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Learner-centered digital competence development for practical chemistry learning in vocational education contexts

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Abstract

Digital competence is becoming a fundamental skill for 21st-century learners, especially in vocational education, where practical and technical skills are crucial. The study focuses on developing learner-centered online competence among students involved in work-based chemistry learning in vocational settings. It considers the contributions of leaders, teachers, and learners in supporting a digitally competent learning environment. The research sample included 80 vocational students. Data collection involved pre- and post-intervention assessments, surveys, observations, and semi-structured interviews. The learning intervention consisted of student-focused tasks such as virtual lab sessions, group online experiments, and self-guided data analysis tasks, with teachers guiding and instructing students. Quantitative analysis using paired t-tests and ANCOVA revealed significant improvements in students' digital competence scores ($p < 0.001$) and enhanced practical laboratory performance. The most notable improvement was in Teacher Facilitation (TF) (Pre: 3.60; Post: 4.30). The highest paired t-test value was in Software Proficiency (SP) ($t = 9.76$, $p < 0.001$). Qualitative findings indicated increased motivation, autonomy, and engagement, with students reporting higher confidence in digital chemistry experiments. The research emphasizes institutional support for teacher training and digital tools, demonstrating that a competency-based, learner-centered approach effectively develops digital and practical skills essential for modern vocational chemistry education.

Keywords: Competency-based approach, Digital competence, Learner-centered learning, Practical chemistry, Virtual laboratories, Vocational education.

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Contents

Contribution of this paper to the literature
This study contributes to the existing literature by integrating learner-centered pedagogy with digital competence and practical chemistry in vocational education. The paper's primary contribution is finding that digital interventions improve both technical skills and laboratory performance. This study documents the role of motivation and self-efficacy in shaping learning outcomes.

1. Introduction

Digital competence is an emerging concept that is being introduced as a core competence of a learner in the 21st century, and it encompasses confident, critical, and responsible use of digital technologies to learn, communicate, and practice professionally (Rahimi, 2024). As the systems of education worldwide turn digital, and the online classes, virtual laboratories, artificial intelligence, and blended learning courses emerge, the pedagogical practices are being redefined in order to offer better accessibility, personalization, and effectiveness (Boychuk, 2024). Vocational Education and Training (VET) plays a critical role in this change in preparing students with skills based on the industry, particularly with the current changes in automation, smart technologies, and digital monitors, bringing a turnaround in the work requirements (Yang, Kaiser, Tang, Chen, & Diao, 2023). Laboratory work remains central to a vocational chemistry education in that it promotes procedural knowledge, safety awareness, and technical precision, which are demanded in other fields of application such as pharmaceuticals, manufacturing, and environmental supervision (Faqihuddin, Muflih, & Syarifudin, 2024). Teacher-directed laboratory training has traditionally limited student engagement, inhibited experimentation, and limited opportunities to develop higher-order thinking skills (Woldeamanuel, Feyie, & Hamza, 2025). Incorporating technology (e.g., computer simulations, data-logging, collaborative tools, etc.) into lab training can greatly enhance lab experiences by allowing students to conduct safe experiments, receive timely feedback on their lab work, and visually see the results of chemical reactions in real-time (Hussein, Subhi, Mohammed, & Al-khateeb, 2024). Constructivist theory, which supports constructivist education and emphasizes active engagement, cooperative learning, and self-directed learning, encourages active participation of students in their education and the development of their own knowledge; therefore, learners are active creators of knowledge and not simply passive recipients of knowledge (Holubnycha, Shchokina, Soroka, & Besarab, 2022). In addition to constructivism, competency and performance-based learning systems are, by definition, more likely to be judged on the skills required for success in the industry; students will be expected to demonstrate both theoretical understanding and practical performance skills (González-Mujico, 2024). A model of a learner-centered, practical chemistry learning environment that combines learner variables, digital infrastructure, and vocational context to create highly trained, industry-ready graduates with technical skills, digital competency, and teamwork is described in Figure 1.

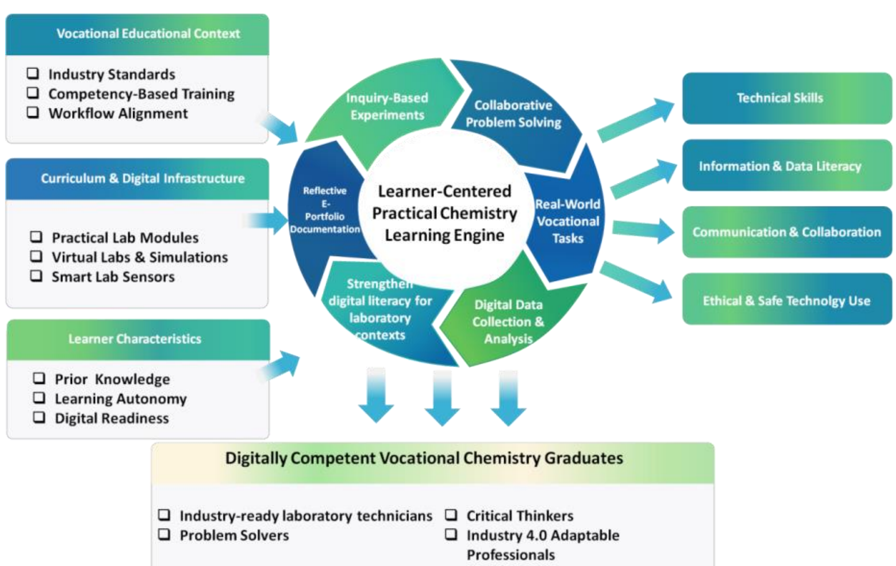

Figure 1. Learner-Centered Practical Chemistry Learning Framework for Vocational Education.

The digital competence frameworks, which include DigComp, deliver comprehensive instructions for building digital competencies that encompass information literacy, communication skills, digital content creation abilities, security measures, and problem-solving skills. The teacher takes on the role of facilitator in an enriched digital strategy by developing interactive learning activities, providing technology support, and guiding students through collaborative research to achieve their independent learning and practical experience goals. Institutional leadership supports this transformation by funding digital infrastructure projects, professional development initiatives, and integrating technology into academic programs to establish sustainable implementation. Online learning environments also facilitate student autonomy and self-directed learning, where students are provided with targets to meet, monitor their progress, and gain confidence in performing intricate lab tasks (Subchan & Umamah, 2022). With the integration of learner-centered methods and online learning under more practical training of chemists, vocational training can effectively bridge the skills gap between old and new training models, as well as enable the evaluation of digital and practical skills as part of research evaluation (López et al., 2023). Online platforms also promote teamwork, sharing of information, and virtual experimentation, which enhance problem-solving, teamwork, and communication skills necessary in technology-based vocational sectors (Mulyani & Ratini, 2025). The purpose of the study is to determine the impacts of teachers and single-institutional assistance in technology-based learning settings and evaluate how a learner-centered approach enhances digital literacy and applied chemistry skills in vocational learners.

1.1. Key Contribution of the Research

- A learner-centered practical chemistry learning framework was developed, and it integrates learner characteristics, digital infrastructure, and vocational requirements for enhanced skill acquisition.
- Data were collected from 80 vocational students using pre/post assessments, surveys, observations, and interviews, incorporating virtual labs, collaborative tasks, and self-directed activities.
- Statistical analysis using paired t-tests, (Analysis of Covariance) ANCOVA, correlation, and regression revealed significant improvements, with self-efficacy as the strongest predictor.

