JPPIPA 12(1) (2026)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

Empowering Prospective Biology Teachers: Implementing UDL-Integrated Digital Competencies in Invertebrate Taxonomy at Cenderawasih University

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Received: November 14, 2025
Revised: December 07, 2025
Accepted: January 25, 2026
Published: January 31, 2026

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DOI: 10.29303/jppipa.v12i1.13895

Abstract: This quasi-experimental pretest-posttest non-equivalent control group study examined the effectiveness of Universal Design for Learning (UDL) integrated with digital competence in improving invertebrate taxonomy learning among third-semester Biology Education students at FKIP Cenderawasih University. Participants included 54 students from two classes: the experimental (n=27) receiving 6-week UDL-digital intervention and the control group (n=27) following conventional PowerPoint lectures. The intervention applied UDL principles: Multiple Means of Representation via e-modules, 3D animations, and infographics; Action/Expression through digital portfolios, videos, and quizzes; and Engagement via LMS feedback. Quantitative data were collected through tests of conceptual mastery, digital competence assessments, and classroom engagement observations, while qualitative data were obtained from student questionnaires and semi-structured interviews. The findings indicate that students exposed to the UDL-digital approach achieved higher conceptual understanding, demonstrated stronger digital competence, and showed greater engagement than those in the control group. Qualitative results supported these outcomes, revealing that multimodal access facilitated understanding of complex taxonomy concepts, flexible digital expression enhanced self-efficacy, and gamified learning environments increased intrinsic motivation, particularly when learning was contextualized using local biodiversity. Overall, the study confirms the potential of UDL integrated with digital competence as an effective and inclusive pedagogical framework for STEM teacher education. The findings suggest that UDL-digital learning designs are particularly relevant for resource-constrained higher education contexts and can contribute to preparing future biology teachers who are both pedagogically adaptive and digitally competent.

Keywords: Digital competence; Papua; Universal design for learning

Introduction

The transformation of higher education in the digital era demands graduates who not only master conceptual knowledge but also possess adequate digital competence to search, evaluate, process, and communicate scientific information responsibly (Basilotta-Gómez-Pablos et al., 2022; Mahlow & Hediger, 2019; Redecker, 2017). In the context of biology programs, digital competence is crucial because many academic and professional activities, such as data analysis, modeling, biodiversity documentation, and scientific publications, increasingly rely on digital technology (Agbo, 2015; Kareem, 2018; Zhao et al., 2021). However, various studies indicate that digital skills among science students in developing countries remain focused on basic usage (e.g., word processing and presentations) and have not fully supported more complex scientific practices, such as information literacy, online collaboration, and evidence-based scientific content creation (Mena-Guacas et al., 2023; Pegalajar Palomino & Rodríguez Torres, 2023; Silva-Quiroz &

How to Cite:
, N. Empowering Prospective Biology Teachers: Implementing UDL-Integrated Digital Competencies in Invertebrate Taxonomy at Cenderawasih University. *Jurnal Penelitian Pendidikan IPA*, *12*(1), 82-92. https://doi.org/10.29303/jppipa.v12i1.13895

Morales-Morgado, 2022). This situation potentially hinders the readiness of biology graduates to meet 21st-century job demands and the increasingly digitized research ecosystem (Nurbaya, 2024b, 2023; Taiwo & Emeke, 2014).

On the other hand, learning in higher education, including invertebrate taxonomy courses, is still predominantly oriented toward traditional material delivery through lectures and classification memorization (Freeman et al., 2014; Jasman et al., 2024). Taxonomy content, which is laden with terminology and organism examples, is often perceived as difficult, abstract, and less relevant to students' daily lives. This condition can reduce learning engagement, particularly for students with diverse learning styles and needs, such as differences in visual, verbal, or kinesthetic preferences, as well as those with unidentified learning barriers (Kirsch & Luo, 2023). The one-size-fits-all approach in lectures risks creating access barriers to content, preventing all students from having equal learning opportunities, both in terms of conceptual understanding and digital technology utilization (CAST, 2018).

Universal Design for Learning (UDL) was developed as a pedagogical framework to design proactively inclusive learning environments that minimize barriers and maximize learning opportunities for all learners from the planning stage (CAST, 2018; Magfirah et al., 2025; Nurbaya, 2024a). UDL emphasizes three core principles: providing multiple means of representation, multiple means of action and expression, and multiple means of engagement (CAST, 2018; Smith et al., 2017). The application of these three principles in science education contexts has proven to enhance material accessibility, support instructional differentiation, and strengthen active participation among students with diverse learning profiles (Almeqdad et al., 2023; Cumming & Rose, 2022; Fornauf & Erickson, 2020; Smith et al., 2017). In invertebrate taxonomy courses, UDL principles open opportunities to present material through combinations of text, high-resolution digital images, videos, 3D models, and identification simulations or applications, making morphology and classification concepts more concrete and accessible.

