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Research Article

Integrating Universal Design for Learning Principles in Chemistry Education

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Abstract
Universal Design for Learning (UDL) is a transformative educational framework for creating inclusive and equitable learning environments. Studies have documented its effectiveness in school chemistry education, particularly in improving accessibility and engagement. This study supported the understanding and application of UDL through a practice-based professional development programme for secondary school chemistry teachers teaching grades IX to XII using open educational resources (OERs) on atomic structure and organic chemistry, specifically designed in alignment with the principles of UDL. Teachers were given six weeks per module to engage with the content and apply UDL principles in their classrooms to improve instructional practices. The study investigated teachers' understanding and application of UDL principles using pre-test and post-test assessments, lesson plan evaluations, classroom observations, and interviews. Test results showed that the intervention improved teachers' UDL competencies, with remarkable gains in content representation in both the modules and student engagement through multiple strategies in atomic structure. However, the improvement in engaging students through multiple strategies during organic chemistry lessons and the use of multiple assessment methods across both modules was smaller, indicating a need for additional support in these areas. Lesson plans and reflection reports showed high proficiency in content representation and student engagement in both modules, and creating multiple means of expression in organic chemistry, but moderate proficiency in creating diverse opportunities for expression in the atomic structure module. This study emphasises the effectiveness of integrating UDL-based OERs into professional development initiatives for secondary school chemistry teachers. Such integration not only strengthens teachers' instructional practices but also contributes to building more inclusive classrooms that accommodate diverse learners' needs. Accordingly, this study recommends supporting teachers' professional development programmes using UDL-based OERs to enhance their instructional practices and inclusive and equitable learning environments in chemistry education and beyond.

Keywords: Chemistry Teachers, Professional Development, Secondary Schools, Universal Design For Learning

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1. INTRODUCTION

Universal Design for Learning (UDL) has been recognised as a transformative educational framework for creating accessible, inclusive, and equitable learning environments and plays a crucial role in meeting the diverse needs of all students with and without special educational needs (SEN) (Center for Applied Special Technology [CAST], 2021; Rose & Meyer, 2002). The UDL framework emphasises three principles, namely multiple means of representation, multiple means of engagement, and multiple means of expression, which aim to create inclusive learning environments by providing multiple ways to access information, engage with content, and express learning (CAST, 2018, 2024). The principle of multiple means of representation emphasises presentation of content or information in multiple formats, such as visual aids, auditory materials, kinesthetic and interactive resources to accommodate diverse learning

preferences and needs, ensuring that all learners have equitable access and comprehension of the instructional materials (Carrington et al., 2020; CAST, 2024; Nave, 2021; Van Boxtel & Sugita, 2022). The multiple means of engagement focus on stimulating learners' interest and motivation by engaging them in a variety of activities such as individual projects, role play, pair work, group discussion, collaborative tasks, hands-on experiments, and problem-solving activities to sustain meaningful engagement with the learning process (CAST, 2024; Rose & Meyer, 2002). The multiple means of expression involve providing students with multiple options to demonstrate their learning, such as through models, prototypes, written reports, oral presentations, or visual and creative outputs, thereby accommodating diverse strengths in expressing what they have learned (Carrington et al., 2020; CAST, 2024; Lambert et al., 2021).

Since UDL is rooted in fostering accessibility and inclusivity, it is increasingly being applied in different educational contexts, including secondary schools (King-Sears et al., 2015; Marino et al., 2014), higher education (Griful-Freixenet et al., 2017; Kumar & Wideman, 2014), professional development for in-service teachers (Craig et al., 2022), and teacher education programmes (Whinnery et al., 2020). UDL enables a flexible approach to education that gives all learners an equal opportunity for success by reducing barriers to instruction, encouraging active engagement through adaptive learning activities, and providing multiple opportunities to express understanding (Craig et al., 2022; King-Sears & Johnson, 2020). The UDL approach is also adopted by educators across various disciplines, including mathematics (Lambert et al., 2021), language (Doran, 2015), and science classes (Marino et al., 2014), as an effective strategy for promoting equity and inclusion, particularly within the context of teaching prescribed curricula.

UDL is also relevant in chemistry education, where learning complex and abstract concepts poses significant challenges to diverse student groups (Easa & Blonder, 2024; Holländer & Melle, 2023). Chemistry is often perceived as a challenging and "gatekeeper" subject due to its abstract and complex nature, usually deterring students from pursuing science in higher education and future careers (Barr et al., 2008; Johnstone, 2010). In the context of chemistry education, UDL has been explored as an approach to make it more inclusive and effective for students with diverse learning needs (Baumann & Melle, 2019; King-Sears et al., 2015; King-Sears & Johnson, 2020; Michna & Melle, 2018). Likewise, studies have documented the effectiveness of UDL in school chemistry classes, particularly in increasing the accessibility of materials and fostering student engagement and understanding (Baumann & Melle, 2019; King-Sears et al., 2015; King-Sears & Johnson, 2020). The use of digital multimedia learning environments designed with UDL principles has been effective in improving students' understanding of chemical reactions (Baumann & Melle, 2019). Holländer and Melle (2023) have developed *ChemDive*, a lesson-planning model for chemistry teachers that integrates UDL principles to enhance accessibility and inclusivity in chemistry instruction for diverse learners. Likewise, Miller and Lang (2016) have reported that applying UDL-oriented approaches such as fostering open-mindedness, promoting supportive communication, and adapting curricula significantly enhances students' learning outcomes in science laboratories by reducing stress levels.

