ASSESSING E-LEARNING CONTENT CURATION AND CRAFTING FOR SCIENCE EDUCATION: A MIXED RESEARCH DRIVEN CROSS-CASE ANALYSIS

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ABSTRACT

The exponential rise in advanced software technologies, low-cost hardware, and internet connectivity has broadened the horizon for academia and industries to provide decentralized e-learning solutions along with hybrid classroom culture, making science, technology, engineering, and mathematics (STEM) education more engaging, interactive, and productive. Among the major innovations, gamified learning and augmented reality (AR) techniques have played a decisive role in creating intrinsically motivated, enjoyable, socially improved, and productive learning environments. However, their efficacy across different streams and standards remains debatable, since STEM students demand tools that are not only interactive and autonomous but also optimally designed in terms of content, depth, scalability, and cognitive ease. To address this gap, the present research investigates the intrinsic motivating factors that encourage STEM students to employ such tools, and the extent to which these expectations are met by existing solutions. A mixed-research paradigm driven cross-case analysis method was adopted. First, a quantitative empirical study was conducted to identify STEM students' specific expectations from e-learning tools. Subsequently, cross-case analysis was applied to evaluate whether, and to what extent, existing VR, AR, and gamified learning solutions satisfy these expectations. The findings reveal that despite significant efforts, current solutions often fail to ensure critical features such as autonomous and interactive learning, cognitive-driven reuse and re-evaluation, behaviour-sensitive intelligent content delivery, and adaptive task recommendation. These shortcomings highlight the need for more optimally designed systems. This study suggests that by assuring these features, gamified learning and AR/VR technologies can become more interesting, engaging, and effective in STEM education. Such advancements can further enhance longer memory retention, problem-solving abilities, and concept building capacities in students, thereby strengthening the overall quality of learning outcomes.

KEYWORDS

Virtual learning environment, Science education, Gamified learning, Augmented reality

1. INTRODUCTION

In recent times, the dramatic increase in advanced computing, low-cost hardware, and internet technology has broadened the horizon of the education system, where e-learning has started occupying a broader space compared to traditional teaching practices. Technologies such as virtual reality, augmented reality, and gamified learning provide immersive and interactive learning features to make education more interesting and engaging [1]. These technologies enable learners to explore, assess, and examine how different methods can be applied to understand a problem and achieve superior solutions through more informative visualizations [1].

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In contemporary education, competence in science, technology, engineering, and mathematics (STEM) is considered a vital dimension of the knowledge economy. However, inadequate resources often reduce the efficacy of this learning paradigm. This challenge has catalyzed academia and industries to create innovative, interactive, and specific e-learning environments for science education [2]. The widespread availability of hardware technologies such as tablet PCs, smart phones, and laptops has further made e-learning a more effective approach to meet decentralized learning demands [2]. Nevertheless, the final outcome of such practices depends on the quality of content provided and the methods employed throughout the knowledge cycle [3]. This gap serves as one of the key motivation behind this study.

Majority of existing approaches such as gamified learning and augmented reality primarily perform computer driven simulations to replicate problem-solving abilities by interacting with virtual objects resembling real-world phenomena [4, 5]. Gamified learning integrates rewards-based mechanisms and multi-level challenges to sustain participation [6], while gamification in non-game contexts enhances engagement and overall learning performance [7, 8]. However, the extent of their effectiveness in science education remains debatable. Moreover, limitations such as lack of teacher involvement, insufficient pedagogical knowledge, and reduced interest negatively impact overall outcomes [9]. Therefore, superior gamification and augmented reality support is required to strengthen motivation, engagement, and cognitive performance in STEM education [2, 10, 11].

Experimentation being crucial part of science education requires real-time realization of phenomena and for this purpose, gamification and augmented reality can replicate laboratory experiences virtually without the risk of accidents [12, 13]. Yet, the absence of feedback systems, project-based learning, and interactive problem-solving restricts the scope of many gamified platforms [16]. In addition, higher task complexity combined with low interactivity discourages adoption [17, 18]. Studies also show that the efficacy of gamification and AR tools is influenced by demographic factors such as age, academic level, teacher ability, and device intelligence [19]. While these factors may have a positive impact on STEM learners, no significant research has evaluated them specifically.

To bridge this gap, this study investigates whether existing gamification and AR-based solutions fulfil the requirements of STEM students, and which features are most crucial for their adoption. The novelty of this approach lies in its dual methodology first, a quantitative research method is applied to characterize STEM students expectations regarding e-learning tools and secondly, a cross-case analysis is conducted to systematically compare available VR, AR, and gamified tools against these identified expectations. By combining these two dimensions, this study not only reveals the limitations of existing solutions but also provides practical insights for academia and industries to design optimized tools for STEM education as shown in the block diagram of Figure 1.