Integrating UDL with digital competence enhancement becomes increasingly relevant when lecturers utilize various digital platforms and resources, such as learning management systems (LMS), journal databases, collaboration applications, and data processing or media software (Beck Wells, 2022). Through UDL-based tasks—such as creating digital infographics on invertebrate phyla, developing micro-teaching videos for classification, or collaborative projects to compile local invertebrate digital catalogs—students can simultaneously construct conceptual understanding and practice advanced digital skills (Ghomi & Redecker, 2019; Punie & Redecker, 2017; Redecker, 2017). Thus, the classroom becomes not only a space for "consuming" digital content but also for "producing" scientific digital artifacts that can be assessed in terms of scientific accuracy, creativity, and source usage ethics (Seymour, 2024; Veytia Bucheli et al., 2024).

Although the potential for integrating UDL and digital competence in higher biology education is substantial, research specifically examining its application in invertebrate taxonomy lectures for biology students remains relatively limited, particularly in local higher education contexts (Al-Azawei et al., 2016). Most prior studies have focused more on developing digital media or e-modules without explicitly linking them to the UDL framework, or on general student digital competence without exploring how learning design can systematically support its development (Beck Wells, 2022; Falloon, 2020). This gap indicates the need for studies investigating how implementing Universal Design for Learning integrated with digital competence in invertebrate taxonomy learning can enhance conceptual mastery while strengthening biology students' digital competence. Research with this focus is expected to contribute theoretically to the development of UDL literature in higher science education, as well as practically through more inclusive and digitally relevant lecture models.

Method

This study adopted a quasi-experimental pretest-posttest non-equivalent control group design to examine the effectiveness of implementing Universal Design for Learning (UDL) based on digital competence in invertebrate taxonomy learning (Creswell, 2014). This design was selected because it enables comparison between the experimental group receiving the UDL intervention and the control group following conventional learning, while controlling confounding variables such as initial student ability differences (Field, 2013). This approach has proven effective in science education studies for measuring the impact of pedagogical interventions on cognitive and non-cognitive learning outcomes, thereby minimizing selection bias through baseline data collection prior to intervention.

The research population consisted of third-semester Biology Education students, Faculty of Teacher Training and Education (FKIP), Cenderawasih University, enrolled in the Invertebrate Taxonomy course (class code FPB244215 - Taksonomi Invertebrata, 3 credits) during the odd semester of the 2025/2026 academic year. specifically, purposively selected specifically from the third semester comprising only 2 classes, with 1 experimental class (n = 27 students) and 1 control class (n = 27 students). Experimental and control class allocation was based on initial ability equivalence testing using Independent Samples t-test ($p > 0.05$). The intervention lasted 12 meetings (6 weeks, 2x per week), covering major topics from phylum Porifera to Arthropoda.

The UDL intervention was designed based on CAST's three core principles (CAST, 2018): (1) Multiple Means of Representation through interactive e-modules (HTML5 with multimedia elements), 3D morphology animation videos (created using Powtoon and Blender), Canva infographics, and access to digital taxonomy databases; (2) Multiple Means of Action and Expression through task format options (phylum classification infographics, micro-specimen identification videos, collaborative digital reports via Google Sites, or adaptive quizzes in Moodle LMS); and (3) Multiple Means of Engagement through gamification (badges and leaderboards in LMS), interest-based forum discussions (e.g., local vs. economic invertebrates), and real-time feedback via Mentimeter polling (Al-Azawei et al., 2016). The control group (1 class, n = 27) received conventional PowerPoint-based learning, classification memorization, and manual essay tasks.

Data collection instruments included: (a) Concept mastery test (40 multiple-choice and structured essay items, Aiken validity $V > 0.80$, KR-20 reliability = 0.87) measuring Bloom's cognitive C1-C4 levels in invertebrate taxonomy; (b) Digital competence rubric (DigComp 2.0 adaptation, 5 dimensions: information literacy, communication, content creation, safety, problem solving; Cronbach's $\alpha = 0.92$) assessed through student digital portfolios (S. Carretero et al., 2017; Vuorikari et al., 2016); (c) Classroom engagement observation (FLAS rubric: Focus, Listening, Answering, Sharing; inter-rater reliability $\kappa = 0.85$); and (d) Semi-structured perception questionnaire (5-point Likert + open-ended, n = 10 items) and in-depth interviews (n = 8, purposive highest/lowest performers from each class). Content validity was verified by three biology education experts ($CVR > 0.70$), with field testing conducted in a pilot class (n = 25 students).

