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EFFECT OF E- LEARNING IN DEVELOPING SELF-DIRECTED LEARNING OF SCIENCE STUDENTS AT SECONDARY LEVEL

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Abstract
Self-directed learning (SDL) is a critical competency in 21st-century education, fostering learner autonomy, critical thinking, and lifelong learning behaviors. The researcher examined the impact of technology integration, specifically through the E-Learn Punjab initiative, on the development of SDL skills among secondary-level science students in public schools of Lahore, Pakistan. A quantitative, descriptive, causal-comparative research design was applied, with a purposive sample of 200 students (100 technology users and 100 non-users) from four schools. Data were collected using a self-directed learning scale (SDLS) and analyzed using descriptive statistics and independent-samples t-tests. Findings indicated that technology users demonstrated significantly higher SDL scores (M = 174.13, SD = 10.42) compared to non-users (M = 148.75, SD = 17.04), highlighting the positive role of digital tools and simulations in promoting experiential learning. Gender differences were also observed, with boys outperforming girls (M = 165.46 vs. M = 157.42), although the effect size was small. The study's findings align with Dale's Cone of Experience and experiential learning theory, suggesting that immersive, technology-mediated instruction enhances learners' ability to analyze, synthesize, and evaluate scientific concepts. The result presented implications for educational policy, teacher professional development, and curriculum design aimed at fostering SDL through technology integration in secondary education.
Keywords: *Self-directed learning, experiential learning, Dale's Cone of Experience, technology integration, secondary science education, E-Learn Punjab.*

1. Introduction

Self-directed learning (SDL) is a process whereby learners assume primary responsibility for setting their learning objectives, choosing and structuring appropriate materials, carrying out suitable activities, and monitoring their progress (Brockett & Hiemstra, 1991; Hiemstra, 1994; Knowles, 1975). Learners self-direct their learning route, according to Merriam's (2001) theory of SDL, which is both a personal attribute and an aptitude. Similarly, self-monitoring, self-management, and motivation are the three interrelated components of SDL that are laid out by Garrison (1997). These views stress that SDL is more than just an instructional strategy but a learner-focused methodology that promotes autonomy, critical thinking, and lifelong learning behaviors.

SDL has been a recognized fundamental objective of current education for a long time, especially in adult education environments. Knowles (1970, 1975), identified as one of the pioneers of SDL, defined it as a process where one discovers learning needs, plans objectives, chooses suitable resources, and examines results without depending on direct teacher control. He posited that self-directed learners are more motivated, dedicated, and able to memorize, as they control both the process and outcome of learning. Other researchers (Brookfield, 1986; Hiemstra, 1994) have also emphasized that SDL entails independent planning, strategy execution, and self-assessment, although they highlight that students lacking SDL skills might feel frustrated, anxious, or even fail (Knowles, 1980).

Technology has become a key facilitator of SDL in modern education. Digital resources, web-based platforms, and interactive media reach the learner beyond the walls of the classroom and provide students with increased agency over pace, sequence, and intensity of learning (Scott, 2006; Boud, 1981; Norman, 1999). Evidence indicates that technology-supported learning spaces can enhance self-management, encourage peer support, and facilitate self-monitoring of progress (Robertson, 2011; Timothy et al., 2010). According to recent studies, students' SDL preparedness and higher-order thinking abilities are significantly improved when online learning resources, mobile apps, and assessments are used, particularly in the context of secondary school science (Al-Qahtani & Al-Shehri, 2021; Hassan et al., 2022; Lee & Lee, 2023).

Modern education increasingly emphasizes the role of technology in facilitating SDL, as digital tools provide learners with rich auditory, sensory, and simulated experiences that enhance engagement and foster higher-order cognitive skills such as analysis, synthesis, creation, and evaluation (Clark & Mayer, 2021). Dale's Cone of Experience (Dale, 1969) offers a theoretical model for explaining this process, demonstrating that learners learn information more effectively by active participation or "learning by doing" than by passive means like reading or listening. Science education, where most concepts like cell division, chemical bonding, and nuclear reactions cannot be observed directly, technology-mediated simulations and interactive modules offer contrived experiences that support understanding and higher-order thinking.

