



Innovating Sustainability Education: Integrating Gamification and Deep Learning in Higher Education

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Abstract

This study explores the use of gamification and deep learning in higher education, examining how it might enhance student engagement, learning outcomes, and sustainability understanding. Evidence suggests that gamification tactics like points, badges, and leaderboards can make learning more engaging and entertaining while also increasing motivation and teamwork. Meanwhile, deep learning technologies enhance learning by tailoring lessons to each student's unique requirements and interests. Moreover, the study delves into how these methods might aid in the comprehension and implementation of sustainability principles, which are fundamental for solving world problems. Analyses of data obtained from 795 students showed that deep learning considerably individualizes learning and improves abilities, whereas gamification boosts engagement and motivation. Furthermore, the results demonstrate that by integrating various approaches, students can have a more comprehensive understanding of sustainability and be more motivated to incorporate sustainable activities into their everyday lives. The findings of this study show that new ways of teaching can help students succeed in school and provide them with the tools they need to build a greener world. The results of this study provide important information for schools and teachers who are trying to improve sustainability education by taking advantage of technological advancements.

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Keywords: Gamification; Deep Learning; Sustainability Education; Student Engagement; Personalized Learning

Introduction

Acquiring sustainability knowledge and awareness is crucial in the dynamic sphere of global education, as it enables individuals to confront the multifaceted environmental, social, and economic challenges of our contemporary era (Islam and Khan 2024; Sekhar and Raina 2021) ^[24, 51] Similar to universities across the globe, Saudi universities are entrusted with the responsibility of equipping students with the knowledge and skills necessary to adopt sustainable principles, develop ethical conduct, and actively participate in efforts to create a more sustainable future (Alsharif, Peters, and Dixon 2020) ^[4]. As a result of this challenge, a novel strategy that has the potential to transform sustainability education—the strategic implementation of gamification and deep learning in Saudi universities—is taking shape.

In recent years, sustainability education has significantly transformed, which now emphasizes providing students with a comprehensive comprehension of environmental, social, and economic sustainability (Druker-Ibáñez and Cáceres-Jensen 2022) ^[13]. However, it has continued to be a challenge to effectively engage students and ensure that sustainability knowledge is effectively transmitted (Tura, Ojanen, and Hanski 2019) ^[57]. The extant body of literature draws attention to a discernible deficiency in which conventional educational methodologies have sometimes encountered difficulty in igniting the passion and dedication required to tackle sustainability concerns in the twenty-first century. This study investigates a novel and dynamic solution that exceeds conventional pedagogical approaches.

The independent variables, namely "Deep Learning Models" (Janiesch, Zschech, and Heinrich 2021) ^[28] and "Gamification Strategies". Illustrate the incorporation of gamification methods and deep learning algorithms into the curriculum of sustainability education programs in universities in Saudi Arabia. These innovative methodologies incorporate an element of engagement, individualization, and practical implementation into the scholastic experience. Gamification strategies, which incorporate components such as award systems, ranking systems, and rewards, hold the potential to engage students and inspire them to explore sustainability subjects further. Deep learning models, which incorporate sophisticated technologies like neural networks and personalized learning algorithms, can customize instruction for every pupil, guaranteeing that subject matter corresponds to their specific learning requirements.

At the foundation of this study lies the mediating variable known as "Student Engagement" (Rivera and Garden 2021) ^[44]. The realization of the transformative potential of gamification and deep learning is contingent upon student engagement. Students actively involved in the learning process are more likely to be engaged, which acts as a mediator between innovative educational strategies and the students' sustainability knowledge and learning outcomes (Bhardwaj *et al.* 2021) ^[5].

The present research is guided by three dependent variables, "Student Learning Outcomes", (Goss 2022) ^[21] "Sustainability Behaviour" (Bhattacharya *et al.* 2023) ^[6] and "Sustainability Knowledge," (Braßler and Sprenger 2021) ^[7] which serve as its ultimate objectives. Our objective is to investigate the impact of gamification and deep learning integration on students' learning outcomes and their ability to implement sustainability principles in practical situations. Through a comprehensive evaluation of the students' sustainability knowledge and an analysis of the degree to which these novel methodologies impact their academic achievements, our objective is to illuminate the potential of this paradigm shift in education. To achieve the research objectives following research questions are proposed".

RQ1: In what ways do deep learning models and gamification strategies augment student engagement in sustainability education at universities in Saudi Arabia?

RQ2: In regard to students' understanding and awareness of sustainability, what is the impact of incorporating gamification and deep learning on their academic achievements?

RQ3: Regarding the attitudes and preferences of students and instructors towards these innovative approaches, how do they perceive the application of gamification and deep learning in sustainability education?

