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ENHANCING STUDENTS' MOTIVATION IN LEARNING GENETICS THROUGH STEM-GBL AMONG NORTHERN MATRICULATION STUDENTS

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ABSTRACT

Game-based learning (GBL) is an active learning technique that utilizes games to improve student learning by promoting critical thinking and problem-solving skills. In this study, the researchers implemented a variant of GBL called STEM-GBL, which incorporates STEM elements into the teaching of Genetics. The purpose of the research was to investigate the impact of STEM-GBL on students' motivation in learning Genetics for the Biology subject. A quasi-experimental research design was employed, with two groups being observed: an experimental group exposed to the independent variable (STEM-GBL) and a control group receiving conventional instruction. The sample consisted of 45 randomly selected students from Penang Matriculation College (experimental group) and Perlis Matriculation College (control group). The mean score for the post-test of motivation was $M = 129.31$ ($SD = 11.27$) for the conventional group, whereas the treatment group recorded a higher mean score of $M = 150.84$ ($SD = 11.27$). The analysis of covariance (ANCOVA) revealed that the difference in students' motivation between the two groups was statistically significant, $F(1,87) = 95.26$, $p = .001$, partial $\eta^2 = .523$, indicating that the p-value was lower than the predetermined significance level ($p < .05$). These findings suggest that integrating STEM-oriented GBL strategies can serve as an effective pedagogical approach to enhance students' motivation in learning complex Genetics concepts.

Keywords: game-based learning, STEM, quasi-experimental design

INTRODUCTION

Genetics is a fundamental component of the Biology curriculum in Malaysian matriculation programmes, as it develops students' conceptual understanding and scientific thinking while preparing them for further studies in science-related fields. A strong foundation in genetics is particularly important because the topic underpins many areas of modern biology, including medicine, biotechnology, and agriculture. However, teaching and learning genetics remain

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challenging. Genetics concepts are often abstract and require students to interpret symbolic representations, mathematical ratios, and complex biological processes occurring at the cellular level (Williams et al., 2012). As a result, students frequently develop misconceptions about key concepts such as genes, alleles, and inheritance patterns, which may hinder meaningful understanding and limit further learning (Orcajo & Aznar, 2005; Tsui & Treagust, 2007).

Beyond cognitive understanding, motivation plays a crucial role in sustaining students' engagement with challenging scientific content. Intrinsic motivation, characterized by curiosity and genuine interest in learning, has been identified as a strong predictor of academic achievement and persistence in biology learning (Deci & Ryan, 2000; Huang, 2023). However, in many Malaysian matriculation classrooms, biology is often perceived as a subject that relies heavily on memorization and examination preparation. Such perceptions may reduce students' interest and motivation to engage deeply with biological concepts (Rahman et al., 2023). Therefore, innovative instructional strategies are needed to enhance students' motivation and engagement in learning complex topics such as genetics.

One promising approach is the integration of Science, Technology, Engineering, and Mathematics (STEM) education with Game-Based Learning (GBL). GBL has been shown to increase learner engagement by incorporating elements such as challenge, feedback, and reward, which sustain students' attention and enjoyment during learning activities (Trybus, 2015). In addition, GBL aligns with social constructivist principles by encouraging collaboration, active participation, and problem-solving in meaningful contexts. Recent studies indicate that integrating GBL within STEM learning environments can enhance students' intrinsic motivation and self-regulated learning by transforming learners from passive recipients of knowledge into active constructors of understanding (Huang et al., 2024; Yu et al., 2023). For example, Huang (2024) reported that students who participated in gamified biology lessons demonstrated higher levels of interest and effort due to the interactive feedback and immediate responses provided by digital learning tools.

Furthermore, neuroscience research provides additional insights into why GBL can enhance motivation and engagement. Gaming activities stimulate dopaminergic reward systems in the brain, which are associated with positive emotions, curiosity, and goal-directed persistence during learning tasks (Zadina, 2022; Gee, 2023). When combined with STEM-oriented problem-solving activities, such as analyzing Mendelian inheritance using digital simulations or interactive quizzes, these learning experiences can support deeper conceptual understanding and increased learner confidence.

Despite these promising developments, empirical studies examining the integration of STEM-based GBL in the Malaysian matriculation context remain limited, particularly in the teaching of genetics. Most existing studies focus on general STEM education or digital learning strategies rather than specifically investigating their effects on students' motivation in genetics learning.