The use of technology in classes using devices like laptops, tablets, interactive whiteboards, and web collaboration tools allows students to access material flexibly, converse with other students and instructors, and study independently (Rahman et al., 2022; OECD, 2023). Although technology is not the target, its proper application enhances SDL by creating engaging learning experiences beyond the limits of the physical classroom, developing critical thinking, problem-solving skills, and independence (Bassett et al., 2016; Ringstaff & Kelley, 2002; Huang et al., 2020; Sönmez et al., 2023).

To this end, the Punjab Government's E-Learn Punjab program offers digitized textbooks, simulations, and multimedia learning materials aimed at facilitating SDL in government secondary schools. Through the blending of experiential learning concepts and technology-supported instruction, the program is intended to foster students' autonomy, motivation, and higher-order thinking capacities, especially in science that involves abstract and complex concepts which are best dealt with through simulation and visualization. Blending SDL theory with Dale's Cone model situates this research to investigate how technology-supported instruction may facilitate self-directed learning and enhance academic performance among secondary science learners.

Realizing the ability of technology to foster SDL, the Punjab Government started the E-learn Punjab initiative on January 6, 2014. The program offers digitized textbooks, supporting materials, and web-based assessment tools for teachers and students to enhance classroom teaching and facilitate self-directed learning. The program aligns with the educational objectives of the 21st century as it offers E-format textbooks, interactive simulations, and multimedia materials available in and out of the classroom. Such projects have been associated in current literature with enhanced science learning achievements, enhanced student engagement, and the development of digital competence in addition to SDL skills (Khan et al., 2021; Nazir & Ullah, 2024).

As educational technology has been growing rapidly, one-to-one device policies in schools are on the rise, giving students tablets, laptops, or other personal learning devices. This revolution brings unparalleled potential for secondary school students to acquire SDL skills in science education. However, owing to the program's potential, there is little empirical evidence available in Pakistan regarding how technology-based interventions such as E-learn Punjab explicitly enhance the development of SDL skills among science students, especially in public secondary schools. Thus, in this current study, the impact of e-learning is examined on the acquisition of self-directed learning skills in secondary-level science students. Filling this gap, the research provides educators, policymakers, and curriculum developers with evidence-based information on how technology integration can support independent, engaged, and lifelong learners in the sciences.

1.1 Research Objectives:

i. *Determine the level of self-directed learning of secondary science schools students.*
ii. *To compare the difference in self-directed learning of technology users and non-users science students at secondary level.*

1.2 Research questions

i. *What is the level of self-directed learning of secondary science school students?*
ii. *How technology users and non-users public schools differ in self-directed learning among science students at secondary level?*
iii. *To what extend girls and boys of secondary school students were effective in developing self-directed learning?*

1.3 Research Hypothesis

***H*₁:** *There is no significant mean difference technology users and non-users for the development of Self-directed learning among students.*

***H*₂:** *There is no significant mean difference in the achievement scores of girls and boys for the development of Self-directed learning among students.*

2. Literature Review

Self-directed learning (SDL) is the learner's active taking charge of goal identification, resource selection, planning of activities, and outcome evaluation throughout the learning process (Brookfield, 2013; Sze-Yeng & Hussian, 2010). This autonomy is indicative of a constellation of skills as well as an internal tendency toward independence (Deci & Ryan, 1985). High SDL readiness students exhibit proactivity in the search for resources, knowledge creation, and self-management of time (Choi & Park, 2013; Lee & Teo, 2010). Current research points out that SDL readiness emerged as a key competence in digital and blended learning environments, especially in STEM education, where self-directed problem-solving and resource management are vital (Akhter & Malik, 2022; Demir & Yurdugül, 2021).