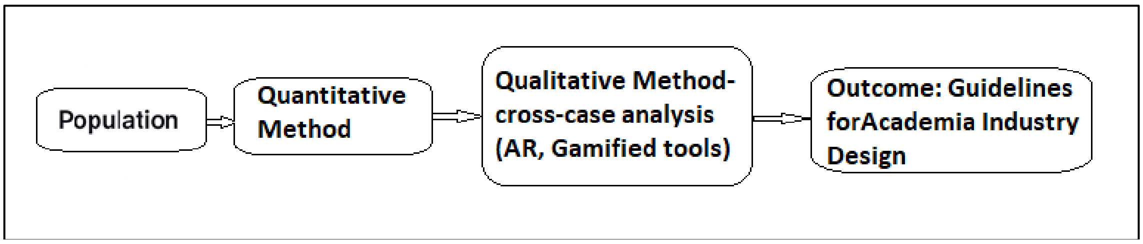

Figure 1. Research Methodology

The diagram first represents the mixed-method approach quantitative method involves descriptive analysis of STEM students expectations using surveys, sample selection, and statistical evaluation and then subsequently the qualitative method examines 14 existing gamified, augmented reality, and virtual reality tools through comparative assessment and feature-wise analysis. This allows mapping gaps between user needs and tool capabilities, thus guiding design improvements. It can be vital for academia-industries to design (or redesign) services or product to cope up with STEM student's demands and to make e-learning more realistic.

The remaining sections of this paper are divided as follows. Section II discusses the related works, followed by research question in Section III. Section IV presents Problem statement, Section V presents overall research methodology, while data analysis and allied depth assessment is given in Section VI. Conclusion used in this manuscript is given in Section VII, which is followed by reference at the end of the manuscript.

2. Literature Review

Since the inception, digital platforms have been preferred by academia-industries to provide decentralized learning facilities to the students or professionals. Despite the fact that e-learning platforms have distinct and diverse significance towards remote learning or teaching practices, their efficacy remains unexplored and non generalizable. This is because of the exceedingly high reliance on user's perceptibility, teacher's ability to instruct, and the collaboration to learn and create knowledge [25]. However e-learning tools can be perceived differently by the different stream's students. For instance, social science students don't demand more experimental concept, while science students do, and hence suitability as well as efficacy of e-learning tool can vary from one to another. It broadens the horizon to assess whether such tools can be effective for a specific kind of subject matter, and hence in this reference this study explores whether it can be vital towards science subject's students for decentralized learning. Science subjects often encompass physics, chemistry, biology and mathematics that often demand more illustrations, interactive suggestions and feedback to complete knowledge cycle. And therefore, the efficacy of the said tool depends whether it provides the ability to create knowledge, feedback, iterative practice and interactive problem-solving facilities etc. To cope up with such demands, different techniques like gamified learning, virtual reality and augmented reality are proposed. Despite numerous studies are done to assess their efficacy for e-learning purposes; whether such tools are effective towards science subject's learning remained least explored. Considering this fact, this study mainly discusses the key strengths or limitations which decides whether and how such tools can be designed for effective e-learning or teaching for science students.

2.1. Gamified Learning

Amongst the major solution, gamified learning, virtual reality and augmented reality are the majorly used technologies for e-learning [25]. This section mainly discusses some of the literatures pertaining to gamified learning and its efficacy towards science education, key demands and scopes etc.

Studies in [25] stated that the collaborative access, reward-based motivation, multiple-levels driven learning environment etc. make gamified learning a potential tool for e-learning purpose. They also stated that unlike context-based teaching gamified e-learning can be more effective to stimulate autonomous learning habits in science students. Here, gamified approach can act as a catalyst to improve participations and engagement. The authors stated that gamified learning methods because of their fun-while-learn ability can improve participation and engagement and hence can be more productive than the classical many-to-one classroom-based teaching [25]. Here, each problem can be designed as a game, where the students try to achieve answer for the challenge(s) while considering overall process as game. It has also been defined as a paradigm involving aesthetics and the use of thought to attract learners, stimulate the action, promote learning and solve problem. Moreover, the provision of “learn-while-playing”, enables it more effective to inculcate cognitive learning behaves amongst students. Inferior gamified learning might decrease intrinsic motivation and participation [23]. Numerous recent studies have affirmed that the students consider gamified learning enjoyable and more socializing that intrinsically motivate them to participate learning practices [24]. Though, studies [13, 10] suggests that introducing reward system can make education more interactive; however, fail in assessing the post-deliveries performance and student’s acceptance especially science students who demand more practical and hands-on-experience, mathematical presentation, while learning. However, its long-term impact on academic performance remains inconclusive. While intrinsic motivation often increases, performance gains vary [24, 26].Poorly designed gamification frameworks may reduce intrinsic motivation, distract students, and create fragmented learning experiences [23]. Recent work emphasizes the need for tailored gamification strategies that consider learner monitoring, non-invasive feedback, and discipline-specific requirements to achieve meaningful educational outcomes [27].