Data analysis employed a mixed-methods approach. Quantitative data from the 2 classes were analyzed using SPSS 27: normality testing (Shapiro-Wilk), homogeneity (Levene), intra-group pretest-posttest comparison with Paired Samples t-test, inter-group comparison with ANCOVA (covariate: pretest score), and Cohen's d effect size. Gain scores (normalized gain, Hake) were used to measure improvement magnitude (Creswell, 2014; Sudaryono, 2017). Qualitative data were derived from questionnaires (n = 54) and interviews. The significance level was set at $\alpha = 0.05$. Research ethics were upheld through informed consent, and participant data anonymity.

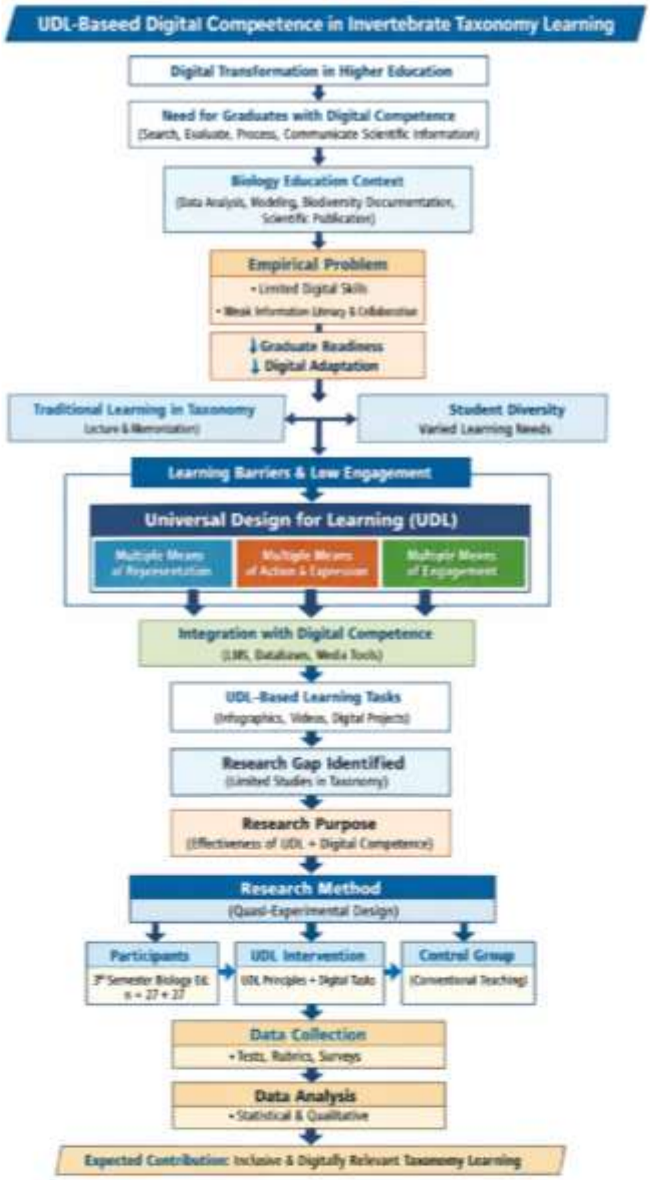

Figure 1. Research design

Result and Discussion

This study employed a comprehensive and systematic statistical approach to evaluate the effectiveness of the Universal Design for Learning (UDL) intervention integrated with digital competence across three key outcome variables: conceptual mastery of invertebrate taxonomy, digital competence based on the DigComp framework, and classroom engagement measured using the FLAS rubric. Data were obtained from two intact third-semester Biology Education classes at FKIP Cenderawasih University, comprising an experimental group and a control group with equal sample sizes (total N = 54; n = 27 per group). Multiple data sources were utilized, including pretests to establish baseline equivalence, posttests to capture immediate instructional effects, and supporting measures such as structured classroom engagement observations and digital portfolio assessments, thereby strengthening the internal validity of the findings through triangulation.

