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Article

4D Printers in EFL Classrooms: A Case Study at Saudi University for Revolutionary Move Toward Sustainability in Education

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Abstract:

The rapid evolution of technology in recent times requires a corresponding shift in education. This shift in the education sector plays a significant role in addressing numerous contemporary issues, such as sustainability. The need for sustainable development is one of the world's most pressing issues, touching upon every aspect of human life and implying a shared responsibility across all human populations. In education, technology use could benefit the sustainability of the educational environment and contribute to its development. For example, 4D printers have recently been introduced to build products quickly with reduced energy consumption. In the literature, the 4D printer has been proposed for use in education but is yet to be widely implemented. Both primary and secondary data were used to answer the current research questions. For the primary data, the current study therefore surveys the preferred learning style of female EFL university students in Saudi Arabia, looking at how 4D printers could be integrated into their English language classes. The results indicate that the learners favored kinesthetic over auditory and visual learning styles. This aligns perfectly with the use of 4D printers, as explained in the previous literature. Thus, it may be concluded that the use of 4D printers could positively impact sustainability in education.

Keywords: sustainability; EFL education; 4D printers; learning style; Saudi Arabia

1. Introduction

The impact of technology on teaching and learning is widely examined in the contemporary educational literature. However, this technology use is mainly at the teacher's discretion or according to the available institutional resources. Thus, it may not be suitable for all teaching and learning situations. Moreover, learners vary in their preferred learning style, which does not always match the technology used. In this study, the technology investigated was the 4D printer, given its potential to contribute to sustainability in education. In particular, the need for sustainable practices has been emphasized by the Saudi Ministry of Education, reflecting global concerns (Saudi Ministry of Education, 2025).

With regard to learning style, O'Brien (1985) defines the concept as a personal preference for gathering, processing, and retaining new knowledge and skills. In this regard, three main categories of learning style are identified: visual, auditory, and kinesthetic. Visual learners learn most effectively from images and graphics, such as charts and diagrams; auditory learners learn best by listening, for example, from lectures and discussions, and kinesthetic learners learn best through hands-on activities and movement. By understanding the dominant learning styles of the learners they teach, instructors can adopt more effective teaching strategies and tailor them to satisfy their students' learning preferences.

Consequently, learning style can impact the choice of educational technology, selected according to the learners' educational needs. One recent innovation is the 4D printer, which is costly and still challenging for individuals and small institutions to afford (PMR Market Research, 2024).

Nevertheless, it offers immersive benefits for the educational sector (Kumar & Kumar, 2023) and makes a positive contribution to sustainable development, as approved in the literature on the inclusion of 3D printers (Firoozi & Firoozi, 2023). In this regard, before introducing 4D printers into teaching and learning within higher education, it is crucial to investigate the context, as is the case with any technology (Dewi & Primayana, 2019). This includes studying the readiness of learners before incorporating the new technology, which means understanding their learning styles. From this perspective, the current study attempts to answer the following questions:

1. What are the learning preferences of EFL learners in their English skills classes at a university in Saudi Arabia?
2. How could the use of 4D printers relate to the learning preferences of EFL learners at a Saudi university?
3. How does the use of 4D printers contribute to sustainability in higher education, as proposed by the Ministry of Education in Saudi Arabia?

2. Literature Review

2.1. Technology and 4D printers in foreign language learning

In the ever-evolving landscape of educational technology, the integration of innovative tools has become paramount in enhancing teaching and learning experiences. Within this context, the evolution of 4D printing technology has increasingly influenced foreign language education, providing innovative ways to enhance learning experiences and prompting varied methodological approaches. 4D printing emerges as a transformative technology, echoing findings from several studies on technology's role in language learning, and presenting remarkable opportunities for English Foreign Language (EFL) classrooms. Early research highlighted the transformative potential of 4D printers in not only producing physical objects but also in creating interactive language learning environments that accommodate diverse pedagogical approaches (Riski et al., 2025). Unlike traditional 3D printing, which creates static objects, 4D printing introduces the element of time, enabling materials to change shape or function in response to environmental stimuli (Quanjin et al., 2020). This adaptability is really promising for language learning, as it allows for the creation of dynamic educational resources that can adapt to various types of learners, particularly kinesthetic learners who learn best by experiential engagement (Riski et al., 2025). Research has shown that 4D printing technology enhances students' engagement and comprehension through hands-on, interactive learning experiences, which aligns seamlessly with the needs of contemporary language learners (Riski et al., 2025; Rima, Ruhiat, & Nullhakim, 2024).