Therefore, this study aims to investigate the effect of STEM-Game-Based Learning (STEM-GBL) on students' motivation in learning Genetics among Malaysian matriculation students. The findings are expected to provide empirical insights for educators and curriculum designers in developing more engaging, brain-aligned, and student-centered instructional approaches for genetics education.

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Background of the Study

Learning Genetics has long been recognized as one of the most conceptually challenging topics in biology education due to its abstract nature, specialized terminology, and integration of symbolic and mathematical reasoning (Williams et al., 2012). Students often develop misconceptions about genes, alleles, and inheritance mechanisms, which hinder deep conceptual understanding and impede continued interest in the subject (Orcajo & Aznar, 2005; Tsui & Treagust, 2007). In Malaysia's matriculation system, these difficulties are compounded by the prevalence of rote memorization and exam-oriented instruction, which often limit learners' engagement and intrinsic motivation (Rahman et al., 2023). Consequently, fostering motivation is crucial for supporting persistence and meaningful learning in abstract biological concepts such as Genetics.

Motivation represents a key affective component of successful learning. According to Self-Determination Theory, intrinsic motivation driven by curiosity, autonomy, and competence is essential for sustained learning and achievement (Deci & Ryan, 2000). However, traditional instructional methods in Malaysian pre-university settings seldom nurture these psychological needs. Students frequently perceive biology as content-heavy and disconnected from real-world contexts, resulting in disengagement and superficial learning outcomes (Rahman et al., 2023).

Integrating STEM principles into GBL has emerged as a promising strategy to enhance students' motivation and engagement. GBL leverages challenge, feedback, and reward systems to sustain attention and foster enjoyment during learning (Trybus, 2015). When coupled with STEM contexts, GBL enhances authenticity by situating scientific concepts within real-world problem-solving scenarios (Yu et al., 2023). Empirical evidence demonstrates that such STEM-GBL environments can promote intrinsic motivation, self-efficacy, and persistence across science disciplines (Gui et al., 2023; Li et al., 2024; Barz et al., 2024). Neuroscientific research further suggests that interactive, game-like experiences activate dopaminergic reward pathways, reinforcing curiosity, attention, and goal-directed behavior (Zadina, 2022; Gee, 2023).

Despite these international advances, limited empirical work has examined STEM-GBL's motivational effects within the Malaysian matriculation context. Most local studies remain descriptive or focus primarily on achievement rather than motivational constructs (Rahman et al., 2023; UNIMAS, 2024). Additionally, many fail to employ validated motivational instruments, which constrains cross-study comparison and theoretical generalization. Addressing this gap is vital for aligning teaching practices with the Ministry of Education's transformation initiatives emphasizing digitalization, learner autonomy, and creativity in STEM education. Accordingly, this study investigates the effect of a STEM- GBL approach on matriculation students' motivation to learn Genetics, contributing to the growing discourse on brain-aligned, student-centred pedagogical design in science education.

Problem Statement

Despite Malaysia's increasing focus on digital and student-centred pedagogies, Genetics instruction at the matriculation level largely remains teacher-centred, emphasizing memorization rather than conceptual understanding. Such approaches often fail to address students' motivational needs, resulting in low persistence and persistent misconceptions about abstract genetic processes (Williams et al., 2012; Rahman et al., 2023). Many students perceive biology as content-heavy and disconnected from real-life applications, which reduces curiosity and engagement in learning (Orcajo & Aznar, 2005; Tsui & Treagust, 2007).

Although international research demonstrates that GBL can enhance enjoyment, persistence, and self-efficacy through interactive feedback (Huang et al., 2024; Li et al., 2024), empirical evidence examining the motivational impact of STEM-GBL within Malaysian matriculation biology classrooms remains limited. Existing Malaysian studies also tend to lack experimental validation and strong theoretical grounding, particularly in integrating STEM elements to support motivational dimensions such as autonomy, competence, and relatedness described in Keller's (2010) ARCS model and Self-Determination Theory (Deci & Ryan, 2000). Furthermore, the limited use of validated motivational instruments, such as the Instructional Materials Motivation Survey (IMMS) or the Science Motivation Questionnaire II (SMQ-II), reduces the reliability and comparability of existing findings.