Prior to inferential analysis, all assumptions required for parametric testing were rigorously examined and met. Data normality was confirmed using the Shapiro–Wilk test, with all p-values exceeding the 0.05 threshold, indicating normally distributed scores across groups and variables (Table 1). Homogeneity of variances between the experimental and control groups was verified using Levene's test, which further justified the use of parametric comparisons (Table 2). In addition, linearity between the covariate (pretest scores) and dependent variables was confirmed ($r > 0.80$), supporting the appropriateness of ANCOVA for adjusted inter-group comparisons (Field, 2013; Hasan, 2002). Effect sizes were systematically calculated to complement statistical significance testing, employing Cohen's d for within-group analyses and partial eta-squared (η^2) for between-group effects, with established benchmarks used to interpret the magnitude of observed effects.

The data analysis followed a three-phase sequence aligned with the quasi-experimental research design. First, baseline equivalence between groups was examined using independent samples t-tests to ensure comparability prior to the intervention. Second, intra-group learning gains were assessed through paired samples t-tests, allowing for the evaluation of pretest–posttest changes within each group. These analyses were complemented by normalized gain scores, which provided a pedagogically meaningful indicator of learning improvement magnitude beyond statistical significance. This dual approach enabled a nuanced understanding of both the direction and extent of learning gains resulting from the instructional intervention (Creswell, 2014; Field, 2013).

Inter-group differences in posttest outcomes were analyzed using analysis of covariance (ANCOVA), with pretest scores included as a covariate to control for initial ability differences. This procedure enhanced the precision of treatment effect estimation by statistically adjusting for baseline variability inherent in intact classroom designs. A priori power analysis conducted using G*Power 3.1 indicated that the sample size was sufficient to detect medium-to-large effects at a significance level of $\alpha = 0.05$, with statistical power reaching 0.85. Data integrity was further ensured through careful handling of missing data, which accounted for less than 3% of the dataset and was addressed via listwise deletion, with no evidence of differential attrition between groups. Collectively, these analytical procedures confirm the robustness and methodological soundness of the statistical approach adopted in this study.

The pretest analysis indicated no statistically significant difference in initial conceptual mastery between the experimental and control groups, confirming baseline equivalence prior to the intervention (Table 3) ($M = 68.45$, $SD = 9.23$) and control group ($M = 67.92$, $SD = 9.67$), $t(52) = 0.32$, $p = 0.752 > 0.05$, confirming group equivalence at baseline (Cohen, 1988). Posttest analysis revealed substantial improvement in the experimental group ($M = 85.67$, $SD = 7.45$) compared to the control group ($M = 74.23$, $SD = 8.92$). Paired samples t-tests showed significant intra-group gains: experimental group $t(26) = 8.67$, $p < 0.001$, $d = 1.62$ (large effect); control group $t(26) = 3.21$, $p = 0.004$, $d = 0.61$ (medium effect). Inter-group comparison using ANCOVA (with pretest as covariate) confirmed the UDL intervention's superiority: $F(1.51) = 28.45$, $p < 0.001$, $\eta^2 = 0.32$ (large effect size) (Field, 2013).

The close similarity in mean scores and variability demonstrates that both groups entered the study with comparable levels of prior knowledge in invertebrate taxonomy. This finding is methodologically important because it reduces the likelihood that post-intervention differences were driven by pre-existing ability gaps rather than instructional effects. Establishing baseline equivalence strengthens the internal validity of the quasi-experimental design and supports subsequent causal interpretation of the treatment outcomes (Creswell, 2014).

Following the instructional intervention, posttest results revealed a marked divergence in learning outcomes between the two groups. Students exposed to the UDL-based digital learning environment demonstrated substantially higher posttest scores than those in the conventional learning condition. This improvement suggests that the integration of UDL principles, particularly multimodal representation and flexible learning pathways, enhanced students' ability to process, organize, and apply complex taxonomic concepts. In contrast, although the control group also exhibited progress, the magnitude of improvement remained comparatively limited, reflecting the constraints of lecture-centered and memorization-oriented instruction in facilitating deep conceptual understanding (Rao et al., 2014; Rogers-Shaw et al., 2018).

Intra-group analyses further clarify the nature of learning gains within each instructional condition. The experimental group experienced a very large pretest–posttest effect, indicating that the UDL-digital intervention was not only statistically effective but also educationally meaningful. This substantial gain reflects the cumulative impact of accessible learning materials, active engagement, and opportunities for digital expression embedded within the instructional design. Meanwhile, the control group's moderate improvement suggests that traditional instruction can still support learning progression, albeit less effectively, particularly for cognitively demanding content such as invertebrate classification and morphological differentiation.