Within the framework of Saudi universities, an area where the widespread adoption of gamification and deep learning technologies has yet to occur, this study investigates unexplored possibilities. Our objective is to investigate the significant effect that these emerging methodologies can have on higher education, all the while contributing to the worldwide effort to achieve the United Nations Sustainable Development Goals (SDGs) and Saudi Vision 2030. This research endeavor transcends academia and represents a transformative effort in sustainability education, carrying significant effects that extend well beyond the boundaries of the university classroom.

Further sections of this research will examine the approaches, results, and discourse that shed light on the possibilities and obstacles associated with the implementation of gamification and deep learning in Saudi universities. This is done with the ultimate goal of transforming sustainability education and furthering the international commitment to a sustainable future.

Review Literature

This research is built upon Self-Determination Theory (SDT) (Miller, Deci, and Ryan 1988) ^[38] cited by (Chiu 2022) ^[10] because it provides a pertinent framework for our study titled "Revolutionising Sustainability Education: Integrating Gamification and Deep Learning in Universities." SDT investigates the influence of motivation on behavior. The investigation aids in comprehending the impact of gamification and deep learning strategies on students' behavior and learning. For instance, gamification may increase intrinsic motivation by rendering learning entertaining, whereas deep learning models may affect extrinsic motivation through rewards or recognition. Student engagement is an essential mediating variable, and SDT enables researchers to examine how strategies affect students' perceived competence, relatedness, and autonomy, thus affecting their engagement. In essence, SDT illuminates the motivational and behavioral aspects of these advancements, thereby providing insight into their influence on the engagement, learning outcomes, motivation, and sustainable behavior of students within the context of higher education.

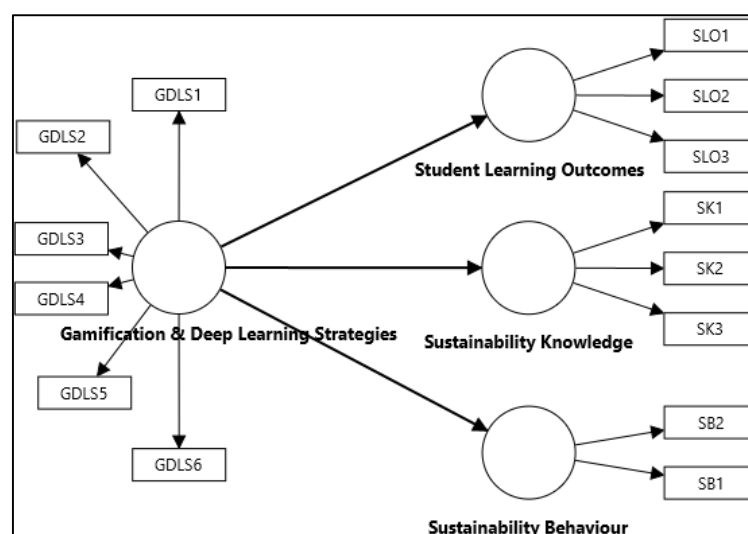


Fig 1: Conceptual Framework of the Study

Gamification Strategies

Gamification strategies encompass applying game elements, principles, and techniques to non-game domains, including marketing, education, and workplace tasks, to stimulate, incentivize, and promote particular behaviors among participants. These approaches are influenced by the gaming industry, encompassing board games, video games, and other interactive forms of amusement, to enhance the enjoyment and satisfaction of tasks or procedures (García-Álvarez *et al.* 2022; Hakami *et al.* 2023; Palaniappan and Noor 2022) ^[16, 22, 40].

Research has indicated the potential of gamification to increase student motivation, and engagement has been extensively praised. Advocates contend that by integrating game elements into the educational experience, such as leaderboards, points, and badges, students are more inclined to engage actively in their studies. This increased engagement has the potential to result in enhanced knowledge retention and improved learning outcomes (Rutledge *et al.* 2018) ^[46]. Gamification has gained significant recognition as an effective instrument in enhancing the accessibility and enjoyment of intricate subjects, including sustainability. It has the potential to dismantle obstacles and simplify complex topics, which may lead to increased comprehension and retention among (Aguilos and Fuchs 2022; Chans and Portuguese Castro 2021; Islam and Ali Khan 2024b) ^[2, 9, 26] gamification provides immediate feedback hence students can monitor their progress, pinpoint areas that require development, and maintain motivation to accomplish their learning goals through the use of immediate feedback. The gamification teaching method addresses UN SDG 4, universal access to equitable, high-quality education. SDG 4 (Goal 4 | Department of Economic and Social Affairs n.d.) Specifically aims to provide educational opportunities to individuals residing in developing countries or facing physical or technical barriers that prevent them from attaining an education. Despite several benefits, several research indicated a critique of implementing gamification in academia (Lim, Sanmugam, and Wan Yahaya 2023; Shehawy, Khan, and Madkhali 2024) ^[32, 54]. An additional challenge pertains to online gamification, which highlights the inadequate technological underpinnings involved in developing a gamified environment online due to connectivity problems and access limitations. In the interim, the dilemma of interaction refers to the difficulty of forming social connections based on the varying preferences of pupils regarding synchronous or asynchronous lessons. As a result, educators are often confronted with the dilemma of whether or not to incorporate gamification into their online courses (Hung 2017; Lim, Sanmugam, and Wan Yahaya 2023) ^[23, 32].