Consequently, these methodological and theoretical gaps limit a comprehensive understanding of how STEM-GBL influences students' motivation toward learning Genetics in Malaysian pre-university contexts. Therefore, controlled and theory-driven research employing standardized motivational instruments is needed to determine whether integrating STEM principles with game-based strategies can effectively enhance students' motivation and learning persistence. Addressing this gap will provide empirical evidence to guide the development of engaging, brain-aligned, and digitally adaptive instructional strategies aligned with Malaysia's educational transformation agenda.

Objectives of the Study

This study aims to investigate the effect of the STEM-GBL approach on matriculation students' motivation in learning Genetics. Specifically, the objectives are:

i) To determine the difference in students' motivation toward learning Genetics between those taught using the STEM-GBL approach and those taught using conventional instruction.
ii) To evaluate the extent to which the STEM-GBL approach influences overall motivation scores after controlling for pre-test motivation levels.
iii) To provide empirical evidence on the effectiveness of integrating STEM principles and game-based learning strategies in enhancing the motivation of Malaysian matriculation biology students.

LITERATURE REVIEW

Teaching Genetics at the pre-university level presents challenges because the subject is abstract, requires specialized terminology and involves intricate relationship between symbolic reasoning and mechanistic reasoning (Williams et al., 2012). These challenges are frequently accompanied by lower motivation and involvement of learners when the teaching-learning process is based on rote learning or lecture as a method of delivery (Rahman et al., 2023). To

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tackle these motivational issues, scholars have worked on merging STEM principles into GBL. The STEM-GBL model offers interactive, problem-based and feedback-rich gaming experiences that could foster interest, autonomy and persistence in understanding complex topic like gene inheritance and molecular processes (Arztmann, 2023; Gui et al., 2023).

Conceptual Framework: Motivation in Learning Genetics

Genetics has been identified as one of the most difficult concepts in biology education because it involves abstract ideas such as molecular level of functioning, complex language and symbolic representation linking molecular mechanisms to observable characteristics (Williams et al., 2012). Such attributes frequently result in cognitive overload, and misunderstanding of the concepts and decrease students' intrinsic motivation and perseverance to learn (Orcajo & Aznar, 2005; Tsui & Treagust, 2007). In traditional lecture-based classes, students often view genetics as primarily being memorization and not comprehension, limiting their interest in the subject matter (Rahman et al., 2023). As a result, the reinforcement of motivation—both intrinsic and extrinsic—has become an important pedagogical objective in maintaining the students' interest and success in Genetics.

Theoretical Underpinnings of Motivation in Game-Based Learning

The motivation benefits of GBL can be framed within the framework of Keller's ARCS Model of Motivational Design, which appealed to four major determinants (Attention; Relevance; Confidence; Satisfaction) in determining learner attraction (Keller, 2010). Attention involves the relevance for curiosity and interest in GBL through dynamic tasks, narrative games, and instant feedback (Huang et al., 2024). Relevance is the perceived utility of a learning activity, and gaming environments enhance this by linking genetic content with authentic problems and interactive simulations (Low & Ellefson, 2024). Self-efficacy concerns students' beliefs about their ability to undertake successful actions; this can be promoted in GBL by gradual levels of difficulty and adaptive feedback structures that accentuates perception of competence (Rachmatullah et al., 2021). Lastly, Satisfaction occurs when learners feel they achieved something worthwhile and are having fun in attaining goals that is commonly supported by game-based structures such as rewards, achievements and progress feedback (Li et al., 2024). Taken together, the ARCS model represents a broad view of how well-designed STEM-GBL activities elicit and maintain motivation during the learning of Genetics through engaging cognitive, affective and behavioral aspects of engagement.

Global Evidence of STEM-GBL's Impact on Motivation

At an international level, it has been found that the integration of STEM methodology using game elements enhances cognitive results and motivational constructs in science education. For instance, Gui et al. (2023) performed a meta-analysis of STEM-GBL interventions and found substantial increases in motivation and engagement, especially when games used authentic problem-solving and feedback loops. Similarly, Barz et al. (2024) revealed that DGBL influences affective motivation outcomes (i.e., enjoyment, persistence, and self-efficacy) in secondary schools positively. Only in genetics teaching, research has shown that Martínez-Carmona et al. (2024) implemented a BreakoutEDU activity on gene expression to

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improve undergraduate emotional involvement and curiosity. Low and Ellefson (2024) developed Punnett Farms, an immersive genetics simulation, in which students experienced high satisfaction with perceived relevance important components of intrinsic motivation. Similarly, Hue et al. (2025) found that the Geneblock game significantly enhanced student interest and comprehension in relation to university learners working on inheritance, drawing attention to the opportunities afforded by interactivity and instantaneous feedback for engagement.