2.2. Augmented Reality Based Learning

Parallel to gamification, augmented reality (AR) has emerged as a promising tool for immersive learning. Several studies confirm its ability to reduce learning time, foster autonomous problem-solving, and improve motivation [28]. Augmented reality has been found potential because of its intrinsic motivational aspects; however, it requires designing the approach optimally to cope up with the pedagogical competencies for educators. Moreover, it should have the ability to expand multi-faceted thinking and problem-solving abilities as well. The students are typically cognitively-overloaded and hence it can be difficult for teachers to manage content and presentation as per (student’s) personalized need [14].

Nevertheless, AR also presents challenges. Cognitive load theory suggests that poorly designed AR content may overwhelm students, reducing learning efficiency [29]. Teacher preparedness and pedagogical adaptation remain major bottlenecks, as educators often lack training to implement AR effectively [14]. While AR enhances motivation and satisfaction, evidence of consistent learning performance improvement in STEM contexts remains limited [30].

2.3. The use of Augmented Reality and Gamified Learning in Science Education

Emerging research highlights the potential of combining gamification and AR to create immersive, decentralized ecosystems that foster both engagement and cognitive performance. Marker-based and marker-less AR applications have been applied to astronomy, laboratory simulations, and flipped classrooms, with promising outcomes in motivation and higher-order thinking [31]. Integrated AR and gamification environments can convert traditional instruction into entertaining, problem-based activities, encouraging deeper learning and collaboration [32].

Despite some progress situation is still far from being resolved. Most studies focus on short-term engagement metrics rather than long-term learning performance [24, 26]. Few studies systematically evaluate how demographic variables (e.g., age, academic level, teacher ability, or device capacity) influence outcomes, despite their clear importance [27]. Furthermore, science education’s demand for interactive experimentation, iterative feedback, and contextualized learning has not been comprehensively addressed in existing gamification and AR frameworks [15].

In augmented reality-based gamified learning the irrelevant content must be reduced to minimize the extraneous cognitive load and improve learning performance. The augmented reality methods must ensure that the students perform knowledge acquisition over autonomous efforts rather than passive acquisition [15]. In augmented reality driven gamified learning model, different open simulators can be designed that in sync with multiuser 3D application server be effective for science education. 3D applications can be well-suited for science experiments and virtual reality-based science-realization. In case of science laboratory and experimentation, 3D models can provide virtual world facilitating a sense of presence and awareness. Consequently, it can improve the interactivity and collaboration amongst students and teachers. It can improve both social-interaction, experience as well as knowledge creation. Additionally, students can make use of different avatars, interactive tools or controller to perform cognitive decision and learning. However virtual classroom using augmented reality approach can help teachers and group of students to simulate problem and get outputs, which might be superior to the classroom-based learning. In reference to science education, the strategic use of gamified learning and augmented reality can enable students participate in the different learning activities where each game is expected to be designed to address a specific problem for which learning has to be provided [33]. The game or allied augmented reality should be designed in such manner that it retains students' affinity to interact and gain cognitive knowledge for eventual (target) knowledge creation. Moreover, the game as well as augmented reality models should be designed in multiple levels that could help students gaining sprit to know and solve more complex problems. This is inevitable for science students. This study mainly performs cross-paradigm approach to understand the specific requirements for augmented reality and gamified learning-based science education and its presence in contemporary solutions.

Overall, the literature establishes that gamified and AR driven learning environments enhance motivation, engagement, and participation, particularly in STEM disciplines. However, their effectiveness in achieving sustained learning outcomes remains unclear, especially in the context of science subjects that demand practical, experimental, and feedback-rich experiences. These gaps justify the present study's focus on systematically evaluating the strengths and limitations of gamification and AR in science education. By aligning student expectations with existing solutions, this study aims to offer evidence-based insights for designing more effective, discipline-specific e-learning frameworks.