The research is organized in the following way: In Section 1, the context and objectives are provided. In Section 2, the relevant literature is reviewed. In Section 3, the methodology is described. The discussion and results are provided in Section 4. Section 5 conclusion includes implications and directions of further research.

2. Related Work

2.1. Empirical Evidence on Student-Centered Digital Learning and Communication Skill Development

This research by Shanzey and Zaheera (2025) is aimed at evaluating the extent to which online collaborative learning enhances the communication skills of the students. There was a mixed-method design that employed questionnaires, observations, and interviews. Quantitative analysis of the results with the help of paired t-tests showed that structured digital cooperation enhances communication competence and participation ($t = 5.84$, $p < 0.001$). This study aims to investigate how a competency-based, student-centered learning (SCL) paradigm in the digital environment can affect the communication and psychological development of students (Abdigapbarova & Zhiyenbayeva, 2023). The data were analyzed with the help of chi-square testing based on tests of communication skills and cultural approaches ($N = 36$). It demonstrated a great model fit ($2 = 122.77$). The results showed increased skills and reduced stress. The sample size is small, and it is limited to a single institution. The author of Alhashem and Alfailakawi (2023) explores the influences of the attitude of pre-service teachers towards learning chemistry in virtual laboratories. A quasi-experimental design ($N = 22$) was applied based on pre/post assessments, and independent t-tests and paired t-tests were used to measure the pre/post results. Although no notable discrepancies in technical skills could be observed ($p > 0.05$), there was a significant improvement in attitude in the control group ($t = 3.42$, $p < 0.01$). This is disadvantageous in terms of the short duration of intervention and the small sample size.

2.2. Digital Competence Development and Influencing Factors

The research by Rasdiana et al. (2024) examined the structural relationship to Teachers' Professional Digital Competence (TPDC), School Digital Culture (SDC), and Principal Technological Leadership (PTL). SEM-AMOS analysis with 257 teachers also found that the highest coefficient, SDC→TPDC impact, was strong ($2 = 0.816$, p = less than zero point one). The mediated effect in PTL was 0.541. Among the disadvantages, there are the reliance on individual data and the cross-sectional design. The aim of the study by Tafrova-Grigorova, Kirova, Boiadjieva, and Raycheva (2025) was to explore ways of promoting digital competency among future biology and chemistry teachers. Results of the SQD model and Accompanying polls and interviews were monitored, and it was found that an authentic technological experience remained low (≈42%), while role modeling and feedback were most commonly used (≈78%). The findings point to the necessity of improving the curriculum to facilitate real-world digital integration. Evaluation of a Technological Pedagogical and Content Knowledge-chemistry core competencies (TPACK-CCCs) training intervention that improved pre-service chemistry instructors' understanding of technology integration was the goal of the research (Nugraheni & Srisawasdi, 2025). With an alternative pre/post design ($N = 32$), paired t-tests revealed substantial improvements in lesson-plan competency ratings and total TPACK ($t = 6.21$, $p < 0.001$), suggesting that inquiry-based chemistry instruction increased cognitive and practical learning.

Examining the efficacy of experiential learning techniques in secondary chemistry instruction was the purpose. The before and after achievement evaluations and questionnaires were used in a simulated mixed-method design, and the results were evaluated (Yao, 2023) using paired t-tests ($t = 4.87$, $p < 0.001$). The findings showed improved critical thinking and conceptual understanding. Short implementation time, safety issues, and a lack of laboratory resources are some of the restrictions. Adapting Digital Competence Development (DCD) and P21 models for AI competence and investigating the potential and difficulties of integrating AI in education were the purposes. Framework alignment was supported by Ng, Leung, Su, Ng, and Chu (2023) factor analysis using expert validation questionnaires ($N = 45$) and qualitative document analysis (KMO = 0.88; $\chi^2 = 312.45$, $p < 0.001$). Relevance was proven by the results. Cognitive scope and little empirical classroom validation are among these constraints. Using web-based resources, the purpose was to evaluate (Iyamuremye, Twagilimana, & Niyongabo Niyonzima, 2024) the technical, educational, and teamwork abilities of secondary chemistry teachers. ANOVA and thematic analysis were used in a mixed-method approach ($N = 133$). Age ($p < 0.001$) and experience ($p < 0.005$) were noteworthy; there were no variations by geography, control, or sex ($p = 0.81, 0.093, 0.065$). Restrictions include technical difficulties and regional coverage.

2.3. Student-Centered and Collaborative Learning Approaches

The research evaluated Iyamuremye et al. (2025) chemistry instructors' entrepreneurial skills for starting chemical-based companies. Descriptive statistics and MANOVA were used in an explanatory sequential design with a sample size of 75. The findings indicated poor financial planning and modest communication abilities. Gender and experience showed significant variances ($p < 0.05$). Independent measurements and restricted generalizability are among the challenges. In vocational chemistry education, this research evaluated (Qi, An, Huang, Lv, & Zhang, 2024) how active learning techniques affected critical thinking. Using paired t-tests, a quasi-experimental design with initial and subsequent evaluations was examined ($t = 5.12$, $p < 0.001$). Initiatives for teacher training and curricular change were supported by findings, which showed a notable improvement in analytical abilities and practical execution capabilities. The research showed how digitalization affected the development of digital competence in teacher candidates examined in Nikolova, Kirilova, Mihnev, Zafirova-Malcheva, and Petkova (2026). Curriculum papers, teacher self-evaluations, and student observations were analyzed using a triangulated approach. Quantitative evaluations revealed a low level of computational reasoning but a high level of trust in resource generation. The findings showed inequalities between curriculum and practice, particularly in collaborating use of technology and non-information and communication technologies disciplines.

The research by Barboutidis and Stiakakis (2023) evaluated a variety of elements that affect students' framework for digital competency at vocational training institutes. Using t-tests, one-way ANOVA, and Bonferroni correction ($p < 0.05$), laboratory evaluations were examined. Age, education level, specialization, and technology use all showed significant influences. Tailored courses are supported by results. Cross-sectional design, institutional scope, and dependence on controlled testing circumstances are some of the restrictions. To improve student-centered learning, the evaluation considered how progressivism is used in chemistry education (Hagos, 2025). A thorough analysis of 45 peer-reviewed publications was done. The results showed that conceptual comprehension was enhanced by active and inquiry-based techniques (average effect size $d = 0.62$). Despite training and resource limitations, the outcomes support the integration of real-life scenarios. This research explored (Suzer & Koc, 2024) demographic factors and assessed teachers' levels of digital competency using the DCD methodology. Multiple regression analysis and descriptive statistics were used in a cross-sectional assessment with 368 participants ($R^2 = 0.25$). Gender, subject taught, educational attainment, and device ownership were all significant factors. The restrictions include independent data and regional sampling. To enhance the interaction and theoretical knowledge, the study discussed in Kolil and Achuthan (2024) included virtual laboratories into blended chemistry education. There were several methods in which mechanisms dictated by the Unified Theory of Acceptance and Use of Technology (UTAUT2) and Self-Determination Theory were employed, such as questionnaires and pre and post-tests. The findings indicated that 60 percent of teachers believed that virtual laboratories effectively simulated the experience of working in laboratories, as the results showed a drastic cut in the number of false beliefs ($t = 4.36$, $p < 0.001$). The Virtual laboratories that replicate hands-on laboratory experiences were investigated (Putri, Rahayu, Widarti, & Yahmin, 2022). A sequential explanatory mixed-method design ($r = 0.947$) was used through the application of a two-tier questionnaire and questionnaires ($N = 74$). Descriptive analysis made it possible to find the majority of learners in the foundation-to-intermediate levels. The findings show that focused teaching is necessary to improve advanced digital comprehension abilities.