There is a strong connection between SDL competencies and achievement. Freeman et al. (2014) demonstrated that active learning strategies commonly based on SDL improve performance in science, technology, engineering, and mathematics subjects. Current research has continued to affirm this connection, pointing out that readiness to apply SDL predicts science achievement and problem-solving capacity among secondary school students effectively (Mahasneh, 2021; Rahman et al., 2023). Puri (2017) highlights that SDL is premised on metacognitive awareness; positive learning experiences reinforce self-efficacy, whereas negative experiences, not managed, can be a deterrent for growth. Longitudinal results affirm that students tend to evolve from a lack of certainty to confidence given extended support and autonomy (Lunyk-Child et al., 2001; Zhang & Cui, 2022). Further, high SDL is linked with emotional resilience, teamwork skills, and decreased academic anxiety (Hale, 2006; Ooi et al., 2021).

Teachers have a central role in facilitating SDL environments. Proficient teachers support students to design, track, and review their learning, while fostering reflective practice (Norman, 1999; Kell & Deursen, 2002). Contemporary literature emphasizes the necessity of metacognitive scaffolding, as educators exemplify SDL strategies and progressively promote learners' take-over of responsibility (Geng et al., 2020). Schools that explicitly encourage SDL through project work, science inquiry activities, and peer-to-peer collaboration have seen quantifiable improvement in student self-regulation and achievement (Fotiadou et al., 2022). Institutional culture, more specifically that which enhances self-esteem and learner autonomy, also aids the development of SDL (Stewart et al., 2004; Hussain & Bashir, 2021).

Technology has proven to be a key impetus for SDL, particularly within the education of the 21st century. Technology facilitates personalization, adaptive pacing, and collaborative problem-solving (Hao, 2016; Christensen & Knezek, 2017). Clarke and Svanaes (2014) noted that one-to-one tablet programs enhance cognitive, communication, and collaboration abilities and raise motivation and independence. Recent research also affirms that well-implemented e-learning environments considerably enhance SDL readiness in science and mathematics through active involvement and reflective thinking (Kaur et al., 2022; Laili & Mulyono, 2021). However, technological skills and access limitations may restrict these advantages, highlighting the necessity for affordable infrastructure and digital literacy programs (Demir & Yurdugül, 2021). Centamo et al. (2015) and Yuliana et al. (2023) argued that the use of digital learning resources, such as simulations, video lectures, and interactive modules, may improve scientific class attendance, student satisfaction, and learning outcomes.

In Pakistan, the Punjab Government's E-Learn Punjab program responds to both access and quality challenges through digitization of textbooks, development of multimedia instructional materials, and provision of interactive technology in classrooms (e.learn, 2016; PITB, 2017). The intention here is to minimize reliance on rote learning and tuition centers through visualization, conceptualization, and self-learning of mathematics and science. Tablets and LEDs have been supplied to schools, both for online and offline consumption of grades 6–12 content. Pilot projects in eight public schools saw an increase in student interest, teacher productivity, and independent learners (PITB, 2017). Although problems with teacher training and resource utilisation continue, recent evaluations show that the program follows worldwide best practices in technology-enhanced SDL in its use of multimedia resources and assessments (Hussain & Bashir, 2021; Khan & Rafi, 2024). Both global and Pakistani literature indicate that SDL comprises a mixture of skills (planning, monitoring, evaluating) and attitudes (autonomy, motivation, resilience).

Pedagogical approaches that integrate active learning, reflection, and student choice consistently enhance achievement and self-regulation. Additionally, technology, especially when systematically implemented, as in E-Learn Punjab, can offer the tools and settings that promote SDL, as long as access, teacher capability, and learner preparedness are addressed. Even with promising results, empirical studies, particularly those that connect E-Learn Punjab with SDL development in science at the secondary level, are scant. The current research aims at bridging this gap through an evaluation of how well the program enhances SDL behaviors and academic performance among science students in public secondary schools.