Deep Learning Model

The utilization of deep neural networks and artificial intelligence methodologies to optimize and tailor the educational experience. By utilizing the capabilities of deep neural networks, deep learning in education enhances how students gain knowledge and develop skills (Kuppusamy and K 2022; Suhluli and Ali Khan 2022) ^[31, 55]. Deep Learning is used in academics for educational data mining to analyze the academic performance of students. This process has the potential to uncover latent information that could be utilized to enhance the institution's current educational system. For example, a university may utilize a predictive model to forecast the future academic performance of its

students to identify those who are at risk of receiving low grades. Thus, the university can encourage them to achieve higher academic standards, resulting in an overall improvement in student performance (Islam and Ali Khan 2024b; Prabowo *et al.* 2021) ^[26, 42]. Personalized learning is a strength of deep learning models. These methods improve engagement and understanding by tailoring content to students. Personalized learning experiences are better at fulfilling unique student needs and learning styles (Zhong *et al.* 2020) ^[60]. A study by (Gazori, Rahbari, and Nickray 2020) ^[17] illustrated deep learning in IoT data processing reduces latency and expenses (Suhluli and Ali Khan 2022) ^[55].

A study conducted by an agriculture university illustrated Deep learning is employed to improve sustainability in agriculture through the prediction of soil, water, climate conditions, and crop varieties (Ryo *et al.* 2023) ^[47]. A study by (Jing *et al.* 2023) ^[29] mentioned the significance of Learning Factories and Skill-Based Education in attaining the Sustainable Development Goals of the United Nations. It emphasizes the importance of industry-educational collaboration in the preparation of a competent labor force for sustainable development. The research emphasizes the significance of experience and knowledge exchange in the pursuit of a more sustainable future. The Norwegian University of Science and Technology (NTNU) uses cost-effective commercial components and microcontrollers like the micro: bit to give students sustainable embedded system design expertise. This innovative teaching technique emphasizes Visible Learning with theoretical lectures and engaging group projects, receiving excellent comments from students and reference groups (Sanfilippo and Austreng 2021) ^[48].

Student Learning Outcomes

In higher education, Student Learning Outcomes (SLOs) are essential since they outline what students should know or be able to do following course or program graduation. These results guarantee congruence with workforce needs and academic standards, thereby guiding teaching, learning, assessment, and curriculum development (Schoepp 2019) ^[50]. By increasing engagement, motivation, and skill development, gamification mixed with deep learning techniques can greatly increase student learning outcomes; but, its efficacy can be affected by several moderating variables (Buckley and Doyle 2016) ^[8]. With customized and deep gamification techniques especially successful, gamification has shown promise to favourably affect student learning results (Schofield 2021) ^[51]. Still, one should take into account difficulties in execution and the necessity of complex solutions depending on personal qualities. Another fascinating area of research is the part cognitive processes and motivation play in the success of gamification and deep learning techniques (Xiao and Hew 2024) ^[58].

Sustainability Knowledge

Sustainability knowledge is a multifaceted concept essential for addressing complex global challenges. In environmental science, sustainability knowledge consists mostly of the integration of social, organizational, and environmental information to solve challenging sustainability issues. Knowledge of sustainability greatly affects business ethics and corporate social responsibility; it is also very important for urban planning and development and can be included in various levels of education to help create a more sustainable

(Lozano *et al.* 2022; Nolet 2015; Papageorgiou *et al.* 2024) [33, 39, 41]. Deep learning techniques and gamification have shown great promise in improving sustainability knowledge and involvement in several business and educational environments. Gamification and deep learning strategies are powerful tools for enhancing sustainability knowledge (Jain *et al.* 2022) [27] and engagement (Rincón-Flores, Mena, and Montoya 2020) [43], leading to improved learning outcomes, increased awareness (Zafar *et al.* 2024) [59], and positive behavioral changes. It has been demonstrated that gamification can powerfully cause long-lasting behavior modification towards sustainability. Two large-scale field experiments showed that playing a sustainability game greatly lowered family electricity use and inspired more attempts to save energy and the apparent value of sustainability. Using the mediating functions of sustainable knowledge and psychological and social norms, gamification can induce users' sustainability knowledge and pro-sustainable intentions. It enhances consumers' awareness of sustainability, which greatly affects their intentions towards being pro-sustainable (Abou Kamar *et al.* 2024) [1].