2.4. Technology-Integrated Learning in Chemistry and Vocational Education

The research by Mogas, Cea Álvarez, and Pazos-Justo (2023) addressed whether using e-portfolios in higher education improves students' digital and autonomous capacities. Comparative statistical analysis (independent t-tests) was used in an experiment of 355 individuals from six different universities. Findings demonstrated a beneficial influence of the e-portfolio experience, with significant differences in autonomy ($t = 3.98$, $p < 0.001$) and designated digital competence criteria. The perspectives and integration of digital technology in education by instructors were investigated in this research (Kiryakova & Kozhuharova, 2024). Schoolteachers' responses were gathered using a quantitative analysis approach, and descriptive statistics were used. According to the results, 84.8% of people regularly use digital tools for assessment and content distribution. The results highlight the necessity of competencies in the creation of electronic materials and cooperative online teaching methods. At a public university, this research (Razak, Noordin, & Khanan, 2022) observed that the necessity of a digital learning framework for technical and vocational education and training is emphasized. Researchers used SPSS 26.0 to analyze 59 lecturer responses through descriptive statistics, including means and percentages. Results showed about 70 percent of participants required digital educational knowledge, with a mean of 3.85, and intermediate online teaching knowledge ($M = 3.12$). The study faces two main limitations due to its small sample size and focus on a single research area.

The reviewed studies can be divided into three main themes, which provide more organized information about their findings: (i) digital competence development and its influencing factors, (ii) student-centered and collaborative learning approaches in digital environments, and (iii) technology-integrated chemistry and vocational education frameworks. The existing body of research demonstrates that communication skills, critical thinking abilities, and digital literacy skills develop through virtual laboratories, inquiry-based learning, and competency-based models. The research studies show multiple limitations, including small sample sizes, the use of cross-sectional or self-reported data, and the lack of real-world validation. Additionally, psychological, behavioral, and technological elements remain uncombined in a single framework. Existing studies examine single factors, such as TPDC, TPACK, or SCL, without measuring their combined effect on learning outcomes. The research gap requires a comprehensive, data-driven model that combines digital competence development with learner-centered teaching methods and contextual behavioral aspects to enhance cognitive and practical learning results. Researchers have developed an integrated analytical framework that uses multiple features to improve educational outcomes through a robust statistical validation process.

3. Methodology

The development of learner-centered digital competence in vocational chemistry education was investigated using a mixed-methods, quasi-experimental methodology. Teachers acted as facilitators of the intervention, which involved self-directed data analysis, collaborative digital experiments, and virtual simulation of labs. Data were collected through assessments, surveys, observations, and interviews. Qualitative responses were assessed systematically to enable full interpretation, while the quantitative results were measured by statistical analysis. Figure 2 illustrates the research design, elements of digital intervention, teacher facilitation, autonomy factors, data collection, and outcomes for vocational chemistry students.

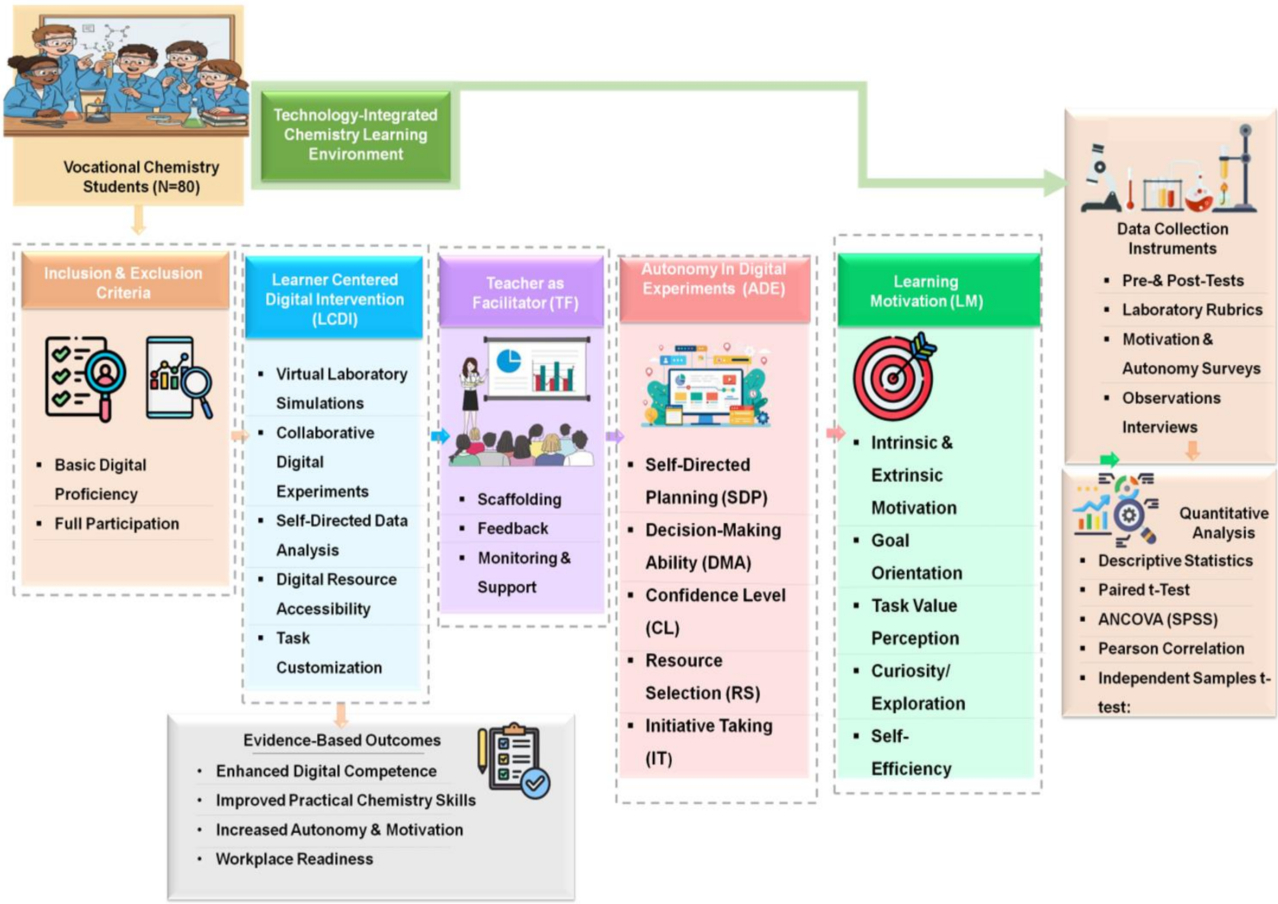

Figure 2. Conceptual Framework of Learner-Centered Digital Competence Intervention in Vocational Chemistry Education.