Studies in Malaysia and the Regional Context

In the context of Malaysia, where high school level matriculation biology serves as a preparation for higher education, interest in incorporation gamified STEM pedagogy is growing due to it being limitedly researched empirically. A study by Rahman et al. (2023) who reported that intrinsic and extrinsic motivation were strong predictors of engagement for Malaysian matriculation biology students, but traditional lecture methods are the norm in most classrooms. An article in University Malaysia Sarawak (2024) heavily underscored the possibility/likelihood of gamification to increase motivation for learning, but warned that a good number of local applications ran without theoretical roots and without systematic assessment. Regionally, Arpaci et al. (2023) applied in Indonesia an educational genetics game based on Arduino, with positive impact on students motivation and concept comprehension. Similarly, Low et al. (2025) identified learning difficulties in cell division among Malaysian secondary school students, highlighting the importance of motivation-enhancing feedback-rich intervention to overcome these conceptual learning challenges in Genetics. Together, these studies indicate the STEM-GBL framework is well-matched to regional educational goals, such as digitalisation and 21st-century learning, but robust local validation is lacking.

Contradictory Findings and Gaps

Despite the increasing worldwide attention toward STEM-GBL, significant research voids and profound issues still exist, particularly in Malaysia. First, there is scant local empirical evidence regarding STEM-GBL's motivation-promoting effect in genetics learning. International research has indicated that it is an effective tool in engaging and motivating learners (Barz et al., 2024; Gui et al., 2023), yet little experimental work among matriculation students in Malaysia was found to investigate these influences. There is a lack focus on motivation-specific instruments in the local initiatives which most are descriptive findings and achievement outcomes (Rahman et al., 2023; University Malaysia Sarawak [UNIMAS], 2024). This gap highlights the urgency of developing controlled interventions to understand how STEM-GBL affects students' intrinsic and extrinsic motivation to learn biology, especially abstract content such as Genetics.

Second, the lack of established motivational scales in much of Malaysian research. The current literature generally uses non-standardized engagement or achievement measures, as it does not include validated motivation instruments such as the Keller's IMMS (Instructional Materials Motivation Survey) or Glynn and Koballa's SMQ-II (Science Motivation Questionnaire II). This restricts the comparability of findings to global literature and undermines construct validity when evaluating motivational effects of GBL interventions (Li, Hew, & Du, 2024). Using validated instruments is needed to adapt the fine-grained changes in

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motivation and distinguish momentary engagement from maintained intrinsic interest for learning Genetics. There are also very few longitudinal and theory-based research designs in regional studies. A majority of studies have used cross-sectional or quasi-descriptive research designs that are looking only at short term effects on a few lessons using game-based lessons. As a result, it is poorly understood how motivational states develop, stabilize or decline during extensive learning episodes (Wang et al., 2022). Longitudinal studies based on motivational models (Keller's ARCS Model, Self- Determination Theory -SDT-) would enable us to follow up the duration of motivation and engagement in different instructional phases during Genetics learning.

Finally, the mechanistic uncertainty is still a major limitation. There is limited investigation into the mediating effects of particular game design elements (e.g., autonomy support, types of feedback: adaptive vs. competitive vs. collaborative) on motivation outcomes. Although previous meta-analyses indicate that there are beneficial trends (e.g., Barz et al., 2024; Li et al., 2024), they regard GBL as a uniform whole without differentiating which mechanics successfully facilitate autonomy, competence, or satisfaction. In the future, a more fine-grained approach is recommended with further mediation or moderation analyses to examine the underlying psychological process of motivational change in STEM-GBL contexts. Closing these research gaps will contribute to enrich theoretical perspectives and guide culturally sensitive evidence-based GBL use in the context of Malaysian matriculation biology education.

The literature included in this review highlights the success of the STEM-GBL method at increasing students' motivation by incorporating game dynamics, feedback, and real world problem solving within genetics instruction. But the data from Malaysia are early. Thus, future research employing more rigorous quasi-experimental or mixed-methods study designs may be necessary to investigate the effects of STEM-GBL on motivational variables (autonomy, competence, relatedness) and learning persistence for matriculation biology students. Additionally, such research will not only address a significant void in local educational practice, but also more broadly add to the conversation around brain-aligned, technology-enabled pedagogy for science education.