Sustainability Behaviour

Sustainability behavior is the behaviors and habits people or groups follow to reduce their negative effects on the environment and advance ecological balance. This idea is sometimes explored in pro-environmental behavior (PEB), which comprises particular acts meant to preserve the surroundings (Gokilavani *et al.* 2024; Medabesh and Khan 2019; Tian, Zhang, and Li 2020) [20, 34, 56]. The ethical issues in applying gamification and deep learning to affect sustainability behavior, the effect of gamification on sustainability behavior in the framework of deep learning strategies, and the analysis and prediction of sustainability behavior using deep learning approaches (Faisal Ali Khan and Ahmad 2020) [14]. The key gamification strategies used to promote sustainability behavior involve leveraging game design principles to create engaging and meaningful user experiences (Schiele 2018) [49], while deep learning techniques can be applied to analyze and predict sustainability behaviour (Mevoli, Leggett, and Davies 2024) [37]. The impact of gamification on sustainability behavior in the context of deep learning strategies has been shown to induce enduring behavior change and drive positive behavior change at scale (Dicheva, Irwin, and Dichev 2019) [12]. However, the ethical considerations in using gamification and deep learning to influence sustainability behavior require further exploration and consideration.

Research Methodology

In "Revolutionising Sustainability Education: Introducing Gamification and Deep Learning in Universities," the study approach centers on looking at how different pedagogical and

experiential learning approaches might successfully inspire entrepreneurial intentions among students. The researchers used a quantitative method (Gill 2020) [18] to compile data from business students at five international institutions selected based on times ranking. A structured questionnaire modified from past studies. Selected using a mix of stratified and intentional sampling techniques, the sample sought to reflect many student viewpoints on entrepreneurship education (Fielding, Lee, and Blank 2016) [15]. The study emphasized on the relationship between several learning strategies and entrepreneurial goals using structural equation modeling (SEM) and confirmatory factor analysis (CFA). Deep learning methods were applied to create synthetic data from an initial 500 responses, therefore augmenting the sample size to 795 for more reliable analysis. Tests of convergent and discriminant validity as well as advanced statistical models like the Importance-Performance Map (IPM) thoroughly validated the results and highlighted which learning activities (Aguirre-Urreta and Rönkkö 2018) [3]—including gamification—had the biggest impact on encouraging entrepreneurial objectives. Incorporating cutting-edge technologies like gamification and deep learning, the all-encompassing approach emphasizes the dedication of the research to furthering sustainability education in university environments.

Data Analysis and Interpretation

Data analysis in this study was done using structural equation modelling applied with partial least squares (SEM-PLS). SEM-PLS was used since it is appropriate for analysing intricate interactions between several variables concurrently, which is necessary in this investigation of how various instructional approaches affect entrepreneurial inclinations. Handling smaller sample numbers and non-normal data distributions, SEM-PLS lets one analyse both direct and indirect effects. It also guarantees the validity and dependability of the measuring models, therefore strengthening the results of the research.

Measurement Model

Using the measurement model of SEM-PLS (Memon *et al.* 2021) [36], latent variables' observable indicators are evaluated, so determine the validity and dependability of the constructs. Reliability is guaranteed by obtaining important conclusions from the structural model depending on indicators properly reflecting the underlying latent variables. As shown in Figure 2 and further detailed in Tables 1 and 2, the measurement model is crucial in confirming the internal consistency, convergent validity, and discriminant validity so guaranteeing that the constructs are well-defined and measured accurately before analyzing the relationships between variables in the structural model.