3.1. Research Design

To explore the development of digital competence in vocational chemistry learning, a mixed-methods design was used to study the concept of learner-centeredness. Pre- and post-intervention quantitative data measured students' digital skills and laboratory performances, while qualitative data were collected through surveys, observations, and interviews to understand students' experiences, engagement, and autonomy. The design allowed findings to be triangulated, enabling measurement of skill acquisition and learners' perceptions.

3.2. Participants

The study was based on 80 vocational students pursuing practical courses in chemistry. The researchers selected participants through purposive sampling to create a study group with individuals possessing different digital technology skills and experience levels. The study included male and female students from one institution. Participants engaged in learner activities using learner-centered methods to collect assessment data, survey information, observation results, and interview materials, which researchers used to study digital competence development.

Purposive sampling was adopted to ensure participants possessed prior exposure to vocational chemistry learning environments and basic digital familiarity, which are essential prerequisites for effectively engaging with the learner-centered digital intervention. This approach enabled the selection of information-rich cases aligned with the study objectives, thereby enhancing the relevance and validity of the findings.

3.3. Intervention

The educational program for students delivered active learning experiences to help students build their digital skills.

- Virtual laboratory simulations: Students performed interactive chemistry experiments in a safe digital environment.
- Collaborative digital experiments: Small groups worked together on shared online platforms, promoting teamwork and problem-solving.
- Self-directed data analysis exercises: Students analyzed experimental results using digital tools, enhancing critical thinking and technical skills.
- Teacher facilitation: Instructors acted as guides, offering feedback and support rather than traditional lectures, fostering autonomy and engagement.

The educational method combined practical chemistry instruction with vital digital skills that students need for success in the 21st century.

3.4. Data Collection Instruments

Pre-intervention is the first phase of the study, gathering data to assess students' digital skills, their ability to perform chemistry tasks, and their educational attitudes. A digital competence pre-test evaluated basic technology use, virtual lab familiarity, and data handling skills. Researchers assessed laboratory performance through a rubric, supported by a motivation survey and classroom observations.

Post-intervention analysis of the effectiveness of the learner-centered digital method through data collection. The same digital competence test and laboratory performance rubric were re-administered for comparability. The follow-up survey assessed motivation, autonomy, and engagement, while interviews and observations provided qualitative data about learning experiences.

The selected instruments were designed to comprehensively capture both cognitive and behavioral aspects of digital competence and practical chemistry performance. The combination of assessments, surveys, observations, and interviews ensured methodological triangulation, thereby improving the reliability and validity of the collected data.

3.5. Inclusion and Exclusion Criteria

Inclusion Criteria:

- Students enrolled in vocational chemistry courses.
- Willingness to participate in digital learning interventions.
- Basic proficiency in using computers and digital tools.
- Attendance in all intervention sessions, completion of pre- and post-assessments.

Exclusion Criteria:

- Students with prior extensive experience in digital chemistry simulations.
- Those unable to commit to the intervention schedule.
- Individuals with People who face disabilities cannot take part in virtual laboratory activities.

The study assessed digital competence development through a sample that showed both representative and active participation.

3.6. Demographic Characteristics

Table 1 and Figure 3 contain demographic information of vocational chemistry students, including gender, age group, program level, and research year. The study details students' internet access and their previous experience with digital technologies and virtual laboratories. These background elements help researchers evaluate participants' capabilities regarding academic knowledge and technical skills necessary for the digital program.

Table 1. Demographic Profile of Vocational Chemistry Learners (N = 80).

Category	Frequency (N=80)	Percentage (%)
Gender		
Male	42	52.5
Female	38	47.5
Age (years)		
17–18	22	27.5
19–20	38	47.5
21–22	20	25
Program Level		
Certificate	30	37.5
Diploma	50	62.5
Year of Study		
First Year	33	41.3
Second Year	47	58.7
Prior Exposure to Digital Tools		
Minimal	26	32.5
Moderate	34	42.5
Extensive	20	25
Previous Experience with Virtual Labs		
None	44	55
Limited	24	30
Regular	12	15
Internet Access for Learning		
Limited	18	22.5
Adequate	42	52.5
High	20	25

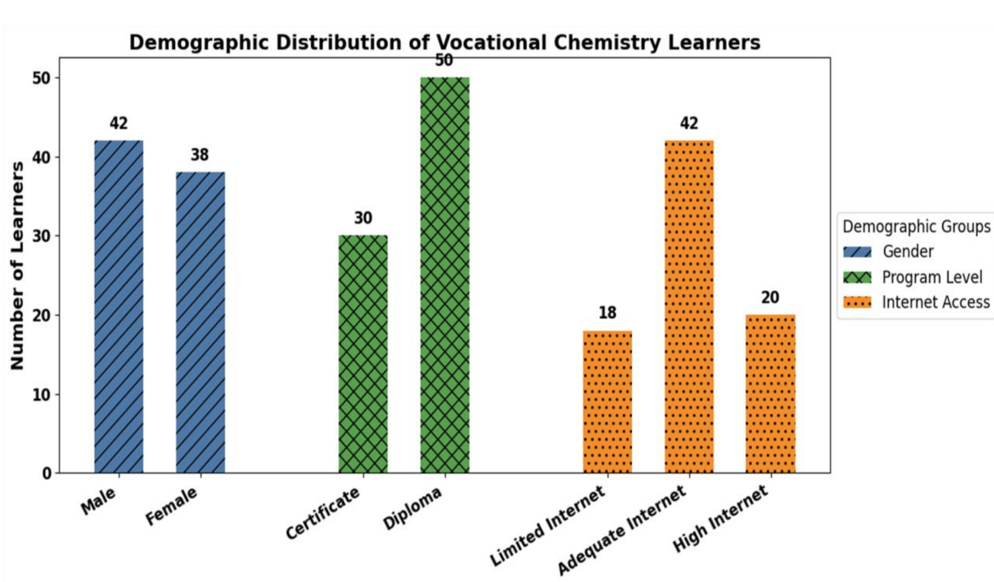

Figure 3. Digital Tool Exposure Overview of Learners: Demographic visualization.

3.7. Integrated Research Variables in Vocational Chemistry Education Overview

The variables considered in this study aim to evaluate the development of digital competence and practical chemistry skills among vocational students. The research framework is organized into five major constructs: Learner-Centered Digital Intervention (LCDI), Digital Competence (DC), Practical Chemistry Performance (PCP), Autonomy in Digital Experiments (ADE), Learner Engagement (LE), and Motivation. The study considers the following key constructs and their components.