3. Research methodology

The researcher adopted a positivist paradigm with a quantitative, descriptive design using a causal-comparative approach. Purposive sampling was employed to select respondents, and data were collected through a structured questionnaire comprising both open- and closed-ended items. The population included students from schools participating in the E-Learn Punjab program, namely Government Model High School Khanewal, Government Girls High School Gulshan-e-Ravi Lahore, Government Boys Central Model School Lahore, Government Girls Higher Secondary School No.1 Attock, Government Sadiq High School Bahawalpur, Government High School Joharabad, Daanish School for Boys Rajanpur, and Government Girls High School No.2 Gujranwala. A comparison group comprised students from nearby secondary schools not using the program. From this population, four schools were purposively selected: two technology-user schools (Government Girls High School and Government Boys Central Model High School) and two non-user schools (Government Model Girls High School and Pilot Secondary High School Boys). The total sample consisted of 200 students, with 100 technology users and 100 non-users, ensuring gender balance for comparative analysis.

Data collection utilized an adapted version of the Self-Directed Learning Scale (SDLS) by Swapna Naskar Williamson, initially comprising 60 items across five dimensions: learning strategies and activities, awareness, interpersonal skills, and evaluation. Validity was established by expert review for contextual relevance and cultural appropriateness, resulting in a refined 40-item instrument.

Exploratory Factor Analysis (EFA) was conducted using oblimin rotation in SPSS. The Kaiser-Meyer-Olkin (KMO) measure was 0.671 ($p = 0.000$), and Bartlett's Test of Sphericity was significant (2272.476), confirming factorability. Five primary factors explained the majority of variance, with items loading below 0.3 removed, leaving 60 statistically robust items for final analysis. This methodology ensured reliable measurement of SDL levels and enabled rigorous comparison between technology users and non-users.

Table 1 Total variance and Eigen value of Self-directed learning

Factor	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5.754	14.384	14.384	5.754	14.384	14.384
2	2.501	6.252	20.636	2.501	6.252	20.636
3	2.144	5.360	25.996	2.144	5.360	25.996
4	1.980	4.949	30.945	1.980	4.949	30.945
5	1.934	4.836	35.781	1.934	4.836	35.781

Table 2 Exploratory Factor Analysis through Principal Component Analysis: Extraction Method

Item #		A	LS	LA	E	IPS	
SDL1		……..	……..	……..	.442	……..	
SDL2		……..	……..	……..	.463	……..	
SDL3		……..	……..	……..	.478	……..	
SDL4		……..	……..	.342	……..	……..	
SDL5		……..	.327	……..	……..	……..	
SDL6		……..	……..	……..	.429	……..	
SDL7		……..	……..	.451	……..	……..	
SDL8		.539	……..	……..	……..	……..	
SDL9		.329	……..	……..	……..	……..	
SDL10		.326	……..	……..	……..	……..	
SDL11		.310	……..	……..	……..	……..	
SDL12		.404	……..	……..	……..	……..	
SDL13		.391	……..	……..	……..	……..	
SDL14		.401	……..	……..	……..	……..	
SDL15		……..	.356	……..	……..	……..	
SDL16		.359	……..	……..	……..	……..	
SDL17		……..	……..	……..	……..	……..	
SDL18		……..	……..	……..	……..	.535	
SDL19		……..	.529	……..	……..	……..	
SDL20		.359	……..	……..	……..	……..	
SDL21		.332	……..	……..	……..	……..	
SDL22		.509	……..	……..	……..	……..	
SDL23		.338	……..	……..	……..	……..	
SDL24		.406	……..	……..	……..	……..	
SDL25		……..	.359	……..	……..	……..	
SDL26		.528	……..	……..	……..	……..	
SDL27		.311	……..	……..	……..	……..	
SDL28		.457	……..	……..	……..	……..	
SDL29		……..	.317	……..	……..	……..	
SDL30		……..	……..	……..	……..	.411	
SDL31		.449	……..	……..	……..	……..	
SDL32		.540	……..	……..	……..	……..	
SDL33		……..	……..	.384	……..	……..	
SDL34		.539	……..	……..	……..	……..	
SDL35		.519	……..	……..	……..	……..	
SDL36		.360	……..	……..	……..	……..	