3. RESEARCH QUESTIONS

Considering overall research intend and allied scopes, this study formulates certain questions, which are given as follows:

RQ1: What are the key factors influencing students towards online learning tool's acceptance and continuation?
RQ2: Can gamified learning and virtual reality be effective towards online learning for science students?
RQ3: What should be the key features of online learning tool(s) to motivate students engage and achieve higher scalability, efficacy and productivity?

4. PROBLEM STATEMENT

The strategic amalgamation of these technologies has been playing central role to serve varied industrial as well as socio-economic purposes. Education being central to innovation and resource building has attracted academia-industries to design and inculcate different approaches and technologies to make educational-deliveries more scalable, efficient and productive. However, identifying suitable paradigm to meet aforesaid demands remains a challenge. This is because; mapping students' expectations, perceiving capacity and corresponding realization through ICTs or digital media is really the mammoth task. Yet, the efficacy of ICTs towards educational deliveries can't be denied. In sync with earlier experiences and during pandemic different mixed responses were achieved by institutions. Noticeably, the mixed response indicates a certain dissatisfaction, limited perceptibility, lower productivity etc. towards the services or educational deliveries de-motivate students to participate with the system. It indicates that for any ICT tool, understanding student's perception, feasibility, demands and interactivity is must. This as a result can help toolmakers or allied institutions craft tools highly in sync with the student's expectations and hence can make it more productive. Undeniably, unlike non-science syllabus or allied education, science education often involves theoretical, derivative as well as experimental discussions which require the system to be more interactive and disruptive. On the contrary, majority of the at hand online platforms consider such ICT tools as merely a platform to "go-through or listen" rather "assess, realize and accommodate". Numerous case studies pertaining to the efficacy of at hand online tools towards online-learning reveal that the students feel annoyed and minimally-involved when learning science subjects online. This is hypothesized to be primarily because of minimum interaction, low-level of self-realization and skewed responsibility with minimum knowledge transfer. In such cases, majority of the existing paradigms or ICT tools are found limited to yield optimal performance. This as a result can serve dual purposes, first to identify the existing problems or limitation and second it can help in designing innovative student-centric platform for higher scalability, effectiveness and productivity. Moreover, it can also help both students/teachers as well as firms to select the best available tool to be considered. Considering above stated factors as research motivation, in this paper a pioneering research effort is made, where at first quantitative research method is applied to understand the key driving forces which motivate or suppress students to participate online-classes. Subsequently, based on the identified preference variables or parameters, different existing ICT platforms especially designed towards science education are compared for their corresponding efficacy or suitability. This research outcome can be vital for the different stakeholders to understand student's expectations, at hand issues and future scope for improvement or innovation. In sync with overall research outcomes, this study contributes a conceptual model as well that embodies strengths of the different models with further enriched potential. It can be vital for business houses as well to innovate and produce better solution to meet next-gen online learning demands.

5. RESEARCH METHODOLOGY

In sync with the overall research intends and allied objectives, this study applied both quantitative as well as qualitative methods, at first, we have applied a descriptive analysis oriented quantitative method, where the close-ended questionnaires were applied to quantify student's expectations from any e-learning tool. Once identifying the specific expectations, an explorative effort has been made to perform relative assessment of the different online tools available for STEM subject's teaching. Thus, based on the relative assessment outcomes, the different tools are characterized for their efficacy and in this manner, the at-hand solutions, their strengths as well as weaknesses along with corresponding future optimization scopes are identified. As stated, this study considered mixed research paradigm, and hence a snippet of the methodologies applied is given as follows:

5.1. Quantitative Method

To ensure that a specific tool (say, gamified learning tools, augmented reality or any virtual reality platform) is good or bad in a specific term for science students, at first it was important to understand what specific need or expectation(s) the students have. With this motive, we have performed quantitative study, where a sufficiently large number of students are examined for their perception towards the key features of aforesaid tools or technologies. The details of the methodology's artefacts are given as follows:

5.1.1. Population Frame

Here, we considered only science students studying in upper school standards, varying from Class Nine (Class IX) to Class Twelve (Class XII). Noticeably, the selected students were having science subjects including Physics, Chemistry, Biology and Mathematics as the core subjects, which often involve conceptual learning, theoretical learning as well as experimental study. In this reference, it requires the tool to be more specific in terms of interactivity, problem-based (query) solving capacity, conceptual as well as illustrative content, behaviour driven content recommendation, multi-level challenges and adaptive autonomous learning or query solving capacity. Noticeably, since we wanted to understand students specific expectations and therefore only students were considered for response collection (say, population frame).