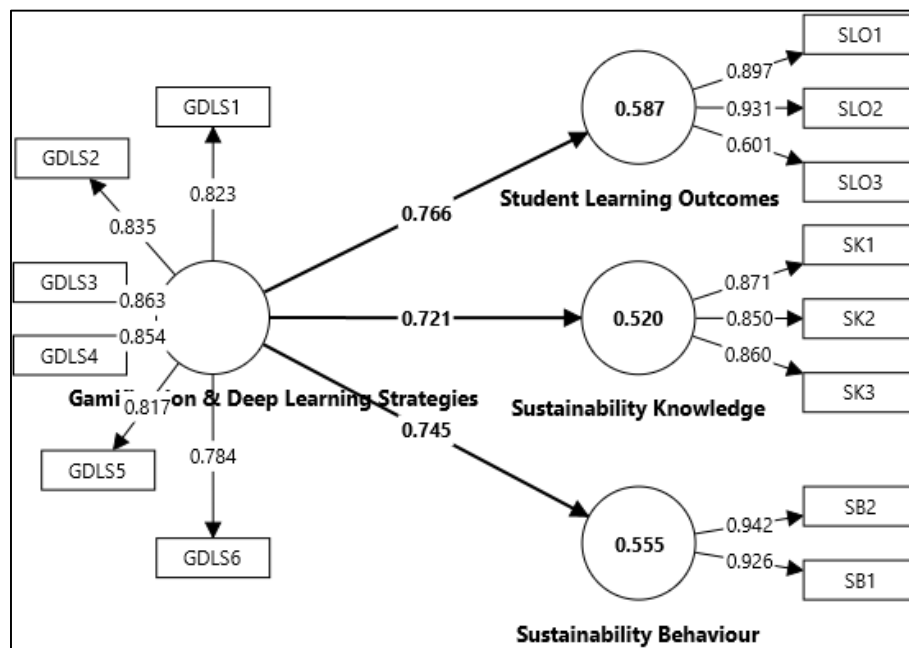


Fig 1: Measurement Model

Table 1: Convergent Validity

Constructs	Cronbach's alpha	Composite reliability (rho_a)	Composite reliability (rho_c)	Average variance extracted (AVE)
Gamification & Deep Learning Strategies	0.909	0.910	0.930	0.688
Student Learning Outcomes	0.750	0.822	0.859	0.677
Sustainability Behaviour	0.854	0.862	0.932	0.872
Sustainability Knowledge	0.825	0.828	0.895	0.740

Table 1 shows how the study evaluated convergent validity using various important parameters. Across all constructions, the results show great internal consistency and dependability. Cronbach's alpha for "Gamification & Deep Learning Strategies" was 0.909; with an average variance extracted (AVE) of 0.688, the composite reliability values ($\rho_a = 0.910$, $\rho_c = 0.930$) clearly show a high degree of dependability, so indicating that the items fairly capture the underlying construct. With an AVE of 0.677, "Student Learning Outcomes" showed similar solid dependability

(Cronbach's alpha = 0.750, composite reliability = 0.859). Reflecting great convergent validity, "Sustainability Behaviour" displayed outstanding internal consistency with Cronbach's alpha of 0.854, a high composite reliability of 0.9932, and an AVE of 0.740, "Sustainability Knowledge" also shown great dependability (Cronbach's alpha = 0.825, composite reliability = 0.895). These findings generally support the validity and dependability of the chosen study constructs for additional investigation.

Table 2: Discriminant Validity

Constructs	Gamification & Deep Learning Strategies	Student Learning Outcomes	Sustainability Behaviour	Sustainability Knowledge
Gamification & Deep Learning Strategies	0.830			
Student Learning Outcomes	0.766	0.823		
Sustainability Behaviour	0.745	0.628	0.934	
Sustainability Knowledge	0.721	0.779	0.722	0.860

Table 2 shows the results of discriminant validity, evaluating the uniqueness of every concept from the others. To validate discriminant validity, the diagonal values—which reflect the square root of the Average Variance Extracted (AVE) for every construct—should be greater than the correlations with other constructs. The square root of AVE for "Gamification & Deep Learning Strategies," 0.830, is higher than that of its

relationships with the other constructions. All of these are greater than their inter-construct correlations, "Student Learning Outcomes" has a square root of AVE of 0.823; "Sustainability Behaviour" has 0.99; and "Sustainability Knowledge" has 0.860. These findings provide good discriminant validity in the model by confirming that the constructions differ from one another.

Table 3: Effect Size (f^2) and Coefficient of Determination (R^2) Values

Constructs	F-square	Constructs	R-square	R-square adjusted
Gamification & Deep Learning Strategies -> Student Learning Outcomes	1.419	Student Learning Outcomes	0.587	0.586
Gamification & Deep Learning Strategies -> Sustainability Behaviour	1.247	Sustainability Behaviour	0.555	0.554
Gamification & Deep Learning Strategies -> Sustainability Knowledge	1.084	Sustainability Knowledge	0.52	0.52

Table's 3 represents f-square values, "Gamification & Deep Learning Strategies" effect size on the other model constructions. Considered a minor influence if an f-square value exceeds 0.02; beyond 0.15, a medium effect; above 0.35, a significant effect. Here "Gamification & Deep Learning Strategies" has a significant influence on "Student Learning Outcomes" (f-square = 1.419), "Sustainability Behaviour" (f-square = 1.247), and "Sustainability Knowledge" (f-square = 1.084). These high f-square values show that gamification and deep learning approaches dramatically affect student results, sustainability behavior, and sustainability knowledge, therefore highlighting their important part in improving entrepreneurial and sustainability education.

