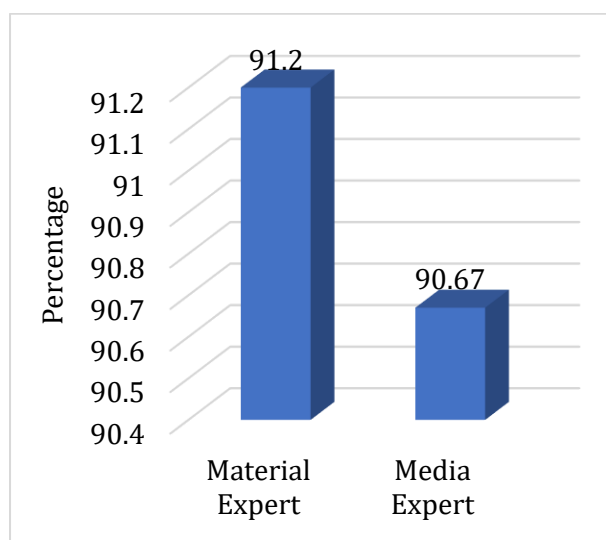


Fig. 3. Expert validation results

The research shows that the electronic Punnett square media obtained a material validity score of 4.56 (91.20%) and a media validity score of 4.53 (90.67%), placing it in the "highly valid" category. These results show that the media meet standards for being relevant to the curriculum, accurately representing ideas, using language, problem-solving, graphic

design, navigation, and code, and being suitable for teaching. It's clear from the high level of validity that all the media parts were made using good instructional media development principles. As for the content, the validator who checked it out said that it fits with what high school students should learn about biology and explains genetics correctly. This is important because genetics is a branch of biology that often leads to misunderstandings due to its vagueness and difficulty of explanation (Tibell & Rundgren, 2010). Visual media is used in genetics lessons to help students connect abstract ideas with real-world examples. This makes the process of building knowledge more effective (Uminski et al., 2025).

Table 3. Suggestions for improvement and follow-up

Validator	Suggestions for Improvement	Follow-up Actions
Material Expert 1	Include more contextual examples of human heredity	Added case examples regarding blood types and color blindness
Material Expert 2	Clarify the relationship between genotype and phenotype	Added explanations and illustrations to the content sections
Material Expert 3	Align biological terms with the latest sources	Revised terminology in accordance with current references
Media Expert 1	Adjust the layout of certain pages	Adjusted the placement of text and images for better proportions
Media Expert 2	Improve color and icon consistency	Standardized the visual design across all pages
Media Expert 3	Add instructions on how to use the media	Added an instructions menu to the media's opening page

Table 4. Small-group trial results

Class	Test	Mean	N-Gain
Conceptual Understanding	Pre-test	50.17	0.60
	Post-test	80.13	
Trial	Respondents	%	
Practicality	Student Response	93.40	
	Teacher Response	91.46	

Table 4 shows that the students' conceptual understanding got better after the Punnett squares were used first. The post-test score was 80.13, up from 50.17 on the pre-test. The N-Gain score for this improvement was 0.60, which puts it in the moderate category. These results show that using Punnett squares is an effective way to help students understand inheritance, especially when determining which genotypes and traits are likely to occur when two genes are crossed. Based on practicality, Students answered 93.40% of the time, and teachers answered 91.46% of the time. The fact that both results were "excellent practical" shows that Punnett squares are simple to use, interesting, and helpful for both students and teachers.

Based on Figure 4, teacher feedback regarding the use of the electronic Punnett square media yielded a score of 93 out of a maximum of 100, representing a practicality rate of 93%. These results indicate that the media falls into the "excellent practical" category.

Teachers assessed the media as easy to use, visually appealing, and functionally sound, noting its ability to facilitate a more effective and interactive learning process for the topic of human heredity. Student answer questionnaires for the electronic Punnett square media had a 91.4% favorable response rate, falling into the "strongly agree" category. Students gave good feedback on visual appeal, usability, subject understanding, problem-solving, and learning motivation. The greatest percentages were recorded for visual appeal and learning motivation, demonstrating that the media effectively produces an engaging learning experience and increases student interest in the topic of human heredity. Furthermore, the media was found beneficial in helping students grasp genetic ideas and solve issues linked to trait inheritance. As a result, the generated medium got a positive reaction and is judged appropriate for use in biology training. Excellent evaluations of a technology's utility and simplicity of use are associated with greater levels of user acceptability (Venkatesh et al., 2016). The study's results show that these requirements were satisfied, as both instructors and students regarded the media as valuable and simple to utilize in the learning process.

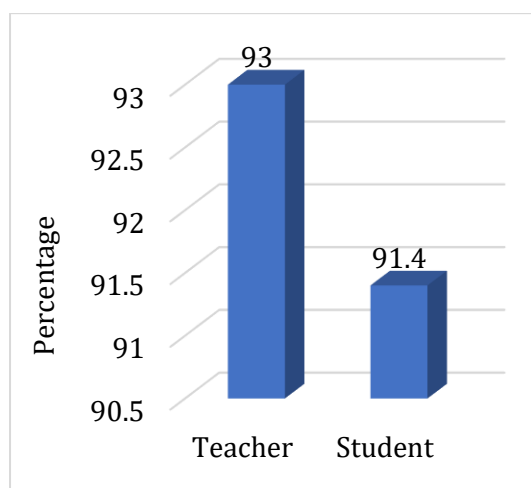


Fig. 4. Practicality test results during the implementation phase

Table 5. Results of the mean, n-gain, and data normality calculations

Class		Mean	N-Gain	Normality
Experiment	Pre-test	50.17	0.85	0.214
	Post-test	92.03		0.087
Control	Pre-test	48.83	0.48	0.196
	Post-test	73.57		0.122

The N-Gain analysis results (Table 5) indicate that the experimental class achieved a score of 0.84 (high category), whereas the control class achieved a score of 0.48 (medium category). These findings demonstrate that the use of the electronic Punnett square media resulted in a greater improvement in conceptual understanding compared to conventional instruction. Normality test results show that all data sets had significance values greater than 0.05: 0.214 for the experimental class pretest, 0.087 for the experimental class posttest, 0.196 for the control class pretest, and 0.122 for the control class posttest.