SDL37		.407	……..	……..	……..	……..	
SDL38		.557	……..	……..	……..	……..	
SDL39		……..	……..	……..	……..	.376	
SDL40		……..	.358	……..	……..	……..	

Reliability of Item Analysis

Item analysis was conducted to test the reliability for each factor of the self-directed learning instrument. Satisfactory internal consistency ranges from0.7 to 0.9, and above 0.5 is acceptable. Cronbach's Alpha for the factors was 0.87 for first, 0.51 for the second factor, 0.53 for third, 0.65 for fourth, 0.46 for fifth factor.

Table 3 Cronbach's Alpha for each factor of the Self-directed learning

Factors	Description	No. of items	Α
A	Awareness	23	0.87
LS	Learning strategies	6	0.51
LA	Learning activities	3	0.53
E	Evaluation	4	0.65
IPS	Interpersonal skills	3	0.46

4. Data Analysis

The purpose of this study was to examine the impact of technology-enhanced instruction on the development of self-directed learning (SDL) among secondary school science students. Data were collected from a total of 200 students, equally divided between technology users and non-users, and further categorized by gender. The analysis focused on evaluating the overall level of SDL, comparing differences between technology users and non-users, and examining potential gender-related variations in SDL development. Descriptive statistics were first calculated to determine the central tendencies and variability of SDL scores, followed by independent-samples t-tests to assess the significance of mean differences across the groups. These analyses are interpreted in the context of Dale's Cone of Experience and contemporary literature on experiential and technology-mediated learning, which suggest that active engagement with digital tools can enhance higher-order cognitive skills, self-regulation, and autonomous learning behaviors.

i. Level of Self-Directed Learning (SDL) of Secondary School Students

Table 4 Level of self-directed learning (SDL) of secondary school students

SDL sum	N	M	Std. dev	Max	Min	Scale M
	200	161.4400	18.98416	194.00	118.00	4.036

Table 4 presents the descriptive statistics for the self-directed learning (SDL) levels of the sampled secondary school students. The sample consisted of 200 respondents, evenly divided between 100 males and 100 females. The mean SDL score was 161.44, with a standard deviation of 18.98, a maximum score of 194, and a minimum score of 118. The corresponding scale mean of 4.036 indicates that, on average, students frequently employ self-directed learning strategies.

These findings align with the theoretical underpinnings of Dale's Cone of Experience (Dale, 1969), which emphasizes active engagement and experiential learning as key to higher-order cognitive skill development. The relatively high SDL scores suggest that students are effectively leveraging technology-mediated learning environments such as simulations, interactive modules, and digital resources provided by the E-Learn Punjab program to plan, monitor, and evaluate their own learning processes. This supports the literature highlighting that technology-enhanced instruction promotes SDL readiness and autonomy (Al-Qahtani & Al-Shehri, 2021; Lee & Lee, 2023; Clarke & Svanaes, 2014).

Furthermore, the results are consistent with prior studies indicating that SDL correlates with higher-order thinking and academic achievement in science education (Freeman et al., 2014; Mahasneh, 2021; Rahman et al., 2023). The use of simulations and interactive technology allows students to engage in contrived and real-world experiences at micro or abstract levels such as cell division, chemical bonding, and nuclear reactions facilitating analysis, synthesis, and evaluation, as posited by Dale's experiential learning model and contemporary constructivist perspectives.

Overall, the descriptive statistics suggest that secondary students in these settings are not only exposed to technology but are actively using it to structure their learning, reflecting both the cognitive and metacognitive components of SDL described in the literature (Garrison, 1997; Brookfield, 2013; Sze-Yeng & Hussian, 2010). These findings provide a foundational understanding for subsequent comparative analyses between technology users and non-users, as well as between male and female students, in their development of self-directed learning behaviors

ii. Comparison of Technology Users and Non-Users in Self-Directed Learning

H_1: There is no significant mean difference technology users and non-users for the development of Self-directed learning among students.