The superiority of the UDL-based intervention was further confirmed through inter-group analysis using ANCOVA, which controlled for pretest scores and isolated the instructional effect of the treatment. The large effect size indicates that the observed differences were not trivial but represented a strong pedagogical impact. This conclusion is reinforced by normalized gain analysis, which demonstrated that students in the experimental group achieved medium-to-high conceptual gains, while those in the control group attained only low gains. Collectively, these findings indicate that integrating Universal Design for Learning with digital competence-oriented activities fosters deeper conceptual understanding of invertebrate taxonomy among biology education students, moving learning beyond surface-level recall toward more meaningful and transferable scientific knowledge.

The findings demonstrate a substantial enhancement of digital competence among students in the experimental group following the implementation of UDL-based digital learning. The very large effect size observed indicates that the intervention did not merely improve surface-level technological familiarity but significantly strengthened students' ability to use digital tools for academic and scientific purposes. This outcome aligns with the study's conceptual framework, which positioned digital competence as an integral learning outcome rather than a supplementary skill. In contrast, the control group's modest improvement suggests that conventional instruction, even when supported by basic digital tools such as presentation slides, is insufficient to foster advanced digital competence required in contemporary biology education.

Based on Table 4, digital competence exhibited marked enhancement in the experimental group (pre: $M = 3.12$, $SD = 0.56$; post: $M = 4.23$, $SD = 0.42$; $t(26) = 9.45$, $p < 0.001$, $d = 1.89$, large effect), while the control group showed minimal progress (pre: $M = 3.08$, $SD = 0.61$; post: $M = 3.45$, $SD = 0.58$; $t(26) = 2.34$, $p = 0.027$, $d = 0.51$, medium effect). DigComp 2.0-dimensional analysis (Carretero et al., 2017) highlighted greatest gains in content creation ($\Delta M = 1.45$) and information literacy ($\Delta M = 1.32$), with digital portfolio scores averaging 4.1/5 ($SD = 0.38$) per rubric assessment.

A closer examination using the DigComp 2.0 framework reveals that the most pronounced gains occurred in the dimensions of content creation and information literacy. These improvements reflect the design of UDL-based tasks that required students to actively produce digital artifacts, such as infographics, micro-videos, and digital taxonomy catalogs, rather than passively consume instructional materials. Through these activities, students were repeatedly engaged in searching for credible scientific sources, evaluating data accuracy, synthesizing information, and communicating biological concepts in ethical and visually coherent digital formats. This finding supports prior research emphasizing that digital competence develops most effectively when embedded within authentic disciplinary practices rather than taught as isolated technical skills (G. Carretero et al., 2017; Ferrari, 2013; Vuorikari et al., 2016).

The high quality of digital portfolios produced by the experimental group further substantiates the effectiveness of the UDL–digital competence integration. Portfolio scores indicate that students were able to meet scientific accuracy standards while also demonstrating creativity, digital ethics, and appropriate use of online biodiversity databases. From a pedagogical perspective, this outcome illustrates how UDL's principle of multiple means of action and expression creates equitable opportunities for students with diverse strengths to demonstrate learning through varied digital modalities (AlRawi & AlKahtani, 2022; Hyatt & Owenz, 2024; Kirsch & Luo, 2023). By allowing choice in task formats, the learning environment reduced barriers associated with uniform assessment methods and encouraged deeper engagement with both content and technology.

Based on Table 5, classroom engagement (FLAS rubric: Fredricks et al., 2016) recorded a 42% increase in the experimental group (pre: $M = 2.8/5$, $SD = 0.7$; post: $M = 4.2/5$, $SD = 0.5$; $t(26) = 9.87$, $p < 0.001$) versus 18% in controls (pre: $M = 2.7/5$, $SD = 0.8$; post: $M = 3.2/5$, $SD = 0.6$; $t(26) = 2.89$, $p = 0.008$). Beyond digital competence, classroom engagement outcomes provide complementary evidence of the intervention's effectiveness. The substantial increase in engagement levels within the experimental group suggests that UDL-based digital learning successfully addressed motivational and affective dimensions of learning that are often overlooked in traditional taxonomy instruction. Gamification elements, interactive platforms, and contextual relevant tasks appear to have enhanced students' focus, participation, and willingness to contribute during learning activities. In contrast, the relatively modest engagement gains in the control group reflect the limitations of lecture-centered approaches in sustaining active involvement. Together, these findings indicate that integrating UDL with digital competence not only enhances students' technical capabilities but also fosters a more engaging and inclusive learning environment, which is essential for complex and conceptually demanding subjects such as invertebrate taxonomy (Baybayon, 2021; Kirsch & Luo, 2023; Nasri et al., 2021).