For every dependent construct, the table's R-square values show the percentage of variance explained by the independent variable, "Gamification & Deep Learning Strategies." With an R-square score of 0.587 for "Student Learning Outcomes," the model explains 58.7% of the variance in these outcomes. Reflecting the stability of the model, the modified R-square of 0.586 shows little change. With an adjusted R-square of 0.554, "Sustainability Behaviour" has an R-square of 0.555, therefore explaining 55.5% of the variance with the model. The R-square for "Sustainability Knowledge" is 0.52, meaning the model explains 52% of the variance; the adjusted R-square shows no change. These numbers show that for all three constructs, the model has a significant explaining ability.

Table 4: Multicollinearity and Model Fit Indices

Items	VIF		Saturated model	Estimated model
GDLS1	2.783	SRMR	0.084	0.103
GDLS2	2.994	d_ULS	0.735	1.116
GDLS3	3.554	d_G	0.478	0.575
GDLS4	3.26	Chi-square	2128.59	2356.574
GDLS5	2.305	NFI	0.76	0.735
GDLS6	1.865			
SB1	2.249			
SB2	2.249			
SK1	1.985			
SK2	1.875			
SK3	1.771			
SLO1	2.615			
SLO2	2.903			
SLO3	1.221			

Table 4 offers a number of important metrics about model fit for the constructs and multicollinearity. The fact that the Variance Inflation Factor (VIF) values for every item are below 5 indicates that there is not multicollinearity in the model. The model fit indices contrast the estimated model—the real model—with the saturated model, a model with perfect fit.

Both near to the acceptable threshold of 0.08, the Standardised Root Mean Square Residual (SRMR) values for the saturated model and the estimated model are 0.084 and 0.103 respectively, therefore showing a fair fit. While the estimated model has somewhat higher discrepancies (d_ULS = 1.116, d_G = 0.575), the d_ULS and d_G values, which

evaluate the difference between the models, point to lower values for the saturated model (d_ULS = 0.735, d_G = 0.478).

Though lower values are usually desirable, the Chi-square values—2128.59 for the saturated model and 2356.574 for the estimated model—show a good fit. Last but not least, the Normed Fit Index (NFI) values (0.735 for the estimated model and 0.76 for the saturated model) are near to the advised threshold of 0.90, thereby indicating the model is adequate but might be improved in fit. Based on these indices, the model shows rather decent validity and fit overall.

Table 5: MV Descriptive Indicators

Items	Mean	Median	Observed min	Observed max	Standard deviation	Excess kurtosis	Skewness	Number of observations used	Cramér-von Mises test statistic	Cramér-von Mises p value
GDLS1	3.405	4	1	5	1.355	-0.995	-0.422	795	4.647	0.000
GDLS2	3.307	4	1	5	1.397	-1.121	-0.383	795	4.941	0.000
GDLS3	3.478	4	1	5	1.232	-0.823	-0.382	795	4.507	0.000
GDLS4	3.478	4	1	5	1.187	-0.73	-0.370	795	4.572	0.000
GDLS5	3.639	4	1	5	1.153	-0.113	-0.738	795	6.284	0.000
GDLS6	3.309	3	1	5	1.161	-0.767	-0.303	795	4.883	0.000
SB1	3.23	3	1	5	1.232	-0.937	-0.279	795	4.731	0.000
SB2	3.196	3	1	5	1.214	-0.841	-0.190	795	4.102	0.000
SK1	3.303	3	1	5	1.118	-0.588	-0.185	795	5.01	0.000

SK2	3.262	3	1	5	1.178	-0.841	-0.167	795	4.263	0.000
SK3	3.254	3	1	5	1.2	-0.812	-0.179	795	4.201	0.000
SLO1	3.286	3	1	5	1.242	-0.708	-0.467	795	5.337	0.000
SLO2	3.326	3	1	5	1.181	-0.621	-0.367	795	4.719	0.000
SLO3	3.54	4	1	5	1.059	-0.548	-0.311	795	5.36	0.000

The table 6 presents descriptive statistics for various constructs, including Gamification & Deep Learning Strategies (GDLS), Sustainability Behaviour (SB), Sustainability Knowledge (SK), and Student Learning Outcomes (SLO), based on responses from 795 participants. The mean scores for most items range from 3.3 to 3.5 on a 5-point scale, indicating that respondents tend to either agree or feel neutral about the statements. The median scores are consistently around 3 or 4, suggesting that many participants rated their experiences positively. The data also shows a full range of responses, with minimum values of 1 and maximum values of 5. The standard deviations, which vary between 1.05 and 1.4, indicate moderate variability in the responses. Additionally, the kurtosis values are negative for all items, reflecting flatter distributions than what we would expect in a normal distribution, while the slightly negative skewness suggests a tendency toward higher ratings. Finally, the

Cramér-von Mises test results show p-values of 0 for all items, indicating significant deviations from normality, although these deviations are minor. Overall, the statistics reveal that responses are relatively evenly spread but lean slightly toward agreement, with only small deviations from a normal distribution.