5.1.2. Sample Size

In this paper, a total of 120 students from different class brackets and demographic diversity have been taken into consideration. To ensure diversity of responses for better generalizability, we collected samples from each science class (i.e., standards; Class IX, Class X, Class XI and Class XII). However, considering complexity of contents, diversity of subjects and allied depth of (complex) theoretical or experimental subjects, a total of 90 responses have been collected from Class XI and Class XII, while remaining 30 samples are collected from Class IX and Class X students.

5.1.3. Sampling Technique

In the present work, we considered random cum convenient sampling method. Here, based on reachability and willingness to respond questions, the semi-structured interviews have been conducted distinctly with the students, where they are briefed about the at hand study and correspondingly their responses are obtained telephonically and other online medias such as Zoom and WhatsApp tool. Once performing strict outlier analysis (repetition, double marking or left non-responded), a total of 120 samples have been considered for further statistical analysis.

5.1.4. Statistical Analysis

In sync with ethical data preservation, we mainly collected student's perception and expectation on pre-defined Five Point Likert scale. Therefore, to extract cumulative inferences, we applied Mean and Standard Deviation information, which are discussed in the subsequent section.

5.2. Qualitative Method

Once identifying the key expectations of science students, the identified features have been considered as the reference variable, in terms of which the different existing tools are examined, whether they fulfil the specific requirements. In this method, a total of 14 gamified learning or augmented reality tools available in the examined for their features. The thorough review are given in the subsequent section.

6. DATA ANALYSIS AND INFERENCING

This section discusses the statistical discussions pertaining to the key factors influencing STEM subject's students to opt for gamified learning and/or augmented reality tools. Additionally, the relative assessment of the different existing tools for their efficacy is also discussed in this section.

6.1. Quantitative Analysis

Noticeably, before assessing different existing tools for their relative efficacy, at first, we have applied certain set of questions signifying the expectations of the students from aforesaid e-learning tools. The cumulative responses obtained from students and its inferences are given in Table 1.

Table 1. Different factors influencing STEM student's use intend and affinity (RQ1)

Variables	**Mean**	**Std. Deviation**
The tool must have subjective introductory for each problem	4.7600	0.59722
Each problem illustration with step-wise instruction or task category should have	4.6400	0.63770
There should be behaviour sensitive content recommendation facility	4.7200	0.45826
Content should provide more interactive, cognitive control to visualize, Analyse and Act	4.2000	0.40825
The extraneous cognitive load must be avoided to make learning simple and fit-to all.	4.0400	0.35119
It should be learner centred, and must not act as merely a content platform	4.7600	0.83066
There should be frequent knowledge assessment, post learning practice to inculcate long term memory amongst students.	4.2400	0.66332
Reward-based frequent knowledge assessment at start and task-end can make it more enjoyable and can motivate for major participation	4.6400	0.63770
There should be multi-level learning, assessment, task (control), and adaptive reward function to increase engagement and fun-while-learning.	4.8400	0.47258
There should be provision of group learning like online-games to encourage participation and social connectivity	4.1600	0.55377
The content and deliverables should be designed in such manner that it inculcates intrinsic motivation	4.3200	0.47610
The contextually significant content must be improved enough to illustrate real-world significance to improve or boost higher order thinking	4.7600	0.66332
The concepts of STEM (mainly, Biology, Physics and Chemistry) must be presented in 3D with autonomous navigation and review facility to make more interactive and hence to inculcate long-term memory.	4.2400	0.83066
The 3D depiction of organic chemistry reactions, organic chemistry and other chemical formation functions with repeat and test facility can make learning more productive.	4.4400	0.71181

Augmented reality and gamified learning amalgamation can make physics learning more encouraging where augmented reality can improve conceptual learning, engagement, contextual understanding, while gamified learning can make it more social, competitive and cognitive decision oriented.	4.6000	0.86603
The online tool must have customized memory driven task recall, reframe and iterative questioning ability.	4.2400	0.83066
Every-task should have an illustrative or exemplary introduction to make understanding better and hence quick in response.	4.6800	0.62716
The augmented reality or virtual reality driven inter-molecular reaction analysis and interactive tasks can make education more fun.	4.8000	0.50000
Socializing gamified learning with query discussion and reasoning can make learning more effective, even over long term decentralized educational practices	4.6800	0.69041
Query posting and reward-based query solving can encourage student to participate	4.0000	0.70711
Interfacing content and virtual drawing (for self-visualization and analysis) and simulation can make education easier and more efficient than classical teaching method	4.1600	0.80000
Biological vocabulary and taxonomy driven Interactive learning platform can improve engagement, retention and hence better performance (more goal-oriented and effective).	4.6800	0.85245
The detailed provision (multimedia, test details, illustration, parallel or similar tasks and problems, illustrations, query solutions, interactive query solving) can make education more effective.	4.0800	0.75939
Feedback-based quick-response system with experts and collaborative learning can make it more effective in terms of learning performance, and long-term memory.	4.6000	0.70711
The continuous decentralized instructional facility from subject matter experts and teachers can help improving performance and retention.	4.2800	0.67823