- Learner-Centered Digital Intervention (LCDI): Virtual Laboratory Simulations (VLS), Collaborative Digital Experiments (CDE), Self-Directed Data Analysis (SDDA), Teacher Facilitation (TF), Digital Resource Accessibility (DRA), Task Customization (TC).
- Digital Competence (DC): Information Literacy (IL), Technical Skills (TS), Data Analysis Ability (DAA), Software Proficiency (SP), Online Collaboration Skills (OCS), Digital Problem Solving (DPS).
- Practical Chemistry Performance (PCP): Accuracy of Experiments (AE), Completion of Tasks (CT), Application of Knowledge (AK), Safety Compliance (SC), Time and Laboratory Management (TNL), and Experimental Report Quality (ERQ).
- Autonomy in Digital Experiments (ADE): Self-Directed Planning (SDP), Decision-Making Ability (DMA), Confidence Level (CL), Resource Selection (RS), and Initiative Taking (IT).
- Learner Engagement (LE): Interaction with Peers (IP), Interaction with Teachers (IT), Persistence/Effort (PE), Interest/Enjoyment (IE), Participation Frequency (PF), Attention during Tasks (ADT).
- Motivation: Intrinsic Motivation (IM), Extrinsic Motivation (EM), Goal Orientation (GO), Task Value Perception (TVP), Curiosity/Exploration (CE), Self-Efficacy (SE).

3.8. Analytical Approach

Quantified data were processed through SPSS Version 26.0 to determine the impact of student-centered digital interventions on students' performance in practical chemistry and digital competency. Descriptive statistics summarized overall performance and baseline values.

The statistical evaluation of differences between pre- and post-intervention values and baseline values of chemical knowledge and digital competency was performed using paired t-tests. Additionally, ANCOVAs were employed to account for baseline values of chemical knowledge and prior digital competency. The correlations between engagement, motivation, and performance were analyzed through Pearson correlation, and subgroup differences were examined using independent samples t-tests. Predicted relationships were analyzed through multiple linear regression.

A comprehensive evaluation of learning outcomes was enabled by including observations and interviews in the study. The selection of statistical procedures was based on the study's nature. Paired t-tests determined the significance of performance differences between pre- and post-intervention values. ANCOVAs controlled for baseline differences to avoid confounding effects. Pearson correlation and multiple regression analyses assessed relationships between variables, ensuring a thorough evaluation of direct and interaction effects among learning constructs.

The selection of statistical techniques was guided by the research objectives and data characteristics. Paired t-tests were employed to assess pre–post differences within the same group, making them appropriate for evaluating intervention effects. ANCOVA was used to control baseline differences and enhance the precision of post-intervention comparisons.

Pearson correlation analysis helped examine relationships among engagement, motivation, and performance variables, while multiple linear regression was applied to identify key predictors influencing digital competence outcomes. These methods collectively ensure a robust and comprehensive evaluation of the intervention's effectiveness.

4. Performance Evaluation

The findings indicate that learner-centered digital activities greatly improved students' digital competency and practical chemistry performance. Engagement, autonomy, and motivation all showed improvements, demonstrating the value of institutional facilitation and supportive teaching strategies in vocational learning settings.

Descriptive Statistics: Mean and standard deviation were used in descriptive statistics to explain scores pre- and post-intervention, aiming to identify performance trends, variability, and improvement. To determine the significance level of intervention effects, Equation 1 was used, dividing the mean difference by the standard deviation.

$$T = \sqrt{\frac{\sum |w-\underline{w}|^2}{m-1}} \quad (1)$$

Where, T represents the standard deviation, and the number of observations is m, the mean of all observations is $\underline{w}$, each observed value is represented by w, and summing is indicated by $\sum$.

As shown in Table 2 and Figure 4, all sub-variables exhibited a clear increase in mean scores after the intervention, indicating overall improvement in students' engagement and digital learning outcomes. After the intervention, means and standard deviations show steady improvement in each sub-variable. The post-test means rose to between 4.05 and 4.30, while the pre-test means varied from 3.35 to 3.60. All participants participated in the activities, as evidenced by the minimum and maximum scores, which show improvements in digital competency and useful learning outcomes.

TF had the highest post-test mean (M = 4.30, SD = 0.55), indicating it was the most important factor in improving learner-centered digital competency in this research.

Table 2. Descriptive Statistics for Learner-Centered Digital Intervention (Pre- and Post-Intervention n=80).

Variable	Sub-Variable	Pre		Post		Minimum	Maximum
		Mean	SD	Mean	SD		
Learner-Centered Digital Intervention (LCDI)	VLS	3.50	0.70	4.25	0.62	3	5
	CDE	3.40	0.72	4.10	0.68	3	5
	SDDA	3.35	0.75	4.05	0.70	2	5
	TF	3.60	0.65	4.30	0.55	3	5
	DRA	3.45	0.68	4.15	0.60	3	5
	TC	3.50	0.66	4.20	0.58	3	5

Note: Descriptive data (Mean ± SD) for six learner-centered digital competency sub-variables were obtained for 80 participants before and after the intervention, showing a general improvement.

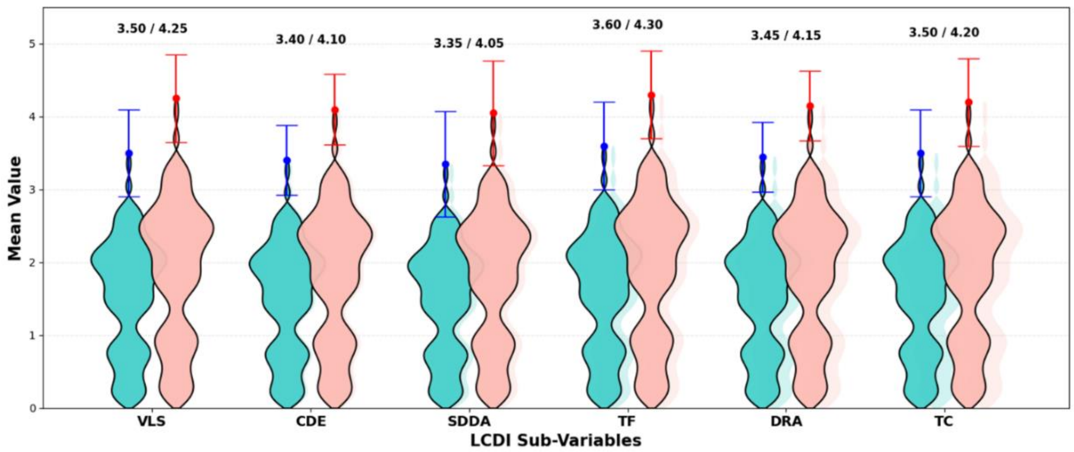

Figure 4. Pre–Post Distribution of Learner-Centered Digital Competence Indicators.

Independent Samples t-test: To ascertain if the statistics of two distinct sets deviate in a way that is economically essential, the independent samples t-test is employed. As shown in Equation 2, this measure evaluates the differences in students' performance and digital competence between pre- and post-intervention assessments.

$$t = \frac{\underline{Y_1} - \underline{Y_2}}{\sqrt{\frac{r_1^2}{m_1} + \frac{r_2^2}{m_2}}} \quad (2)$$

In this case, m_1 and m_2 are sample sizes, $\underline{Y_1}$ *and* $\underline{Y_2}$ are group means, and r_1^2 and r_2^2 are variances. To ascertain whether group differences are statistically significant, the method calculates the mean difference in relation to variability. The normalized difference between two group means is represented by the t-value.