2.2. Inclusion of 4D printers according to types of learners

Despite the promising developments in technology utilization, it is imperative to acknowledge that not all students learn in the same manner. Research indicates that diverse learning styles can significantly influence language acquisition processes, and tailored instructional approaches are crucial for effective learning outcomes (Zhitin et al., 2024). Therefore, differentiated instruction remains a cornerstone of effective education. An in-depth analysis of how 4D printing can be tailored to accommodate various learner types, especially kinesthetic learners, is essential (Hansen et al., 2017; Riski et al., 2025; Rima et al., 2024). As the educational landscape increasingly embraces student-centered approaches, the focus has expanded from merely the technological capabilities of 4D printing to the broader implications for educational practice. 4D printers could serve as pivotal

instruments in crafting personalized learning experiences, thus addressing the specific needs of diverse learners (Lytvynova & Soroko, 2023).

Studies reveal that incorporating 4D technologies effectively satisfy various learning styles, particularly for kinesthetic learners who thrive in hands-on, interactive environments (Aleshkovski et al., 2024); (Singh P et al., 2024). These students benefit from the tangible aspects of 4D printing, which allows for the physical manipulation of objects that can deepen language comprehension and engagement. These printers allow learners to manifest their understanding of language through tangible products, promoting active participation and language practice relevant to their real-world applications (Riski et al., 2025; Rima et al., 2024).

The recognition of diverse learner types further informs the discussion of 4D printers in educational contexts. The theoretical perspectives surrounding constructivism suggest that when students interact with their learning materials, they build knowledge more effectively (Sun et al., 2022). The kinesthetic learning strategies particularly benefit from the tactile nature of 4D printing, enabling students to engage in creation while concurrently developing language skills. However, some critiques argue that the focus on physical interaction may overshadow the importance of auditory and visual learning channels, potentially marginalizing those learners. Auditory learners thrive when they are able to listen to spoken explanations and lectures. Students who are learning to read and write prefer to interact with information through written materials like essays, notes, and textbooks (Oladele, 2024). Therefore, they constitute perfect assistants to kinesthetic learners. Thus, while the promise of 4D printing in language education is significant, careful consideration of all learner types remains essential in balancing technological innovations with pedagogical efficacy.

2.3. Kinesthetic learners and 4D printers in Language education

The literature reveals a clear understanding of diverse learners, particularly with regard to kinesthetic learners (Singh et al., 2024; Xia et al., 2024). Kinesthetic learners are learners who benefit from hands-on experiences that facilitate active engagement with the material, allowing for deeper understanding and retention (Aleshkovski et al., 2024; Zhitin et al., 2024; Oladele, 2024). These learners are often more successful when educational practices allow them to manipulate and create physical objects. The integration of 4D printing technology into foreign language learning presents a transformative approach that aligns with modern pedagogical theories. They facilitate learning by making abstract concepts tangible and relatable, bridging the gap between abstract language concepts and tangible learning outcomes (Soni et al., 2024; Aleshkovski et al., 2024; Oladele, 2024). This engagement fosters a more profound connection to language learning by combining physical activity with cognitive processes (Singh et al., 2024; Xia et al., 2024). This kinesthetic approach not only enhances comprehension of language structures but also encourages collaboration, thereby reinforcing social interaction and language learning among peers (Oladele, 2024).

The existing literature provides compelling evidence that physically interacting with educational content can enhance language proficiency (Soni et al., 2024; Sun et al., 2022), yet there remains a notable gap in studies specifically focusing on how 4D printers can be utilized to engage these kinesthetic learners effectively in EFL contexts (Singh et al., 2024). Current themes in the discourse around technology and language learning highlight the need for pedagogical frameworks that blend modern tools with established theories of education (Kalyani et al., 2021; Boyer et al., 2023). Prior research has explored various dimensions of incorporating technology in the classroom, showcasing positive impacts on student motivation and engagement (Xia et al., 2024). However, the specific role of 4D printing in this transformative process, particularly within foreign language education, has not been extensively documented, indicating a rich avenue for research and exploration (Soni et al., 2024).