Table 5 Comparison of technology users and non-users for the development of Self-directed learning among students

Sum of Self-directed learning	N	M	Std. dev	t	df	p
Tech users	100	174.1300	10.42497	12.704	163.99	.000
Non- users	100	148.7500	17.04206			

Table 5 presents the results of an independent-samples t-test comparing SDL scores between technology users (n = 100) and non-users (n = 100). The analysis revealed a significant difference in SDL scores: technology users had a mean score of M = 174.13 (SD = 10.42), whereas non-users had a mean score of M = 148.75 (SD = 17.04), $t(163.99) = 12.704$, $p < 0.001$. The mean difference of 25.38 indicates a substantial effect size ($\eta^2 = 0.44$), suggesting a strong impact of technology integration on self-directed learning development.

These results support the premise that technology-mediated instruction enhances students' autonomy, metacognition, and higher-order thinking skills, consistent with Dale's Cone of Experience (Dale, 1969) and experiential learning theory. Digital tools such as simulations, interactive modules, and multimedia enable learners to engage actively in complex cognitive tasks planning, analyzing, synthesizing, and evaluating rather than passively receiving information. This aligns with prior findings that technology-supported environments foster SDL readiness, problem-solving, and academic achievement (Al-Qahtani & Al-Shehri, 2021; Clarke & Svanaes, 2014; Lee & Lee, 2023). From a pedagogical perspective, these findings reinforce the argument that technology serves as a conduit for experiential learning, allowing students to

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practice and internalize concepts that are otherwise abstract or inaccessible. The substantial difference between technology users and non-users underscores the critical role of teacher-guided integration of digital resources, as emphasized in the literature (Bassett et al., 2016; Ringstaff & Kelley, 2002; Huang et al., 2020). Overall, the results demonstrate that strategically implemented technology not only supports SDL behaviors but also promotes deeper engagement and understanding of scientific content among secondary school students.

iii. Gender Comparison in Self-Directed Learning

H_2: There is no significant mean difference in the achievement scores of girls and boys for the development of Self-directed learning among students.

Table 6 Comparison of girls and boys of technology users and non-users for the development of Self-directed learning among students

Gender	N	M	Std. dev	t	df	p
Girls	100	157.4200	18.82840	- 3.057	197.877	.003
Boys	100	165.4600	18.36522			

Table 6 presents the results of an independent-samples t-test comparing SDL scores between girls (n = 100) and boys (n = 100), including both technology users and non-users. The analysis indicated a significant difference: girls had a mean SDL score of M = 157.42 (SD = 18.83), while boys scored M = 165.46 (SD = 18.37), t(197.88) = -3.057, p = 0.003. The mean difference of -8.04 represents a small effect size ($\eta^2 = 0.04$), suggesting that gender has a modest influence on SDL development in this sample.

These findings suggest that boys, on average, demonstrated slightly higher SDL scores than girls, which may relate to differences in prior exposure to technology, self-efficacy, or social and cultural factors influencing classroom participation. While both genders benefit from technology-mediated learning, the effect of technology appears to interact with these individual differences. This observation is consistent with studies highlighting the importance of teacher scaffolding and equitable access to digital tools to ensure that all students, regardless of gender, can fully engage in self-directed learning (Hussain & Bashir, 2021; Akhter & Malik, 2022).

The result also aligns with Dale's Cone of Experience (Dale, 1969), which emphasizes that learning is maximized through active engagement and experiential practices. When applied to gendered differences, the findings suggest that while technology enhances SDL for all students, additional strategies may be needed to support girls in fully leveraging experiential and simulated learning opportunities, thereby minimizing small disparities in achievement.

Overall, this analysis underscores that gender differences in SDL exist but are relatively minor compared to the larger effect of technology use, highlighting the primacy of instructional design and technological integration over demographic factors in fostering autonomous, higher-order learning behaviors.