Table 1. Normality Test

Variable	Group	Sig. (p-value)	Interpretation
Conceptual mastery	Experimental	0.421	Data is normally distributed
	Control	0.553	
Digital Competence	Experimental	0.318	
	Control	0.384	
Class engagement	Experimental	0.487	
	Control	0.365	

Table 2. Homogeneity Test

Variable	Group Comparison	F statistic	Levene's Test Sig.
Conceptual mastery	Experimental vs Control	0.45	0.504
Digital competence	Experimental vs Control	0.67	0.416
Class engagement	Experimental vs Control	0.32	0.573

Table 3. Baseline Equivalence and Main Effects Analysis (Conceptual Mastery)

Analysis Type	Group n=27	M	SD	t/F statistic	df	p-value	Effect Size	Interpretation
Pretest (Independent t-test)	Experimental	68.45	9.23	t = 0.32	52	0.752	-	No significant difference (equivalent)
	Control	67.92	9.67					
Posttest Means	Experimental	85.67	7.45	-	-	-	-	-
	Control	74.23	8.92	-	-	-	-	-
Paired t-test (Intra-group)	Experimental	-	-	t = 8.67	26	<0.001	d = 1.62 (large)	Significant gain
	Control	-	-	t = 3.21	26	0.004	d = 0.61 (medium)	Significant gain
ANCOVA (Inter-group)	Combined	-	-	F = 28.45	1.51	<0.001	η^2 = 0.32 (large)	UDL superiority

Table 4. Digital Competence Analysis Summary

Analysis Type	Group n=27	Pre M ± SD	Post M ± SD	t statistic	df	p-value	Cohen's d	Interpretation
Paired t-test (Intra-group)	Experimental	3.12 ± 0.56	4.23 ± 0.42	9.45	26	<0.001	1.89 (large)	Marked enhancement
	Control	3.08 ± 0.61	3.45 ± 0.58	2.34	26	0.027	0.51 (medium)	Minimal progress
DigComp Dimensions (ΔM)	Content Creation	-	-	-	-	-	1.45	Greatest gain
	Information Literacy	-	-	-	-	-	1.32	Greatest gain
Portfolio Assessment	Experimental	-	4.1 ± 0.38	-	-	-	-	Rubric average

Table 5. Classroom Engagement Analysis (FLAS Rubric)

Analysis Type	Group	n	Pre M ± SD	Post M ± SD	% Increase	t statistic	df	p-value	Interpretation
Paired t-test (intra-group)	Experimental	27	2.8 ± 0.7	4.2 ± 0.5	42%	9.87	26	<0.001	Large improvement
	Control	27	2.7 ± 0.8	3.2 ± 0.6	18%	2.89	26	0.008	Moderate improvement

The thematic analysis of data collected from semi-structured interviews with selected students and perception questionnaires administered to all participants revealed rich and contextualized insights into students' learning experiences during the UDL–digital intervention. A very high proportion of positive responses indicates that most students perceived the learning design as meaningful, accessible, and supportive of their learning needs. The convergence of findings from interviews, questionnaires, classroom observations, and digital portfolios strengthened the credibility of the qualitative results through methodological triangulation, ensuring that the themes reflected shared experiences rather than isolated opinions.

Collectively, the three themes illustrate how the implementation of UDL principles (CAST, 2018; Dean et al., 2017) reshaped invertebrate taxonomy learning by reducing access barriers, increasing active participation, and enhancing relevance for pre-service biology teachers. Students' accounts revealed that multimodal content, flexible modes of expression, and engaging digital activities enabled them to move beyond rote memorization toward deeper conceptual understanding and meaningful scientific communication. These qualitative insights help explain the large quantitative gains observed in conceptual mastery, digital competence, and classroom engagement, particularly within the context of a resource-constrained university in Eastern Indonesia. By illuminating the learning processes behind the statistical outcomes, the qualitative findings contribute a nuanced understanding of how UDL-based digital learning operates in practice and underscore its potential as an inclusive pedagogical approach in higher science education (Baybayon, 2021; Creswell, 2014; Lawshe, 1975; Lohmann et al., 2018).