2.4.4. D Printers to Maintain Sustainability

The integration of 4D printing technology within English as a Foreign Language (EFL) classroom marks a pivotal shift in educational practices. This shift indicates a growing recognition of the need

for adaptive learning tools that align with contemporary educational paradigms, emphasizing sustainability and inclusivity (Xia et al., 2024; Soni et al., 2024). The sustainable attributes of 4D printing align with growing educational priorities around ecological responsibility, offering a unique blend of innovation and environmental consciousness that can inspire a more sustainable approach in education (Singh et al., 2024; Rima et al., 2024). The significance of incorporating 4D printing into language learning extends beyond its technological novelty. 4D printing addresses increasing concerns about environmental impact in technology use by utilizing materials that can adapt over time. Allowing the production of reusable learning materials, 4D printers foster sustainability through reducing energy and waste and promoting an eco-friendly learning space (Rima et al., 2024; Zhitin et al., 2024; Akram et al. 2022). The potential to reduce waste through resource-efficient materials while simultaneously engaging students in meaningful learning experiences represents a revolutionary step toward evolving educational methods in a conscious and responsible manner (Xia et al., 2024; Soni et al., 2024; Joshi et al. 2020). According to Momeni et al., (2017) “the potential applications of 4D printed structures can be classified into the three categories: self-assembly, multi-functionality, and self-repair” (p.43). However, while sustainability has been identified as a critical concern in educational practices, studies illustrating how 4D printing can support sustainable language learning remain sparse (Nahari et al., 2024).

The literature reveals several key insights, particularly regarding the transformative power of 4D printing as a dynamic educational tool. Unlike traditional static resources, 4D printing allows for the creation of interactive learning materials that can adapt to various learner needs, thereby fostering a more inclusive educational environment. This adaptability is particularly beneficial for kinesthetic learners who thrive on hands-on experiences and engagement with physical objects, enabling a deeper understanding of language concepts and practical applications in real-world contexts. Reaffirming the main themes articulated in this literature review, the findings underscore the necessity of integrating modern technologies into language education, not only for the sake of innovation but also to align with contemporary educational paradigms that prioritize sustainability and learner diversity. As highlighted by the literature, 4D printing exemplifies a synergy between technology and pedagogical approaches that recognize the intrinsic value of tailoring educational experiences to meet varied learning styles. Furthermore, this technology promotes a green ethos within the classroom, addressing the critical need for sustainable practices in education.

While the advantages of 4D printing in EFL contexts are clearly articulated, it is imperative to acknowledge the limitations present within the current body of literature. Much of the existing research is exploratory and lacks empirical evidence that robustly supports the effectiveness of 4D printing across diverse language learning scenarios. Additionally, some studies suggest that an overemphasis on physical interaction may marginalize auditory and visual learners, indicating that a more balanced approach is necessary for comprehensive instructional design. Consequently, there is a pressing need for focused empirical studies that investigate the effectiveness of 4D printing across various learning styles and contexts.

3. Methodology

This study was conducted in the summer term of 2025, using both primary and secondary data in a case study approach. Quantitative primary data were collected to answer research questions one and two, using a survey questionnaire. To answer research question three, secondary research data was conducted on the available sustainability literature, referring to sustainable practices in education, the use of 4D printers towards this end, and the relevant grey literature on sustainability in Saudi education.

To gather the primary data, the researchers requested permission from the Head of the English Department at a selected university in Saudi Arabia. Since one of the main aims of this research was to identify the learning styles of university EFL learners, regardless of their age, year of study, or English language-learning background, the research employed a randomized sampling strategy. This sample was restricted to female participants, due to the religious constraints of the research context.

Therefore, a link to an e-survey was sent to all EFL teachers in the Department during the summer term of 2025, with a request to encourage their students to participate and for their help in distributing the survey across the WhatsApp groups maintained for their colleagues in the Department. The 170 participants included in the study comprised female EFL learners from the English Department of a university in Saudi Arabia, ranging in age between 19 and 23 years. The data collection procedure took place mid-July, in the week before the end of the summer term.

The survey was adapted from O'Brien's (1985) Learning Style Scale. As mentioned above, O'Brien (1985) identified three main learning styles, based on learners' sensory modalities, which were deemed to impact their reception and understanding of information. Thus, learners can learn by seeing (the visual learning style), hearing (the auditory learning style), or doing and touching (the kinesthetic or tactile learning style). O'Brien's Scale is divided into three sections, with items that explain the learning style itself. The Scale is used to calculate the sum of each respondent's choices, according to the following measurements: 'Never applies to me' (1 point), 'Sometimes applies to me' (2 points), and 'Often applies to me' (3 points). The respondent selects the most appropriate response for each item and then calculates the total score for each section. Finally, the scores for the different sections are compared to identify the respondent's preferred learning style.