Structural Model

In SEM, or structural equation modelling, the structural model shows the expected relationships between latent components in the research. It allows the research of both direct and indirect effects by showing how the independent factors influence the dependent variables. By use of structural model analysis, researchers can assess the degree and relevance of these connections, therefore providing valuable fresh viewpoints on the basic mechanisms producing the observed events.

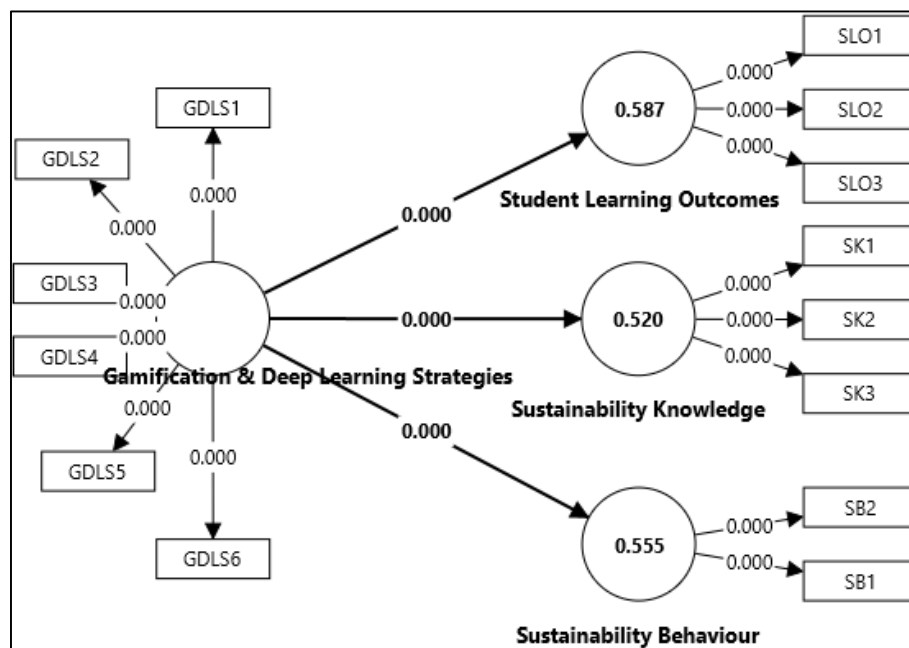


Fig 1: Structural Model

Table 6: Effect Testing

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics ((O-STDEV))	P values
Gamification & Deep Learning Strategies -> Student Learning Outcomes	0.766	0.766	0.016	47.245	0.000
Gamification & Deep Learning Strategies -> Sustainability Behaviour	0.745	0.745	0.018	40.755	0.000
Gamification & Deep Learning Strategies -> Sustainability Knowledge	0.721	0.721	0.021	33.670	0.000

Table 6 represents the main outcomes—Student Learning Outcomes (SLO), Sustainability Behaviour (SB), and Sustainability Knowledge (SK)—showcasing the effects of gamification and deep learning strategies (GDLS). The findings show that every one of these domains benefits much from GDLS. With an estimate of 0.766, for example, the impact on Student Learning Outcomes is very noteworthy

since these techniques clearly help students greatly. Comparatively, the influence on Sustainability Knowledge stands at 0.721; the effect on Sustainability Behaviour is assessed at 0.745. The very high T-statistics and a p-value of 0.000 indicate that every relationship is rather important. These results underline how including gamification and deep learning techniques not only improves students' learning

environments but also encourages sustainability behavior and knowledge of sustainability.

Discussion

The findings of the survey show a generally favorable view of gamification and deep learning in improving students' participation and knowledge of environmental issues (Islam and Ali Khan 2024a; Medabesh and Khan 2020) ^[25, 35]. With a mean of 3.405, respondents judged their agreement with gamification components improving engagement in learning activities suggesting that such characteristics somewhat increase engagement. Likewise, the mean score of 3.307 for the personalizing provided by deep learning technologies reflects a view that these technologies can meet individual learning requirements. Given a mean of 3.478, immediate feedback via gamification was judged crucial for tracking improvement. Moreover, students showed confidence that these approaches improve their knowledge of sustainability; this was also shown by a mean score of 3.478 for the conviction in gamification's capacity to simplify sustainability topics. A higher mean of 3.639 shows that gamified learning environments were identified for fostering teamwork which is aligned with the previous studies (Shehawy, Khan, and Madkhali 2024) ^[54]. While students felt gamification raised motivation and enjoyment (mean of 3.309), confidence in reaching learning goals was somewhat lower, with a mean of 3.230. With a mean of 3.196, the supposed contribution of gamification to skill development shows a modest confidence in its efficiency. With a mean of 3.302, students showed a more skeptical attitude on the reflection of actual comprehension in gamified tests, though. These approaches produced knowledge about sustainability principles assessed at 3.262; awareness of global sustainability issues rated somewhat higher at 3.286. Complying with sustainable practices and adopting behaviours that support sustainability scored means of 3.326 and 3.540, respectively, therefore demonstrating the favorable influence of education on environmental actions (Shehawy and Ali Khan 2024) ^[53]. Though there are differences in perspective across many facets, the results imply that gamification and deep learning greatly affect