METHODOLOGY

Research Design

This study employed a quasi-experimental research design to compare the effectiveness of different teaching approaches in enhancing students' motivation toward learning Genetics. The design involved two groups: an experimental group exposed to the STEM-GBL approach and a control group receiving conventional instruction. The quasi-experimental design allowed the researcher to examine the effect of the independent variable (STEM-GBL) on the dependent variable (students' motivation) while maintaining natural classroom settings without reorganizing existing classes.

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Sample and Population

The population of this study consisted of matriculation students in Northern Malaysia aged between 18 and 20 years, enrolled in the One-Year Programme (PST). A total of 90 students participated in the study, with 45 students from Penang Matriculation College (experimental group) and 45 students from Perlis Matriculation College (control group). Both colleges share similar academic structures and follow the Biology syllabus developed by the Matriculation Division, Ministry of Education Malaysia.

The selected students have comparable academic and cognitive backgrounds, as they are enrolled in science streams that include Physics, Chemistry, Biology, Mathematics, and English. Two Biology lecturers from the respective colleges participated in the study. Prior to the implementation, both lecturers received training sessions to ensure consistency and confidence in applying the STEM-GBL instructional approach.

Sampling Technique

The sampling process was conducted in two stages. First, two matriculation colleges with comparable academic status were purposively selected from the Northern Zone. Second, one intact class from each college was randomly selected to participate in the study. This approach ensured that the learning environment, syllabus, and instructional context were comparable across both groups. The selected colleges follow the same Biology curriculum prescribed by the Matriculation Division, and the students share similar socio-economic and educational backgrounds.

Data Collection

Data were collected systematically using Google Forms distributed through Google Drive. The motivation questionnaire was administered to measure students' motivation toward learning Genetics. Control procedures were implemented to ensure the validity of the data collection process, including standardized instructions and consistent administration procedures across both groups.

Validity and Reliability

A pilot study was conducted with 45 Module I matriculation students to examine the reliability and clarity of the research instruments. The pilot study helped identify necessary improvements in the wording and structure of the questionnaire items before the actual study. The Instructional Materials Motivation Survey (IMMS) developed by Keller (1987) was used to measure students' motivation. The instrument measures motivational dimensions based on the ARCS model (Attention, Relevance, Confidence, and Satisfaction). Because the number of items in each subscale differs, Keller (2010) recommends calculating the mean score for each subscale before combining them to obtain the overall motivation score.

The reliability of the IMMS instrument has been previously reported with a Cronbach's Alpha coefficient of .96 (Keller, 2010). In this study, the pilot test produced an internal

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consistency reliability coefficient of .91, indicating satisfactory reliability for measuring students' motivation. The validity of the instrument was established through expert review. The panel consisted of two Biology subject-matter experts from Penang Matriculation College and one English lecturer from Kedah Technical Matriculation College. The experts evaluated the clarity, accuracy, and appropriateness of the questionnaire items to ensure content validity.

RESULTS

Descriptives Analysis

Table 1 shows that the mean score of the post-test to measure the Motivation questionnaires of the experimental group was (*M*=150.84,*SD*=11.61) while in the student score of the control group was (*M*=129.31,*SD*=11.27). The increase in post-test scores compared to the pre-test was 18.64 for students of the experimental group (STEM-GBL) while the control group students only increased only by 4.00 marks. The increase for students of the experimental group was higher compared to the students of the control group. Hence, there is a different between mean scores of experimental group and control group for students' motivation.

Table 1. Students' Motivational post-test between the group of students who took part in STEM-GBL teaching approach and Conventional approach.

Group	Number	Mean score	Standard deviation	Difference in mean score (Compare with pre-test)
STEM-GBL approach	45	150.84	11.61	18.64
Conventional approach	45	129.31	11.27	4.00

Statistic Inferential

Table 2 shows that $F(1,87) = 95.26$, $p=.001$, partial eta squared = .523, the result is significant as $p<.05$. There is a significant difference in the mean scores of post-test of motivation between treatment group which using STEM-GBL approach and control group which use a conventional approach after controlling for scores on the pre-test of motivation (Pallant, 2020). Thus, H_{01} is rejected.