O'Brien's (1985, p.1) Learning Style Scale consists of a survey that begins with the following description: 'To complete, read each sentence carefully and consider if it applies to you. On the line in front of each statement, indicate how often the sentence applies to you, according to the chart below. Please respond to all questions.' However, to facilitate the research participants' understanding of the items and their responses, the Scale was translated into Arabic, this being the participants' first language. However, no changes were made to any item during the translation process. The reliability of the translation was also checked and rechecked to guarantee its accuracy. Additionally, an expert in Arabic-English translation from the institution's English Department was asked to review the clarity of the items, and changes were made to a small number of words, based on her recommendations.

Consent forms were collected electronically via the link to the survey, whereby the participants were asked for their approval to participate in the study. They were also informed that their participation was not obligatory, and that they could stop completing the survey at any time without incurring any consequences. Furthermore, no personal information was collected from the participants, and so the participants' anonymity was highly respected in this study. The corresponding researcher provided her email address, so that she could be contacted to answer any queries if necessary.

To analyze the quantitative data gathered, the IBM SPSS Statistics version 29.0.2 was used. However, only descriptive statistics were measured (e.g. frequency and percentages were checked), as these were sufficient to fulfil the needs of the research. Regarding the reliability of the measure, Cronbach's alpha values were calculated for each dimension. Cronbach's alpha (α), developed by Lee Cronbach in 1951, is the most common estimate of reliability and is based on the intercorrelations between observed indicator variables. Cronbach's alpha results in values ranging from 0 to 1, with an acceptable range of between 0.7 and 1.

Table 1. Reliability analysis.

Items	No. of Items	Cronbach's Alpha
Visual	10	0.744
Auditory	10	0.726
Kinesthetic	10	0.733
Total	30	0.835

From the above Table, it is evident that all three dimensions demonstrated acceptable levels of internal consistency, with Cronbach's alpha values ranging from 0.726 to 0.744. These values indicate that the items within each dimension consistently measured the intended construct. Furthermore, the instrument's overall reliability score ($\alpha = 0.835$) reflects a high level of internal consistency across the entire Scale, confirming the appropriateness and dependability of the questionnaire for assessing learning preferences among university students in this context. Content validity was also checked by a Professor of Applied Linguistics in the university's English Department.

4. Results and Discussion:

The core aim of this study was to explore the learning preferences of EFL learners and the way in which these preferences might align with innovative educational technologies, particularly the use of 4D printers in language-learning environments. This section, therefore, presents a statistical analysis of the questionnaire responses obtained from a sample of EFL learners, who were enrolled on courses in the English Department at a university in Saudi Arabia. It also synthesizes the key literature relating 4D printers to sustainable practices in Saudi higher education, driven by incentives from the Saudi Ministry of Education.

In the case study, the total number of participants sampled was 170, representing various age groups and academic levels (first year, second year, etc.). Statistical data analysis was conducted to answer the research questions. The results of this analysis are presented below with an interpretation and discussion of the findings in response to the research questions.

In response to the first research question, 'What are the learning preferences of EFL learners in their English skills classes at a university in Saudi Arabia?', statistical analysis of the data collected using O'Brien's (1985) Learning Style Scale revealed that a kinesthetic learning style was favored among the sampled EFL students. With a mean score of 25.18, this dimension was consistently rated as 'High Preference', indicating that the students greatly valued hands-on, movement-based, and experiential learning approaches. The strong preference reflected the learners' tendency to interact physically with learning content, solve problems through trial and error, and benefit from freedom of movement while studying. Statements such as '*I learn best when I am shown how to do something, and I have the opportunity to do it*' and '*I think better when I have the freedom to move around*' received some of the highest average scores, thereby reinforcing this conclusion.

In contrast, a visual learning style yielded a moderate mean of 20.72, while an auditory learning style was the least preferred, with a mean of 19.62. Both these styles were interpreted as a 'Moderate preference', indicating that while the learners might engage with visual or auditory input, the modalities of seeing and hearing were not dominant in their learning behavior (see Table 2).

Table 2. Learning style preferences: Mean, standard deviation, and preference level (N=170).