students' engagement, understanding, and commitment to sustainability.

Conclusion

The present research emphasises the transforming possibilities of including gamification and deep learning technology into sustainability education in colleges. The results imply that both approaches greatly improve student involvement, drive, and comprehension of difficult sustainability issues. While deep learning technologies provide tailored learning experiences that meet individual needs, gamification—through points, badges, and leaderboards—increases engagement and promotes teamwork. These strategies taken together help students to retain knowledge, grow their skills, and inspire them to apply sustainability principles in practical settings. Notwithstanding the difficulties—technical constraints and different student preferences for engagement, among other things—gamification and deep learning have shown favourable overall effects on student learning outcomes and sustainability knowledge. These creative approaches help to deepen knowledge of sustainability by making learning more interactive and customised, thereby inspiring behaviour that fits with world sustainability targets. Teachers should think about honing these strategies going ahead to meet obstacles and maximise their capacity to transform sustainability teaching.

Implication of Study

For institutions striving to improve sustainability education as well as for teachers, this study has major ramifications. Universities may develop more interesting, customised, and successful learning environments by including gamification and deep learning technologies. This method not only increases student involvement and motivation but also helps them to grasp sustainability ideas and promotes actual implementation of sustainable activities. These instruments allow teachers to better match their approaches with the demands of their students, therefore producing a generation more dedicated to tackling worldwide environmental issues.

Annexure I

	Items	Mean	Median	Observed min	Observed max	Standard deviation	Excess kurtosis	Skewness	Number of observations used	Cramér-von Mises test statistic	Cramér-von Mises p value
1	To what extent do you agree that gamification elements (such as points, badges, or leaderboards) enhance your engagement in learning activities?	3.405	4	1	5	1.355	-0.995	-0.422	795	4.647	0.000
2	How effectively do you feel deep learning technologies personalize your learning experience based on your individual needs and preferences?	3.307	4	1	5	1.397	-1.121	-0.383	795	4.941	0.000
3	How important is immediate feedback (through gamification) in helping you monitor your progress in your learning journey?	3.478	4	1	5	1.232	-0.823	-0.382	795	4.507	0.000
4	Do you believe that gamification and deep	3.478	4	1	5	1.187	-0.73	-0.37	795	4.572	0.000

	learning can effectively enhance your understanding of sustainability concepts?										
5	How effectively do gamified learning environments promote collaboration and social interaction among students?	3.639	4	1	5	1.153	-0.113	-0.738	795	6.284	0.000
6	To what extent do you find gamification elements increase your enjoyment and motivation in the learning process?	3.309	3	1	5	1.161	-0.767	-0.303	795	4.883	0.000
7	How confident are you in your ability to achieve the learning outcomes set for your course due to gamified learning strategies?	3.23	3	1	5	1.232	-0.937	-0.279	795	4.731	0.000
8	To what extent do you feel that gamification has contributed to your skill development in the subject matter?	3.196	3	1	5	1.214	-0.841	-0.19	795	4.102	0.000
9	How well do you think gamified assessments reflect your actual understanding and competencies in the subject area?	3.303	3	1	5	1.118	-0.588	-0.185	795	5.01	0.000
10	To what extent do you feel knowledgeable about sustainability concepts as a result of gamified and deep learning methods?	3.262	3	1	5	1.178	-0.841	-0.167	795	4.263	0.000
11	How often do you apply your understanding of sustainability concepts in real-world scenarios after engaging with gamified learning?	3.254	3	1	5	1.2	-0.812	-0.179	795	4.201	0.000
12	How aware are you of current global sustainability challenges as a result of your education?	3.286	3	1	5	1.242	-0.708	-0.467	795	5.337	0.000
13	How frequently do you engage in behaviors that promote sustainability (e.g., recycling, conserving energy) as a result of your educational experiences?	3.326	3	1	5	1.181	-0.621	-0.367	795	4.719	0.000
14	To what extent has your education influenced your commitment to sustainable practices in your daily life?	3.54	4	1	5	1.059	-0.548	-0.311	795	5.36	0.000

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