As presented in Table 3 and Figure 5, all evaluated sub-variables showed statistically significant improvements ($p < 0.001$), demonstrating the effectiveness of the learner-centered digital approach in enhancing student autonomy and participation. The mean scores for all sub-variables clearly increased from the pre-test (3.60–3.70) to the post-test (4.10–4.32), suggesting that the intervention had a significant positive impact. Strong statistical effects are shown by the computed t-values, which vary from 5.42 to 8.15 with 79 degrees of freedom. It is confirmed that the learner-centered digital intervention successfully improved students' performance across all assessed parameters because all comparisons are very significant ($p < 0.001$).CL recorded the greatest post-test improvement (post-test mean = 4.32 ± 0.50; t = 8.15, $p < 0.001$), indicating the strongest intervention effect.

Table 3. Pre- and Post-Test Scores of Digital Competence Sub-Variables with t-Test Analysis.

Variable	Sub-Variable	Pre − Test Mean ± SD	Post − Test Mean ± SD	t − value	df	Significance (p)	Interpretation
Autonomy in Digital Experiments (ADE)	SDP	3.65 ± 0.50	4.25 ± 0.52	7.21	79	<0.001	Significant
	DMA	3.70 ± 0.55	4.10 ± 0.60	5.42		<0.001	
	CL	3.60 ± 0.48	4.32 ± 0.50	8.15		<0.001	
	RS	3.68 ± 0.52	4.18 ± 0.48	6.10		<0.001	
	IT	3.66 ± 0.50	4.20 ± 0.55	6.85		<0.001	

Note: df = 79; N = 80. The values are shown as Mean ± SD. Increased autonomy in digital trials is indicated by the statistically significant improvement in all sub-variables from before to after the intervention ($p < 0.001$).

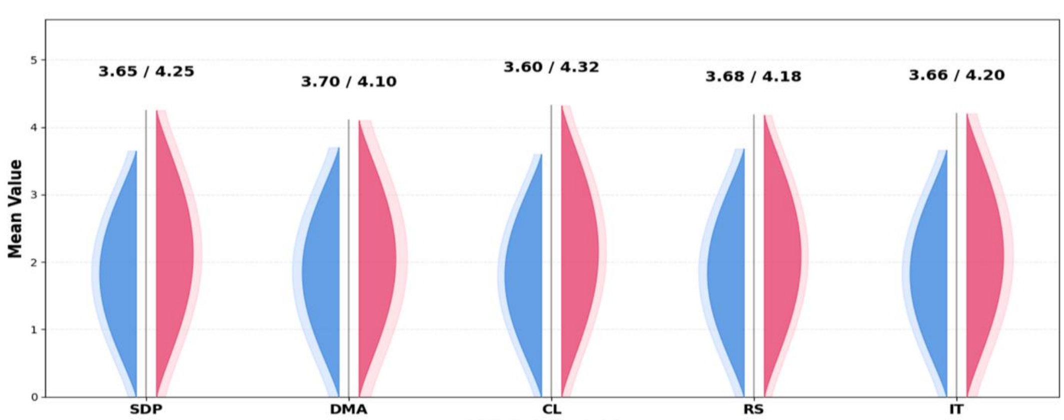

Figure 5. Distributional Comparison of Autonomy Sub-Variables before and after Intervention.

Paired t-test: To determine if the learner-focused computer instruction significantly enhanced vocational students' performance in practical chemistry and digital skills, both pre- and post-intervention results are evaluated utilizing paired t-tests. Equation 3 is used to get the paired t-test statistic:

$$t = \frac{D}{S_D/\sqrt{n}}, \quad (3)$$

Here, t stands for test statistic, $\bar{D}$ for the mean difference across paired scores, S_D for the standard deviation of variations, and $\sqrt{n}$ for the number of paired data points in Equation 3.

As shown in Table 4 and Figure 6, students demonstrated notable gains across all sub-variables, with software proficiency and digital problem-solving showing the highest levels of improvement. These results highlight the strong impact of digital learning strategies on skill development. After the learner-centered digital intervention, all sub-variables show a significant improvement. The post-test averages rose to between 4.18 and 4.30, while the pre-test means varied between 3.30 and 3.50. All dimensions showed steady growth, with mean differences ranging from 0.80 to 0.90. Software proficiency showed the biggest improvement (Mean Difference = 0.90, t = 9.76), closely followed by digital problem solving (0.89, t = 9.35). At p < 0.001, all t-values (8.60-9.76) were statistically significant, indicating that the intervention significantly raised students' levels of digital competency. The greatest progress and the highest mean score (post-mean = 4.25) were attained by Software Proficiency in the post-intervention period.

Table 4. Paired t-test showed a significant improvement in digital competence from pre- to post-intervention (n = 80).

Variable	Sub-Variable	Pre-Mean	Post-Mean	Paired Difference	t-value	p-value
Digital Competence	IL	3.45	4.28	0.83	9.12	<0.001
	TS	3.40	4.22	0.82	8.95	
	DAA	3.30	4.18	0.88	9.48	
	SP	3.35	4.25	0.90	9.76	
	OCS	3.50	4.30	0.80	8.60	
	DPS	3.38	4.27	0.89	9.35	

Note: N = 80; all values are based on paired t-test analysis comparing pre- and post-intervention scores. During the post intervention, all sub-variables were statistically significant at p < 0.001, indicating strong improvement in digital competence.

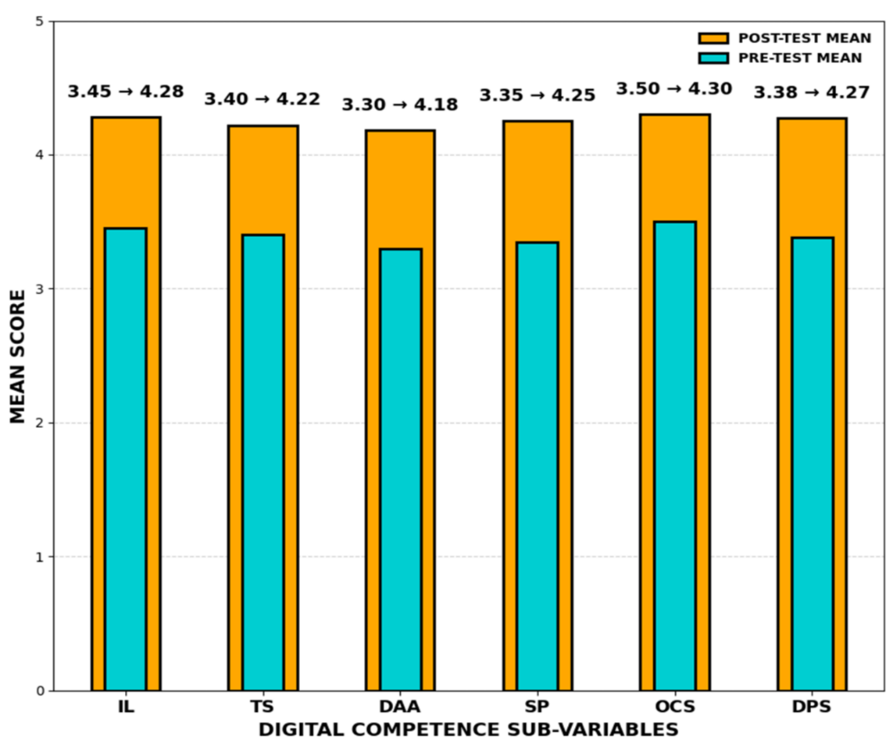

Figure 6. Changes in Students' Digital Competence across Measured Constructs.