Consequently, all data were determined to be normally distributed and met the prerequisites for further statistical analysis.

Table 6. Results of the effectiveness test for the Punnett square electronic media

Variable	t	df	Sig.
Pre-test	1.555	58	0.125
Post-test	8.742	58	0.000

Based on Table 6, the Sig. value is greater than 0.05; therefore, there is no significant difference between the initial abilities of the experimental class and the control class. Thus, both classes possessed relatively equivalent initial abilities prior to the intervention. Since the classes had comparable initial abilities, they were suitable for testing the effectiveness of the electronic Punnett square media. The post-test results yielded a t-value of 8.742 with a significance value of 0.000 (Sig. < 0.05). These results indicate a significant difference in students' conceptual understanding between the experimental and control classes following the intervention. The higher average post-test score in the experimental class demonstrates that the use of the electronic Punnett square media had a significant impact on improving students' conceptual understanding compared to the instruction received by the control class.

Researchers have found that using Punnett square electronic media helps students understand concepts a lot better. The experimental class's average score went up from 50.17 on the pre-test to 92.03 on the post-test. The N-Gain that was found is 0.85, which is a lot. On the other hand, the control class only got an N-Gain of 0.48, which is in the middle range. The fact that the two groups got better at different rates shows that the Punnett square media works better than the old way of teaching. Mayer (2021) says that pictures in media can help students organize what they know, see how ideas fit together, and figure out what they mean. When students study human genetics, seeing alleles, genotypes, traits, and the crossing processes helps them see how things that were hard for them to understand before are connected.

Students require visualization skills when studying genetics, as the topic is highly complex. The visualization provided by the Punnett square tool enabled students in the experimental group to achieve better results in building their conceptual understanding. Genetic structures—such as chromosome forms, alleles, phenotypes, and genotypes—cannot be observed directly, making it difficult for students to grasp these concepts. The simulation feature allows students to better visualize the crossing process, including changes in allele pairs and the formation of generations in real-time. This aligns with findings by Afnan and Puspitawati (2024), who discovered that technology-based learning materials incorporating visual imagery help students understand complex biological concepts and make the learning process more enjoyable.

The simulation feature is a key strength of the Punnett square tool. This standout feature allows students to conduct crossing experiments in various ways. Conventional Punnett squares are typically used primarily for mathematical calculations. In contrast, the digital model's simulation feature enables students to adjust parameters, observe the effects, and directly compare inheritance patterns. In the context of science education,

Wahidin et al. (2025) revealed that digital simulation features foster interactivity, boost student interest, and strengthen conceptual understanding through direct interaction with the subject matter.

Research by Ningrum et al. (2026) on the use of digital models in science education further reinforces these findings. Their study demonstrates that such learning media consistently help students improve their knowledge and understanding of the concepts being studied. The tool provides a learning environment where students can take notes, modify specific factors, and receive immediate feedback. The effectiveness of digital media relies heavily on its ability to present information and offer opportunities for active student engagement—such as through Q&A sessions during discussions and presentations. The Punnett square tool helps students understand that the outcomes of genetic crossing experiments are not merely numerical figures but result from the allele pairings of the two parents. Rutten et al. (2012) reinforced these findings by revealing that simulation features help students better grasp scientific concepts by enabling them to manipulate variables, determine cause-and-effect relationships, and examine phenomena that are difficult to observe directly.

The simulation features and problem-solving exercises integrated into the Punnett square tool help students better understand genetic concepts related to heredity. Students do more than just fill in a Punnett square; they apply the genetic knowledge they have acquired to solve real-world problems. They learn to gather genetic information, observe various allele combinations, trace family genes, and draw conclusions from the crosses they have performed. These problem-solving activities greatly assist students in constructing their own understanding, as they actively receive information, think critically, and make decisions. Aristaningsih et al. (2025) state that problem-solving-based learning can enhance students' cognitive abilities by fostering higher-order thinking skills—such as connecting ideas, analyzing data, and applying knowledge in new situations. This approach is particularly effective for genetics, given that the concept of the gene is difficult to grasp through verbal explanation alone.

Problem-solving exercises embedded in the digital tool allow students to receive immediate results or feedback on the tasks they have completed. Sailer and Homner (2020) found that technology-integrated learning environments—which offer engaging activities and feedback—can boost student interest and deepen their understanding of material they find challenging or difficult to master. In our research, the exercises within the Punnett square tool serve both as an evaluation method and as an integral part of the learning process. These questions help students identify their errors and discover or construct an accurate understanding of the concepts. According to Damopolii and Kurniadi (2019), problem-solving techniques in technology-based learning help students better understand concepts, thereby leading to academic success. This method renders the learning process more active and student-centered.

CONCLUSION

Based on the research results, it can be concluded that the Punnett square electronic media has met the criteria of being valid, practical and effective in increasing students' understanding of concepts in human heredity material. The use of this media provides a more interactive learning experience through simulation features that help students

visualize the crossing process, understand the relationship between genotype and phenotype, and explore various possible combinations of alleles. The significant difference in posttest results between the experimental class and the control class shows that Punnett square electronic media is able to support a more meaningful learning process. Thus, this media can be an alternative for biology learning to help students understand the concept of abstract heredity material.

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