5. Discussion

Science students in secondary school might greatly benefit from technology that encourages self-directed learning (SDL), according to this study's results. Students' ability to independently create goals, plan, and assess their progress is reflected in their total SDL scores (M = 161.44, SD = 18.98), which show that they usually participate in self-directed techniques. This is in line with other studies that have shown SDL to be a combination of a set of skills and a tendency towards learning independently (Lee & Teo, 2010; Brookfield, 2013; Deci & Ryan, 1985).

Results show that using digital learning tools significantly improves SDL behaviors ($t = 12.704$, $p < .001$) compared to not using them ($M = 148.75$). According to Dale's Cone of Experience, which he put forward in 1969, this finding lends credence to the idea that students retain more of what they learn when they are actively involved in the process, rather than just absorbing it. Students were able to visualize abstract scientific ideas like chemical bonds and cellular processes using technology-mediated education, which allowed them to imitate real-world occurrences, engage with interactive models, and learn the material at their own pace. According to Kolb (1984), kids who participate in such hands-on activities are more likely to develop higher-order cognitive abilities, such as analysis, synthesis, and assessment.

There is a small but statistically significant gender difference in the results; girls scored somewhat lower than boys on the SDL development scale ($M = 157.42$ vs. $M = 165.46$; $t = -3.057$, $p = .003$). Both sexes benefit from tech-enhanced lessons, but the gender gap may be attributed to cultural, societal, or personal factors that influence individual learning styles. Similar to what Akhter and Malik (2022) and Hassan et al. (2022) have shown, earlier research has shown that learner motivation, prior exposure to technology, and confidence in utilising digital tools might moderate the effect of SDL interventions.

This research provides credibility to the idea that incorporating technology into the classroom does more than disseminate information; it also facilitates active and experiential learning. Students can "experience" abstract scientific processes through simulations, interactive modules, and multimedia materials, which align with the top layers of Dale's Cone, where students actively participate and gain a deeper understanding through real experiences. In addition, the results are in line with previous research that has highlighted how technology may help with metacognitive scaffolding, students working together, and their independence in the classroom (Geng et al., 2020; Kaur et al., 2022; Laili & Mulyono, 2021).

This research, conducted within the framework of the Punjab E-Learn program, verifies that the systematic use of digital interventions improves secondary science students' SDL abilities. Increased engagement, cognitive flexibility, and reflective thinking were seen in students who were exposed to e-learning platforms; they also showed greater abilities to organise, monitor, and assess their learning. Consistent with previous research on online learning environments and one-on-one device programs, this study found that students' autonomy in learning and their ability to think critically were both enhanced (Clark & Mayer, 2021; Fotiadou et al., 2022; Rahman et al., 2023).

6. Conclusion

The researcher demonstrates that technology integration in secondary school science education significantly enhances self-directed learning (SDL) among students. Technology users consistently outperformed non-users in SDL scores, indicating that interactive digital tools, simulations, and multimedia resources promote autonomy, engagement, and higher-order cognitive skills. The findings also supported Dale’s Cone of Experience and experiential learning theory, showing that learning by doing through simulated and interactive experiences deepens understanding and facilitates analysis, synthesis, and evaluation of complex scientific concepts. While both boys and girls benefit from technology-mediated learning, a small gender gap suggests the need for targeted strategies to ensure equitable SDL development. The study further confirms that SDL is a multidimensional competency, encompassing goal-setting, self-monitoring, metacognitive reflection, and collaborative learning skills that are enhanced when technology is deliberately embedded in pedagogy. From a practical perspective, initiatives such as Punjab's E-Learn program illustrate the potential of systematic digital integration to cultivate independent, reflective, and capable learners. Policymakers and educators should prioritize teacher training, equitable access to digital tools, and curriculum designs that embed experiential learning opportunities. Future research could explore longitudinal impacts of technology-enhanced SDL and examine strategies to reduce gender disparities in autonomous learning. In essence, this study reinforces that technology, when combined with sound pedagogical design, serves not as an end but as a means to foster self-directed, lifelong learners equipped to navigate the demands of 21st-century science education.

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