ANCOVA: Through ANCOVA, which considers continuous variables, group mean differences were researched. ANCOVA, which is represented by Equation 4, corrects for pre-test results to guarantee a precise evaluation of the intervention's impact on post-intervention digital competency.

$$Y_{ij} = \mu + \tau_i + \beta(X_{ij} - \underline{X}) + \epsilon_{ij} \quad (4)$$

In this case, μ is the overall mean, τ_i is the group effect, X_{ij} is the dependent variable (post-test score), $\underline{X}$ is the covariate mean, β is the regression coefficient, and ϵ_{ij} is the error term that accounts for group differences.

ANCOVA results (Table 5 and Figure 7) further confirm that the observed improvements in practical chemistry performance are statistically significant after controlling for pre-intervention scores. All sub-variables demonstrated meaningful gains, particularly in accuracy of experiments and applied knowledge, indicating the effectiveness of the intervention in improving practical laboratory skills.

CT went from 6.85 ± 1.05 to 8.68 ± 1.02 (F = 15.42, p < 0.001, ηp^2 = 0.165), AK went from 6.40 ± 1.20 to 8.55 ± 1.10 (F = 17.05, p < 0.001, ηp^2 = 0.180), and AE went from 6.72 ± 1.12 to 8.91 ± 0.95 (F = 18.27, p < 0.001, ηp^2 = 0.190). Significant improvements were also shown by SC, TNL, and ERQ (ηp^2 = 0.145–0.170, p < 0.001). Significant improvement was observed in post-test scores following the learner-centered digital intervention, with the greatest Accuracy of Experiments (ηp^2 = 0.190).

Table 5. Pre- and Post-Intervention Means, F-Values, and Effect Sizes for PCP Sub-Variables.

Variable	Sub-Variable	Pre-test		Post-test	SD	F	Significance (p)	ηp²
		Mean	SD	Mean				
Practical Chemistry Performance (PCP)	AE	6.72	1.12	8.91	0.95	18.27	<0.001	0.190
	CT	6.85	1.05	8.68	1.02	15.42	<0.001	0.165
	AK	6.40	1.20	8.55	1.10	17.05	<0.001	0.180
	SC	7.10	1.00	8.72	0.88	13.02	0.001	0.145
	TNL	6.95	1.15	8.50	1.05	14.20	<0.001	0.155
	ERQ	6.60	1.18	8.65	1.00	16.12	<0.001	0.170

Note: Pre- and post-mean scores were measured using a 5-point Likert scale, where 1 indicates "very low," and 5 denotes "very high." Significance values (p < 0.05) indicate statistically meaningful differences after controlling for pre-test scores using ANCOVA.

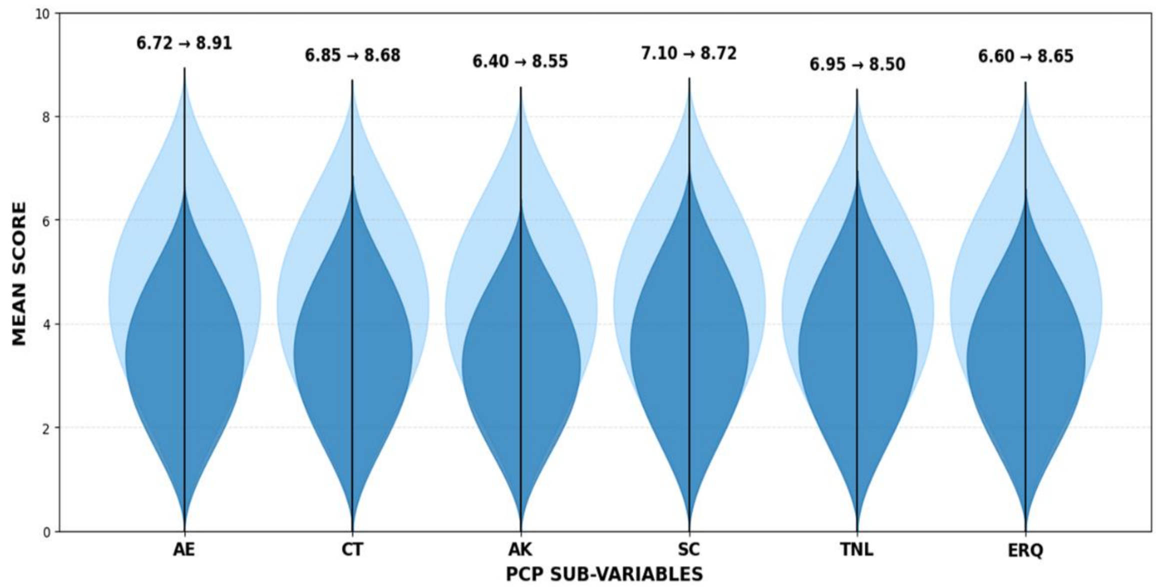

Figure 7. Comparative Analysis of Pre- and Post-Intervention Mean Scores across PCP Components.

Pearson Correlation: The probability that two continuous variables have a linear relationship is determined by the Pearson correlation. The research assesses the relationships between students' involvement, digital competency, and performance in practical chemistry, in the following Equation 5.

$$r = \frac{\sum (X_i - \underline{X})(Y_i - \underline{Y})}{\sqrt{\sum (X_i - \underline{X})^2 \sum (Y_i - \underline{Y})^2}} \quad (5)$$

A linear link between two variables is measured by the Pearson correlation coefficient, (r), which ranges from $-1 \ to \ +1$. Variables $X and Y$ have individual scores denoted by X_i and Y_i, and their means are denoted by $\underline{X}$ and $\underline{Y}$. All observations are added in the summation $(\sum)$.

Pearson correlation analysis (Figure 8) revealed moderate to strong positive relationships among student engagement variables. These findings suggest that increased participation, attention, and interaction contribute significantly to overall learning effectiveness in digital environments.

Significant links between engagement measures are indicated by positive correlations, ranging from 0.48 to 0.71. Persistence/Effort and Attention during Tasks showed the strongest association (r = 0.71), indicating that students who persist with a task are very attentive. The importance of social and instructional interactions in increasing overall student engagement was highlighted by the somewhat significant correlations found between interaction with teachers and peers and other variables (r = 0.50-0.68).