*Source-Primary Data

As depicted through the statistical results an interesting fact has been revealed that almost 95.2% of the respondents expect that the e-learning tool should have introductory section for any assignment being presented in the tool (M=4.76, SD=0.59). This as a result would help students to understand subject matter better rather than jumping to the questions answer discussions. In this reference, almost 92.8% of the students stated that each problem category should have illustration with step-wise instruction (M=4.64, SD=0.63). Such illustrations can make further discussion more realizable and understanding, which would not only increase the sense of attachment but an accomplished learning journey every time, when a students use the tools. When discussing real-time interaction, almost 94.4% of the respondents stated that the use discontinuity is the major issue where they often switch from one task to another based on the ease of understanding and learning ability. In this case, they often leave certain set of tasks that make overall learning incomplete. To alleviate it, there should be behaviour sensitive content recommendation facility (M=4.72, SD=0.45). Interestingly, almost 84% of the students expected that the content should provide more interactive, cognitive control to visualize, analyses and act, so as to make learning better (M=4.20, SD=0.40). It can help long-term knowledge creation. In sync with content, content-depth and relevance to the specific STEM subject , this study revealed that 80% of the respondents agreed that the extraneous cognitive load must be avoided to make learning simple and fit-to all (M=4.04, SD=0.35). The students also expected that the overall learning process must be learner-centred which could provide knowledge, hands-on experience based on students personalized need, and it should not act merely as a content platform (M=4.76, SD=0.83). This statement is backed up by a total of 95.2% of the students. Moreover, a total of 84.8% of the STEM students expected that there must be frequent knowledge assessment, post learning practice to inculcate long term memory amongst students (M=4.24, SD=0.66). In reference to the gamified learning tools, a total of 92.8% of the respondents stated that in gamified learning environment the reward-based frequent knowledge assessment at start and task-end can make it more enjoyable and can motivate for major participation (M=4.64, SD=0.63). Additionally, there should be multi-level learning, assessment, task and adaptive reward function to increase engagement and fun-while-learning (M=4.84, SD=0.47). This expectation was backed up by a significantly large 96.8% of the STEM subject's students. To make gamified learning and augmented reality-driven learning environment effective, group-based learning can be vital (M=4.16, SD=0.55). In this relation a total of 83.2% of the students expected that the aforesaid tools must have the provision for group learning like online-games to encourage participation and social connectivity. Being decentralized and autonomous in nature, unlike class-room-based study, the e-learning contents and allied deliverables should be designed in such manner that it inculcates intrinsic motivation (M=4.32, SD=0.47). Students, counting almost 86.4% stated that intrinsic motivation or cognitive thought is something that drives an individual to opt and use gamified learning or augmented reality-driven e-learning tools. Further, to retain consistent interest, the aforesaid tools must ensure improved contextually significant content to illustrate real-world significance that would make learning not only more interesting but would retain students for long and would inculcate higher order thinking (M=4.76, SD=0.66). The concepts of STEM must be presented in 3D with autonomous navigation and review facility to make more interactive and hence to inculcate long-term memory (M=4.24, SD=0.83). This expectation was affirmed by a significantly large 84.8% of the respondents. The 3D depiction of organic chemistry reactions, organic chemistry and other chemical formation functions with repeat and test facility can make learning more productive (M=4.44, SD=0.71). This study also revealed that the augmented reality and gamified learning amalgamation can make physics learning more encouraging where augmented reality can improve conceptual learning, engagement, contextual understanding, while gamified learning can make it more social, competitive and cognitive decision oriented (M=4.60, SD=0.86). Emphasizing more on continuation and retention ability, a total of 84.8% of students stated that the online tool must have customized memory driven task recall, reframe and iterative questioning ability (M=4.24, SD=0.83). Moreover, students expect that each task should have an illustrative introduction to make understanding better and hence quick in response (M=4.68, SD=0.62). This expectation was backed up by a total of 93.6% of the respondents. In reference to very specific STEM-oriented needs, a sum of 96% of the students stated that the augmented reality driven inter-molecular reaction analysis and interactive tasks can make education more fun (M=4.80, SD=0.50). This study indicated that a total of 93.6% of the respondents believe that socializing gamified learning with query discussion and reasoning can make learning more effective, even over long term decentralized educational practices 9M=4.68, SD=0.69). Similarly, feedback-based quick response system with experts and collaborative learning can make it more effective in terms of learning performance, and long-term memory (M=4.60, SD=0.70). Almost 85.6% students stated that the continuous decentralized instructional facility from subject matter experts and teachers can help improving performance (M=4.28, SD=0.67). In decentralized e-learning platforms, one key challenge is whether the students are comfortable to raise query and get the answers for the same to complete knowledge cycle. In this reference, when asked a total of 80% of the students agreed in affirmation that the query posting and reward-based query solving can encourage student to participate (M=4.00, SD=0.70). This expectation has been supported by a total of 80% STEM students. A major fraction of students counting almost 83.2% stated that most of the existing e-learning tools present information merely in the form of 2D that makes learning boring and even raises numerous questions when discussing chemistry subject. In this reference, significantly large fraction of the respondents stated that interfacing content and virtual drawing (for self-visualization and analysis) and simulation can make education easier and more efficient than classical teaching methods (M=4.16, SD=0.80). In the similar conjuncture, biological vocabulary and taxonomy driven Interactive learning platform can improve engagement, retention and hence better performance (M=4.68, SD=0.85). The detailed provision (multimedia, test details, illustration, parallel tasks, illustrations, query solutions, interactive query solving) can make education more effective (M=4.08, SD=0.75). Though, a total of 80% students backed up this expectation; however, higher standard deviation indicates difference of opinion. Thus, the above discussed factors have been considered as the key driving forces or expectations which can make e-learning more effective for STEM subject students. Now, considering these key identified parameters (Table 2), the different at hand solutions are examined for their efficacy.