Table 2. ANCOVA analysis for Students' Motivation between Treatment Group and Control Group

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	17237.313[a]	2	8618.657	159.362	.000	.786
Intercept	742.877	1	742.877	13.736	.000	.136
premot	6804.413	1	6804.413	125.816	.000	.591
Group	5151.940	1	5151.940	95.261	.000	.523
Error	4705.142	87	54.082			
Total	1787903.000	90				
Corrected Total	21942.456	89				

R Squared = .786 (Adjusted R Squared = .781)

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Table 3 shows that the partial eta squared value ($\eta p^2 = .523$) indicates that approximately 52.3% of the variance in students' post-test motivation scores can be attributed to the teaching approach used in the study. According to Cohen's (1988) guidelines, this value represents a large effect size, indicating that the STEM-GBL approach had a substantial impact on students' motivation toward learning Genetics.

Table 3. Univariate Tests- Effect Size (Students' Motivation)

Dependent Variable: postmot

	Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Contrast	5151.940	1	5151.940	95.261	.000	.523
Error	4705.142	87	54.082			

Figure 1 shows that the estimated marginal effect of STEM-GBL on students' motivation is 52 percent ($p < 0.05$). On average, using STEM-GBL teaching approach is associated with a 52 percent increase in student achievement compared to student that using conventional teaching approach holding pre-motivation score constant.

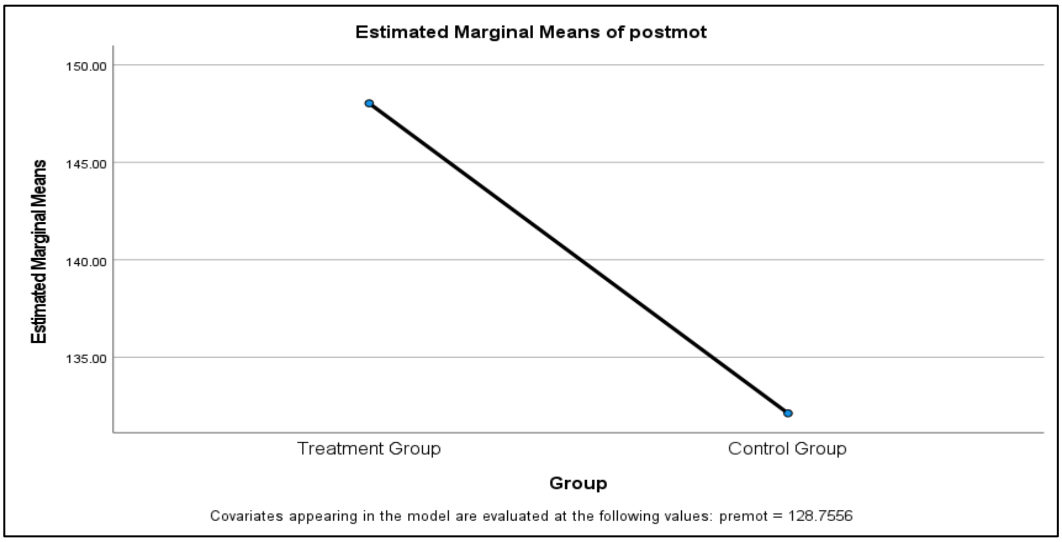

Figure 1. Estimated Marginal Means of Post-Test (Students' Motivation)

DISCUSSION

We have succeeded in showing that the STEM-GBL intervention methodology has significantly improved the matriculation students' motivation towards Genetics learning. There was a combined increase in the motivation levels for participants of the experimental group who had received ($M = 18.64$) as compared to those in the report-only condition ($M = 4.00$) which were consistent with support findings obtained by ANCOVA, $F(1,87) = 95.26$, $p < .001$, partial $\eta^2 = .523$) is consistent with the idea that the differences before learning are relatively small compared to those after learning, with post-test variation being primarily due to variance related to STEM-GBL intervention. This is consistent with Objective 1 and verifies that students learning Genetics exposed to STEM-GBL was significantly more motivated in wanting to learn than one being instructed conventionally.

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With regard to Objective 2, the ANCOVA findings that statistically adjust for pre-test motivation provide clear evidence for an independent and measurable impact of the STEM-GBL intervention on motivation outcomes. This would indicate that the design elements of STEM-GBL (problem-solving tasks; challenge–feedback cycles and game-based reinforcement) establish an more psychologically positive or supportive learning environment that increases students' sense of autonomy and competence with corresponding support for Self-Determination Theory (Deci & Ryan, 2000). These processes might account for why difference in gains remained significant even after controlling for initial differences in motivation.