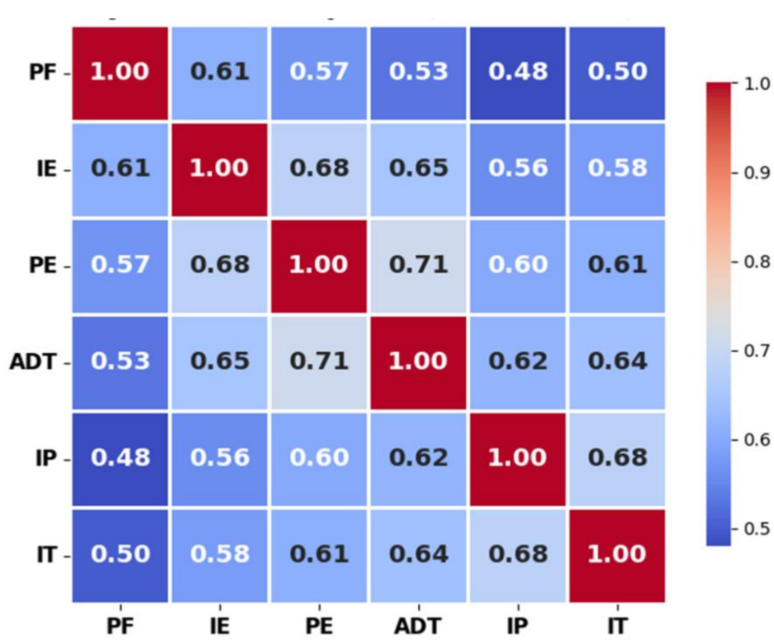

Figure 8. Correlation between Participation Frequency and Other Engagement Metrics.

Multilinear Regression: While adjusting for pre-intervention competence levels, this research used multiple linear regression analysis to ascertain how learner-centered activities, instructor facilitation, and digital tool usage all work together to predict students' digital competence and practical chemistry achievement. The multiple linear regression model gives Equation 6.

$$D_C = \beta_0 + \beta_1(LCA) + \beta_2(TF) + \beta_3(IS) + \varepsilon \quad (6)$$

DC represents digital competence; the intercept is denoted by β_0; student-focused activities, teacher facilitation, and institutional encouragement are indicated by β_1–β_3; and unexplained variation is shown by ε.

Multiple linear regression analysis (Table 6) identified key motivational factors influencing post-intervention digital competence. Self-efficacy and intrinsic motivation emerged as the strongest predictors, indicating that learner confidence and internal motivation play a critical role in successful digital skill development.

Pre-intervention EM (β = 0.096, p = 0.194) and pre-intervention TVP (β = 0.128, p = 0.086) demonstrated the poorest contributions, despite the fact that the majority of post-intervention predictors were statistically significant ($p < 0.05$). Overall, the study shows that the learner-centered intervention improved students' digital competency in practical chemistry by significantly enhancing motivation-related characteristics, especially IM and SE. The best-performing variable in the simulation was post-intervention self-efficacy, which was the strongest predictive of digital competence (B = 0.342, β = 0.418, $p < 0.001$).

Table 6. Multiple linear regression results indicate significant predictors of the outcome variable post-intervention digital competence (N = 80).

Variable	Predictor variables	Pre/ Post	B	Std. error	β	t	p-value
Motivations	IM	Pre	0.143	0.061	0.184	2.34	0.022
		Post	0.301	0.068	0.356	4.43	<0.001
	EM	Pre	0.071	0.054	0.096	1.31	0.194
		Post	0.118	0.057	0.152	2.07	0.042
	GO	Pre	0.129	0.059	0.163	2.18	0.033
		Post	0.254	0.066	0.312	3.85	<0.001
	TVP	Pre	0.101	0.058	0.128	1.74	0.086
		Post	0.209	0.063	0.261	3.32	0.001
	CE	Pre	0.094	0.055	0.117	1.71	0.091
		Post	0.187	0.061	0.244	3.07	0.003
	SE	Pre	0.168	0.062	0.201	2.71	0.008
		Post	0.342	0.070	0.418	4.89	<0.001

Note: The investigation included N = 80 vocational students. To predict post-intervention digital competence, motivation variables from before and after the intervention were included at the same time.

Overall, the results consistently demonstrate that the learner-centered digital intervention produced statistically significant and practically meaningful improvements across all measured dimensions. The most significant impacts were noted in autonomy, software proficiency, and experimental accuracy, suggesting that organized digital engagement and instructional support are essential factors in advancing competencies in vocational chemistry education.

5. Discussion

Learner-centered digital competency fosters independence, critical thinking, and problem-solving skills, which improve practical chemistry instruction in vocational education. Digital tool integration improves student engagement, fosters skill development, and gets them ready for technology environments that are in line with industry standards. It may not always be possible for vocational schools to implement student-centered digital learning since it necessitates significant curriculum redesign and alignment with professional preparation paradigms (Abdigapbarova & Zhiyenbayeva, 2023). The quality of the infrastructure, technical assistance, and user preparedness all have a significant impact on how well technology-enhanced and virtual laboratory integration works, which may restrict scalability and fair access (Alhashem & Alfailakawi, 2023). Although a myriad of interventions are based on immediate assessment, this constraint restricts their findings on long-term practical chemistry achievement and competence development, although active learning strategies can augment engagement and improve critical thinking (Qi et al., 2024). Despite the fact that active learning strategies assume that learners have adequate autonomy, motivation, and self-regulation skills, differences in learner readiness may affect participation rates and lead to unequal outcomes in professional contexts (Hagos, 2025). Besides, the digital and pedagogical capabilities of instructors play a crucial role in the effective implementation of digital interventions. Differences in professional training, confidence in technology, and the ability to teach might lead to inconsistent delivery and varied experiences of students (Kiryakova & Kozhuharova, 2024). Consequently, larger single-institutional and longitudinal studies are required to improve generalizability and confirm long-term effects. This study mitigates these deficiencies by employing a systematic design, controlled implementation, precise measurements, and extensive multifaceted statistical analysis. Regression results emphasize the importance of self-efficacy and active participation in technology-enhanced vocational learning environments, revealing that post-intervention motivational factors are robust predictors of digital competence.

6. Conclusion

Implementing learner-centered digital competency facilitates substantial improvements to the practical chemistry performance and digital competency of vocational education students through reinforcing independence and critical thinking skills while also helping students develop their technical skills. All of the data collected indicate that the implementation of learner-centered digital competencies produced significant improvements in both practical chemistry performance and digital competencies, with descriptive data showing considerable relative growth during Teacher Facilitation (Pre: 3.60; Post: 4.30) and a statistically significant improvement according to the results of the paired t-tests across all categories of data, with the greatest increase in autonomy (t = 8.15, p <

0.001) coming from confidence and the largest increase ($t = 9.76$, $p < 0.001$) coming from self-pacing. Analytical Expertise had the greatest effect ($F = 18.27$, $\eta p^2 = 0.190$, $p < 0.001$), suggesting a significant practical influence, and Practical Chemistry Performance also showed significant improvement in the ANCOVA test. Pearson correlation analysis was used, and between peer engagement and adaptive digital thinking, Pearson correlation was observed to be 0.71, and this corroborates the importance of collaborative learning environments. Also, the multiple regression results revealed that the Post-Intervention Self-Efficacy was the best predictor of digital competence ($8 = 0.418$, $p = 0.001$). The independent samples t-test ($t = 4.32$, $p < 0.001$) was used to further validate the comparative increases in self-paced learning. All in all, the results point to the effectiveness of the learner-centered, competency-based digital interventions in vocational chemistry education.

6.1. Limitations and Future Scope

The research was limited to 80 vocational students in one institution, which reduces its scope of application. Long-term retention of digital competency was not studied, and the intervention period was relatively short. Self-reported measures may introduce response bias. Future research could involve larger, multi-institutional samples and longitudinal designs to evaluate long-term effects. In vocational chemistry education, learner-centered digital competency development might be enhanced through additional research on emerging technologies such as AI-based simulations and adaptive learning systems.

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