Table 2. Feature-wise comparison (RQ1 and RQ3)

Sl.No.	FEATURES	Game/Augmented reality driven Learning Tools													
		D2L	CLASSDOJO	SOCRATIVE	MINECRAFTEDU	PLAYBRIGHTER	ZONDLE	COURSE HERO	MAVEN	CLASS REALM	CLASS CRAFT	KAHOOT	NEARPOD	TAPATTY	VIRTUAL LAB/ELISA
1	Subjective introductory for each problem	N	N	Y	Y	N	N	Y	Y	N	Y	N	Y	N	Y
2	Sufficient illustration with step-wise instruction(s)	N	N	N	N	N	N	Y	Y	N	Y	Y	Y	N	Y
3	Behavior sensitive content recommendation facility	Y	N	N	N	N	N	N	N	N	Y	Y	N	Y	N
4	Interactive, cognitive control to visualization of content(s)	Y	Y	N	Y	N	N	Y	N	Y	Y	Y	N	Y	Y
5	Minimum or negligible extraneous cognitive load	Y	Y	N	N	N	Y	Y	N	Y	Y	Y	Y	Y	Y
6	Learner centered	Y	N	Y	N	N	N	N	N	Y	N	Y	Y	Y	Y
7	Frequent knowledge assessment	Y	N	N	N	N	Y	N	Y	Y	N	Y	N	N	N
8	Reward-based frequent knowledge assessment at start and task-end	Y	N	Y	N	Y	N	N	N	Y	N	Y	N	Y	N
9	Multi-level learning, assessment, task (control), and adaptive reward function	N	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y

10	Group learning like online-games	N	Y	N	N	N	N	Y	Y	Y	Y	Y	N	Y	Y
11	Inculcates intrinsic motivation	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y	N	Y	Y
12	Improved contextually significant contents to illustrate real-world problems to improve or boost higher order thinking	N	N	N	N	N	Y	N	Y	Y	Y	Y	Y	N	Y
13	3D-visualizarion with autonomous navigation and review provision	N	N	N	N	N	N	Y	N	N	Y	N	N	Y	Y
14	Augmented reality and gamified learning amalgamation	N	Y	N	N	N	N	N	N	N	Y	N	N	Y	Y
15	Personalized/customized memory driven task recall, reframe and iterative questioning ability.	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	Y	N
16	Illustrative or exemplary introduction for each task	Y	N	N	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y
17	More interactive and autonomous controllable augmented reality	N	Y	Y	Y	Y	N	N	Y	N	N	Y	Y	N	Y
18	Socializing gamified learning environment with query discussion and reasoning	N	Y	Y	N	Y	N	Y	Y	Y	Y	Y	Y	Y	Y
19	Query posting and reward-based query solving	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
20	Interfaced content and virtual drawing (for self-visualization and analysis)	Y	N	Y	N	N	N	N	Y	N	Y	Y	Y	Y	Y
21	Biological/Mathematics/Physics/Chemistry vocabulary and taxonomy driven Interactive learning platform	Y	Y	Y	N	N	Y	Y	Y	N	N	Y	Y	Y	Y
22	Multimedia, test details, illustration, parallel or similar tasks and problems, illustrations, query solutions, interactive query solving ability	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