The first theme highlights how multimodal representation significantly enhanced accessibility and comprehension in learning invertebrate taxonomy. A large majority of students reported that the combination of text, high-quality images, videos, and three-dimensional animations helped transform abstract and terminology-heavy content into concrete and understandable concepts. The use of locally relevant examples, such as Papua invertebrate species, further strengthened meaning-making by connecting scientific concepts to students lived environments (Nurbaya et al., 2022). Students emphasized that visualizing morphological structures and segmentation patterns allowed them to construct mental models more effectively, reducing reliance on rote memorization and supporting deeper conceptual understanding (Agbo, 2015; Nurbaya, 2023). This finding is consistent with Mayer's cognitive theory of multimedia learning, which posits that well-designed multimodal representations can reduce extraneous cognitive load while enhancing germane processing, particularly for complex scientific content. In contrast, students in the control group, who primarily relied on static PowerPoint slides, continued to experience difficulties in understanding spatial relationships among anatomical features across different phyla. These challenges underscore the limitations of single-mode instructional approaches in taxonomy learning and reinforce the pedagogical advantage of UDL's multiple means of representation. By accommodating diverse perceptual and cognitive preferences, multimodal instruction proved more effective in supporting inclusive access to taxonomic morphology concepts (Garrison & Cleveland-Innes, 2005; Kilis & Yıldırım, 2019; Rao et al., 2015).

The second theme illustrates how flexibility in digital expression substantially enhanced students' creativity and self-efficacy, particularly among those who initially demonstrated lower academic performance. Allowing students to choose how they demonstrated their understanding, through infographics, short videos, or digital catalogs, encouraged active knowledge construction rather than passive content reproduction. Many students reported that designing digital products related to Eastern Indonesian biodiversity required them to integrate morphological characteristics, classification criteria, and ecological relevance, fostering a sense of ownership over their learning. This autonomy helped shift students' self-perception from exam-oriented learners to emerging biologists capable of communicating scientific knowledge meaningfully. Evidence from portfolio analysis further supports this finding, as most student-produced artifacts met rigorous scientific standards, including high taxonomic accuracy and the use of credible international databases such as WoRMS and iNaturalist. These outcomes align with the UDL principle of Multiple Means of Action and Expression, which emphasizes reducing barriers by offering varied pathways for demonstrating learning (CAST, 2018). From a motivational perspective, the opportunity to experience mastery through flexible digital production aligns closely with self-efficacy theory, where successful task completion strengthens confidence and persistence (E. Moreira-Fontán et al., 2019; O. E. Hatlevik et al., 2018; S. Wang et al., 2023). For pre-service science teachers, these mastery experiences are particularly critical, as they simultaneously reduce technology-related anxiety and cultivate positive beliefs about their capacity to integrate digital tools into future classroom practice (Çebi & Reisoğlu, 2020; Instefjord & Munthe, 2017; Pérez-Rodríguez & Delgado-Ponce, 2012).

The third theme underscores the powerful role of gamification and LMS-supported collaboration in fostering intrinsic motivation among students participating in the UDL-digital intervention (Baybayon, 2021; Czerkawski & Lyman, 2016; Dean et al., 2017). Gamified elements such as leaderboards, badges, and weekly quizzes reframed routine content review into meaningful and enjoyable challenges, especially when tasks were contextualized using locally relevant invertebrate examples. Students reported increased study frequency and persistence, indicating that competitive yet low-stakes gamification encouraged consistent engagement with complex taxonomy content. By linking achievement to authentic outputs, such as local mangrove invertebrate catalogs, learning became both personally relevant and academically purposeful. Learning management system analytics further corroborated these perceptions, revealing substantially higher levels of peer interaction and sustained participation in the experimental group compared to controls. The emergence of interest-based discussion threads allowed students to connect ecological concepts with real-world and socio-economic contexts, strengthening peer learning and knowledge co-construction. These findings strongly align with Self-Determination Theory (Ryan & Deci, 2000; C. Wang et al., 2022), as the intervention supported students' needs for autonomy through task choice, competence through visible progress indicators, and relatedness via collaborative forums. In combination, these motivational supports contributed to deeper and more sustained engagement, reinforcing evidence that UDL-aligned gamification within LMS environments is particularly effective for challenging STEM content in pre-service teacher education contexts (Cabero-Almenara et al., 2019; FitzGerald et al., 2018; Hyatt & Owenz, 2024).