Regarding Objective 3, the findings contribute to a growing body of empirical studies that are investigating the integration of STEM concepts and pedagogical practices with GBL that can positively influence learners' motivational constructs in various educational settings. Ezeugwu et al also made similar findings. (2016) who showed that Algebra in the game based learning method can provide a better motivating factor compared to students in a typical classroom. Their quasi-experimental study at the primary education level also used ANCOVA and showed significant effect at p <. 05, closely representing the methodological soundness and findings of our study.

The findings of this study provide several important implications for educational practice, research, and curriculum development. First, the results demonstrate that the integration of STEM-GBL can significantly enhance students' motivation to learn Genetics at the matriculation level. This suggests that incorporating game-based elements such as challenge, feedback, and interactive problem-solving into Biology instruction can create more engaging learning environments, particularly for abstract topics such as genetic inheritance. Therefore, educators may consider adopting STEM-GBL strategies to promote active participation and sustain students' interest in learning complex scientific concepts.

Second, the study contributes to the growing body of research on innovative pedagogical approaches in science education, particularly within the Malaysian pre-university context. The large effect size observed in this study indicates that integrating STEM elements with GBL can meaningfully influence motivational outcomes. This provides empirical evidence supporting the effectiveness of technology-supported and student-centered learning strategies in improving students' engagement with science subjects.

Third, the findings have implications for curriculum designers and policymakers. The successful implementation of the STEM-GBL approach suggests that incorporating interactive digital learning strategies into the Biology curriculum may help address students' motivational challenges in learning abstract scientific topics. Such approaches align with Malaysia's educational transformation agenda, which emphasizes digital learning, creativity, and student-centered pedagogy. Consequently, the integration of STEM-based game learning activities could be considered in the development of future instructional materials and teaching practices in matriculation Biology education.

Moreover, studies in the field of international research in science education verify these results. For example, Hwang et al. (2019) discovered that game-based STEM learning environments raised students' intrinsic motivation and engagement in secondary science education. Similarly, Sung and Hwang (2018) found that when engaging in STEM activities using digital games, participants showed more interest and persistence to learn the complicated

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scientific concepts. These investigations demonstrate that a game-based task coupled with STEM problem-solving contexts afford substantial cognitive demand and immediate feedback, which is highly related to increased motivation.

Collectively, the current findings add to this corpus of evidence for the Malaysian matriculation settings where Genetics is generally considered as abstract and conceptually challenging. By showing STEM-GBL's effectiveness to enhance motivation, this study underpins a plea for research-based, interactive educational innovation in pre-university Biology (Rahman et al., 2023). Also, because the effect size ($\eta^2 = .523$), the findings highlight the instructional implications of developing cognitively-demanding, technology-infused Genetics learning experiences that utilize game-based mechanics.

The findings of this study suggest a number of recommendations to be implemented in future studies;

i) The application of the approach using STEM-GBL teaching approach should be further expanded for other subjects in matriculation.
ii) The evaluation of the effectiveness of this module involves a very limited sample and is limited to matriculation students in northern Malaysia only. Therefore, the results of this study cannot be digitized for all matriculation students in Malaysia. For further studies it is proposed that the same studies be conducted in various other types of educational institutions so that the results obtained can be compared and normalized.

CONCLUSION

The study is designed to overcome this instructional difficulty for the teaching of Genetics at the Malaysian Matriculation level where students tend to face a great deal of problems with the high abstract concepts involved. Traditional teaching methods, in which a substantial amount of class time is spent on lecturing, have failed to maintain students' motivation. This is a continuing literature gap, specifically about the efficiency of blending STEM-based pedagogies with GBL approaches which can improve pre-university students' Genetics learning motivation. This research confirmed that such positive impact is observed empirically through the STEM-GBL methodology in the classrooms, evidence from which suggests a power to invade against passive and non-proactive traditional Genetics teaching. By showing a significant motivation gain in the experimental group versus the control one, it directly addresses the research gap and verifies that an interactive problem-based learning environment may support students' preparedness for mastering complex biological concepts.

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Author Contributions: Hanna Mohd Hussaini and Salmiza Saleh wrote the manuscript. The authors have read and agreed to the published version of the manuscript.

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