23	Feedback-based quick-response system with experts and collaborative learning	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
24	The continuous decentralized instructional facility from subject experts and teachers	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	SCORE	**13/24**	**14/24**	**14/24**	**10/24**	**10/24**	**10/24**	**14/24**	**17/24**	**15/24**	**19/24**	**21/24**	**15/24**	**18/24**	**20/24**

Note-This assessment is based on self-evaluation and self-experience, and therefore doesn't intend to appreciate or defame any product

6.2. Qualitative Analysis

In the previous section, we applied an analytical approach to identify the key factors influencing STEM students' willingness to adopt gamified learning and other augmented reality driven e-learning tools. Once these expectations were identified, in this section the different e-learning tools are examined to assess whether they fulfil the students expectations. To evaluate the features of the different tools, we performed in-depth assessments by visiting their websites, reviewing catalogues, analysing demonstration videos, and collecting primary responses from students who had used them for study.

In addition to the gamified learning tools listed in Table 2, there are several other applications such as The Elements by Theodore Gray, The Explorers, Hopscotch-Programming, The Human Body by Tinybop, Inventioneers, Kotoro, MarcoPolo Weather, Monster Math, Prodigy Math Game, Shapr 3D CAD modelling, SkySafari, Trainyard, and World of Goo designed to serve specific STEM related learning goals. However, since these applications address only a single aspect of STEM learning, they were excluded from comparative evaluation.

The qualitative assessment revealed several important trends where most of the existing tools provide engaging interfaces and task-driven learning structures; however, they remain heavily oriented towards general-purpose learning rather than STEM-specific requirements. The majority lack proper introductory modules, discipline-focused illustrations, and problem-solving scaffolds that students in science subjects particularly expect. This mismatch often results in reduced motivation and inconsistent engagement, as STEM learners require structured guidance to complement self-directed learning.

While some tools provide multilayered task assignments that reduce cognitive overload and sustain engagement, few incorporate continuous feedback, query resolution, or social learning mechanisms. This deficiency leaves students working in isolation, without adequate teacher support or peer interaction, which is a critical drawback for decentralized STEM education.

Third, only a limited number of tools attempt to integrate both gamified learning and augmented reality simultaneously. As a result, students often receive either a reward driven experience or a visualization driven experience, but rarely both. This restricts deeper exploration of complex STEM concepts and limits the potential for long-term memory retention.

Finally, commercial motives dominate many platforms, leading to a "fit to all" Learning Management System (LMS) design where responsibility for content innovation falls on teachers. Since teachers often focus on subject delivery rather than interactive content design, the intended benefits of gamification and AR remain underutilized.

The evaluation highlights several deficiencies like limited STEM-specific tailoring of existing tools, lack of integration of gamification with AR, insufficient feedback systems and teacher involvement, minimal emphasis on illustrations and problem-solving aids that STEM learners expect and commercially oriented LMS models that deprioritize subject-specific innovation.

These findings directly reflect why student engagement, retention, and willingness to adopt such tools remain inconsistent. They also emphasize the need for hybridized platforms that combine gamification and AR with tailored content, adaptive feedback, and collaborative features which gaps that informed the subsequent research conclusions.

7. CONCLUSION

This study, one of the first of its kind, assessed the efficacy of gamified learning and augmented reality tools for STEM education using a mixed-methods approach. Quantitative analysis was used to capture student expectations, while qualitative evaluation compared the ability of existing tools to meet these expectations.

The findings indicate that gamified and AR-based tools can be vital for STEM e-learning, but their effectiveness depends strongly on content precision, problem-solving integration, and interactive feedback mechanisms. The absence of these features significantly suppresses student motivation and adoption. Moreover, a combined gamification and AR framework holds promise for enhancing engagement, higher-order thinking, and long-term memory. The study is limited by the scope of available tools reviewed, reliance on student self-reports for qualitative inputs, and the absence of large-scale, longitudinal performance data.

Future research should focus on developing hybrid AR and gamified platforms, embedding AI for personalized content recommendations, and ensuring stronger teacher student and parent integration to foster sustained engagement. In particular, incorporating 3D visualization, real-time assessment, and socially interactive learning modules can significantly enhance the utility of such systems for STEM education.

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