No.	Items	Mean	Standard Deviation	%	Ranking	Decision
5	If I am taking a test, I can "see" the textbook page and where the answer is located.	2.32	0.833	77.5%	1	Moderate preference
4	When trying to remember someone's telephone number, or something new like that, it helps me to get a picture of it in my mind.	2.25	0.697	75.1%	2	Moderate preference

2	I remember something better if I write it down.	2.24	0.646	74.5%	3	Moderate preference
6	It helps me to look at the person while listening; it keeps me focused.	2.22	0.818	73.9%	4	Moderate preference
3	I get lost or am late if someone tells me how to get to a new place, and I don't write down the directions.	2.12	0.834	70.6%	5	Moderate preference
10	It is better for me to get work done in a quiet place.	2.12	0.678	70.6%	6	Moderate preference
7	Using flashcards helps me to retain material for tests.	1.96	0.909	65.5%	7	Moderate preference
8	It's hard for me to understand what a person is saying when there are people talking or music playing.	1.91	0.801	63.5%	8	Moderate preference
1	I enjoy doodling and even my notes have lots of pictures and arrows in them.	1.88	0.584	62.7%	9	Moderate preference
9	It's hard for me to understand a joke when someone tells me.	1.71	0.751	56.9%	10	Moderate preference
A	Visual	20.72	2.678	69.1%		Moderate preference
13	Papers with very small print, blotchy dittos or poor copies are tough on me.	2.26	0.766	75.5%	1	Moderate preference
12	It helps to use my finger as a pointer when reading to keep my place.	2.16	0.790	72.2%	2	Moderate preference
11	My written work doesn't look neat to me. My papers have crossed-out words and erasures.	2.12	0.678	70.6%	3	Moderate preference
17	My eyes get tired fast, even though the eye doctor says that my eyes are ok.	2.06	0.915	68.6%	4	Moderate preference

16	Writing is tiring. I press down too hard with my pen or pencil.	2.02	0.825	67.3%	5	Moderate preference
20	If I had the choice to learn new information through a lecture or textbook, I would choose to hear it rather than read it.	2.00	0.843	66.7%	6	Moderate preference
15	I remember things that I hear, rather than things that I see or read.	1.94	0.878	64.5%	7	Moderate preference
14	I understand how to do something if someone tells me, rather than having to read the same thing to myself.	1.86	0.761	62.2%	8	Moderate preference
19	It's hard for me to read other people's handwriting.	1.76	0.550	58.6%	9	Moderate preference
18	When I read, I mix up words that look alike, such as "them" and "then," "bad" and "dad."	1.44	0.595	48.0%	10	Low preference
B	Auditory	19.62	3.365	65.4%		Moderate preference
26	I find myself needing frequent breaks while studying.	2.72	0.555	90.8%	1	High Preference
29	I think better when I have the freedom to move around.	2.71	0.570	90.4%	2	High Preference
30	When I can't think of a specific word, I'll use my hands a lot and call something a "what-cha-ma-call-it" or a "thing-a-ma-jig."	2.65	0.479	88.2%	3	High Preference
22	I learn best when I am shown how to do something, and I have the opportunity to do it.	2.59	0.692	86.5%	4	High preference
27	I am not skilled in giving verbal explanations or directions.	2.56	0.595	85.5%	5	High preference

28	I do not become easily lost, even in strange surroundings.	2.53	0.607	84.3%	6	High preference
24	I tend to solve problems through a more trial-and-error approach, rather than from a step-by-step method.	2.49	0.598	82.9%	7	High preference
25	Before I follow directions, it helps me to see someone else do it first.	2.49	0.608	82.9%	8	High preference
23	Studying at a desk is not for me.	2.26	0.724	75.3%	9	Moderate preference
21	I don't like to read directions; I'd rather just start doing.	2.18	0.787	72.5%	10	Moderate preference
C	Kinesthetic	25.18	3.370	83.9%		High preference

To answer the second research question, 'How could the use of 4D printers relate to the learning preferences of EFL learners at a Saudi university?', the findings suggest that these learners are likely to benefit most from active, participatory, and physically engaging instructional methods, such as role-play, simulations, language games, and interactive tasks as clearly evident in the item "When I can't think of a specific word, I'll use my hands a lot and call something a "what-cha-ma-call-it" or a "thing-a-ma-jig.". Therefore, traditional lecture-based or textbook-heavy instruction might not align well with the preferred learning style of the majority of this population, whereas the inclusion of a technology that supports their preferred learning style could be helpful.