Contextual adaptation emerged as a cross-cutting sub-theme, with 72% of experimental students appreciating localized content. "iNaturalist integration let us identify actual Jayapura market invertebrates—taxonomy felt relevant to future teaching in Papua schools" (Questionnaire #23). This culturally responsive approach addresses equity gaps in Indonesian teacher education, where one-size-fits-all methods disadvantage regional learners. Control group frustration with decontextualized memorization ("Why memorize global species when we teach local biodiversity?") underscores UDL's Multiple Means of Engagement for motivationally diverse classrooms (Gronseth et al., 2020).

Portfolio quality analysis offered concrete, artifact-level evidence of the pedagogical impact of the UDL–digital intervention. Students in the experimental group consistently produced higher-quality learning products across multiple formats, with infographics, videos, and digital catalogs all achieving mean rubric scores above 4.0 out of 5. These artifacts demonstrated strong scientific accuracy, thoughtful visual organization, and appropriate digital ethics, including proper attribution and the use of credible data sources. In contrast, learning products from the control group—primarily traditional written essays—received notably lower scores, indicating more limited synthesis, weaker visual communication, and less evidence of higher-order digital competence.

This clear shift from passive content reception to active scientific communication illustrates UDL's transformative potential in preparing pre-service biology teachers for contemporary learning environments. By engaging students in authentic, multimodal knowledge construction, the intervention supported not only conceptual understanding but also professional identity development as future educators and science communicators (G. Carretero et al., 2017; S. Carretero et al., 2017). Methodological rigor was ensured through established trustworthiness strategies, including member checking with high confirmation rates, triangulation across qualitative and quantitative instruments, and systematic audit trail documentation (Creswell, 2014; Miles et al., 2014). Together, these procedures strengthen the credibility and dependability of the findings, reinforcing the conclusion that UDL-based digital pedagogy yields meaningful and verifiable improvements in both learning processes and outputs.

These qualitative insights help clarify the mechanisms underlying the strong quantitative outcomes observed in this study. Multimodal access to content, particularly through visuals, animations, and locally contextualized examples, provides a plausible explanation for the substantial conceptual learning gains achieved by the experimental group (normalized gain $g = 0.62$). By reducing cognitive load and supporting multiple pathways for meaning-making, UDL-based representations enabled students to engage more deeply with complex invertebrate taxonomy concepts. This alignment between students lived experiences and scientific content appears to be a key factor driving the observed improvements in conceptual mastery. Similarly, the flexibility in modes of expression inherent in the UDL framework helps explain the large gains in digital competence ($d = 1.89$) and the marked increase in classroom engagement as measured by the FLAS rubric (42% gain). Opportunities to choose digital formats empowered students to demonstrate understanding creatively while building confidence in their technological abilities, while gamified and collaborative LMS features sustained motivation and active participation. Collectively, these findings extend existing UDL literature by demonstrating its effectiveness when explicitly integrated with digital competence frameworks in STEM teacher education within developing-country contexts. Importantly, the study offers a transferable and practical instructional model for resource-limited institutions such as FKIP Cenderawasih University, where inclusive, technology-enhanced pedagogy is both necessary and impactful (Ghomi & Redecker, 2019; Redecker, 2017).

Conclusion

This study demonstrates that implementing Universal Design for Learning (UDL) integrated with digital competence significantly enhances conceptual mastery, digital skills, and classroom engagement among third-semester Biology Education students at FKIP Cenderawasih University. The quasi-experimental design revealed large effect sizes across all measures, with normalized gains confirming deeper learning compared to conventional methods. Qualitative themes—multimodal accessibility, flexible digital expression, and gamified motivation—elucidate how UDL's three principles address taxonomy learning challenges in resource-constrained contexts, validating the UDL–DigComp hybrid model for STEM teacher preparation. These findings offer practical implications for Indonesian biology education: integrating multimodal content in taxonomy curricula, implementing digital portfolios as key assessments, and leveraging LMS-based gamification to enhance engagement. While limited by a relatively small sample size and short intervention duration, the results advocate scaling UDL–digital approaches across FKIP programs to prepare inclusive, digitally proficient teachers for Papua's diverse classrooms. Future longitudinal studies should explore sustained impacts on teaching practice and student biodiversity learning outcomes.

Acknowledgments
The author would like to thank the Head of the Biology Education Study Program at Universitas Cenderawasih for their support in this research.

Author Contributions
Conceptualization, methodology, validation, formal analysis, writing—original draft preparation, writing—review and editing, visualization, supervision, project administration, NN. The author has read and agreed to the published version of the manuscript.

Conflicts of Interest
The authors declare no conflict of interest.

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