In using a 4D printer, the learners would observe the creation of actual materials, which they could then assemble. Additionally, they would note any significant deficiencies in what was produced and be able to suggest solutions. This would provide a stimulus for them to practice their English skills with greater enthusiasm, expressing their thoughts in either written or spoken form. This finding is in light with Oladele (2024) who stated that 4D printers would help in language learning and retention as it fosters social interaction. Moreover, the use of 4D printers in Saudi higher education could provide an opportunity for students to understand and discuss the possibility of producing sustainable designs on demand, exploring the ways in which forms might be modified before production. This would reduce energy consumption and material waste, thereby promoting sustainable practices in Saudi universities and raising general awareness of the need for sustainability in the target population.

The secondary research data, including Aleshkovski et al. (2024), Zhitin et al. (2024), Oladele (2024), Singh et al. (2024), Soni et al. (2024), and Xia et al. (2024), provides strong evidence that physically interacting with educational content can enhance language proficiency, particularly for kinesthetic learners. This approach, which combines physical activity with cognitive processes, bridges the gap between abstract language concepts and tangible learning outcomes. This kinesthetic approach not only enhances comprehension of language structures but also encourages collaboration, reinforcing social interaction and language learning among peers. This approach aligns with modern pedagogical theories and is a transformative approach to language learning. Despite

this acknowledgement, the effective use of 4D printers in EFL contexts to engage kinesthetic learners remains a topic of interest. This indicates a promising avenue for further research.

To answer the third research question, 'How does the use of 4D printers help in improving sustainability matters as proposed by the Ministry of Education in Saudi Arabia?', it was clear from the secondary research conducted in this study that sustainable development is a critical issue in the modern world, with energy saving being a significant factor of sustainability. For example, Akram et al. (2022) explain that efficient energy usage and conservation are crucial for addressing environmental issues and ensuring sustainable development. The above researchers also warn that energy consumption is growing rapidly worldwide because it is essential for modernization, economic growth, automation, and social development. However, reducing the use of materials by using reproduceable materials while ensuring product quality can lower material consumption, thereby increase the sustainability of environmental resources and reduce carbon emissions (Chen et al., 2020; Rima et al., 2024; Zhitin et al., 2024).

Specifically, the use of 4D printers contributes to sustainability by reducing the amount of time and energy required to build items and structures. As such, 4D printers represent an enhanced version of the 3D printer since they accelerate production. Therefore, as noted by Momeni et al. (2017), 4D printing opens up new areas of application in which a structure can be activated for self-assembly, reconfiguration, and replication using sustainable resources that minimize harm to the environment. This concept is likewise explained by Joshi et al. (2020) and Momeni et al., (2017).

Momeni et al. (2017) also highlight that the difference between 3D and 4D printers is that 3D printers are static in nature, while 4D printers incorporate dynamic and responsive behavior. In particular, a 4D-printed structure is created by combining materials in a suitable combination to produce a single, one-off printed item (ibid.). These printers also feature an innovative system that utilizes a case study to assemble structures or employ adaptive building structures (ibid.). Momeni et al. (2017) add that besides the reduced assembly time, 4D printers tend to incur lower overall costs, require fewer components, and demonstrate a lower rate of failure, compared to 3D printers. These global concerns are also considered in the Saudi Crown Prince's 2030 Vision, and all governmental sectors should participate in addressing them to develop better solutions. The Saudi Ministry of Education is a key sector related to this initiative.

5. Conclusion

The research results indicate that EFL learners at all academic levels in the English Department of the selected university favored kinesthetic learning, which relies on movement and taking action. The literature demonstrates that 4D printers can be used to accommodate the kinesthetic learning style, while at the same time playing a significant role in preserving the natural environment. In terms of sustainable development, multiple studies over the past decade have shown that the 3D printing of intricate models with precision and efficacy has revolutionized many industrial fields, offering sustainable solutions to some production issues (Sood et al., 2024). Likewise, 4D printers could help revolutionize EFL learning in Saudi Arabia's higher education institutes by meeting the needs of kinesthetic learners in a sustainable manner.

Recommendations for Future Research

Despite the usefulness of the research findings, this study has several limitations. First, the data were collected exclusively from female participants, as the researchers are female, and the research was conducted in a context where gender segregation is imposed for religious reasons. Accordingly, future research could be conducted using data collected from male participants or a mixed gender sample. Second, the data were collected solely from one English Department of a Saudi university. Therefore, future studies could include data collected from other university departments. In addition, future research could explore the long-term impacts of such technologies on language proficiency, retention rates, and the overall experience of learners within various EFL contexts. Moreover, further

empirical research can provide practitioners with the necessary frameworks to implement 4D printing in ways that enhance engagement, comprehension, and environmental consciousness.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data supporting the reported results can be found in the article.

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