Bhutan, a small Himalayan Asian country, provides free education from early childhood to university level and scholarships to pursue postgraduate studies on a merit basis both within the country and abroad (Rai et al., 2021). Despite these inclusive and equitable policy measures, the Bhutanese Education System (BES) has traditionally followed a one-size-fits-all model with limited differentiation in curriculum and assessment methods and classroom practices to accommodate the diverse learning needs of students, including those with disabilities (Dorji & Schuelka, 2016; Subba et al., 2019). The rigid and content-laden curriculum limits flexibility in instructional approaches and constrains the use of alternative assessment methods (Chanbanchong et al., 2010). Additionally, the BES primarily relies on high-stakes, standardised examinations to promote students through successive grade levels (Dorji, 2023; Rai et al., 2021), which may not accommodate the varied abilities and learning styles of all students. The majority of Bhutanese teachers also lack specialised training in inclusive education, limiting their capacity to effectively address diverse learning needs and promote inclusion and equity within the classroom (Chanbanchong et al., 2010; Chhetri et al., 2023; Sakurai, 2017). Furthermore, teacher education programmes in Bhutan also lack adequate content and emphasis on preparing future teachers to understand and apply the principles and practices of inclusive education (Chhetri et al., 2023).

The above-mentioned systemic gaps, including rigid and content-laden curriculum, reliance on standardised assessment methods, limited specialised training for teachers in inclusive education, and insufficient opportunities for adopting inclusive pedagogies, are particularly evident in chemistry education in Bhutan. Chemistry is widely perceived as a difficult and abstract subject in Bhutan due to a combination

of educational, psychological, and resource challenges (Chogyel & Wangdi, 2021; Penjor et al., 2019; Rai et al., 2025; Utha et al., 2023). The chemistry curriculum is voluminous and content-laden, which limits teachers from using innovative and scientific inquiry pedagogies (Penjor et al., 2019). Chhetri et al. (2022) have also reported that the primary cause of anxiety among higher secondary school students, which negatively impacts their academic performance, is the heavy content and rigid structures of the chemistry syllabus. Likewise, teachers have to shoulder heavy teaching loads, which limit them in implementing innovative pedagogies, conducting practical classes, and adopting inclusive teaching practices (Chogyel & Wangdi, 2021).

In response to the challenges of chemistry education in Bhutan, a professional development programme leveraging Open Educational Resources (OERs) designed using UDL principles was developed for secondary school chemistry teachers, covering two key topics: atomic structure and organic chemistry. As part of the professional development, teachers received training on lesson planning, instructional strategies, and assessment grounded in the UDL principles. Teachers were required to engage with the modules, complete embedded learning tasks, and apply the acquired UDL knowledge and skills in their classroom practices.

1.1. Research Questions

This study aimed to investigate how effectively chemistry teachers integrate UDL principles into their teaching practices using the designed OERs. To comprehensively address this overarching aim, the study was further structured around the following sub-questions:

1. How did professional development using Open Educational Resources enhance teachers' understanding of Universal Design for Learning principles?
2. How did professional development with Universal Design for Learning-based Open Educational Resources influence teachers' instructional practices in the classroom?

2. METHODS

2.1. Designing Open Educational Resources

In alignment with the National Curriculum Framework of BES, OERs on atomic structure and organic chemistry were collaboratively developed by chemistry teacher educators of Samtse College of Education (SCE) and curriculum developers from the Department of School Education, Ministry of Education and Skills Development (MoESD). The foundational design of OERs was based on the three core principles of UDL, emphasising how teachers can: (1) represent content in multiple ways, (2) engage students through diverse methods, and (3) provide multiple opportunities for students to express their learning. The primary objective of the OERs was to strengthen teachers' Knowledge, Attitudes, and Practice (KAP) for promoting inclusion and equity in their classroom practices.

2.2. Sample and Sampling

The study adopted a purposive sampling strategy as secondary chemistry school teachers were the target group. SCE, in collaboration with the MoESD, jointly developed the selection criteria that focused on teaching experience, leadership qualities, and commitment to promoting chemistry education in Bhutan's secondary schools. A total of 38 secondary chemistry school teachers who met the criteria were selected for professional development. Each teacher was assigned a four-digit numerical identifier, such as 5071, for anonymising, tracking progress, and record-keeping purposes.

2.3. Orientation Workshop on Universal Design Learning

A face-to-face workshop was organised to orient teachers with the basic knowledge and application of UDL. The key objectives of the workshop were to: introduce the principles of UDL; demonstrate their

application in learning and teaching chemistry; guide teachers in designing lesson plans incorporating UDL principles; and encourage reflection on student learning barriers and strategies to overcome them.

During the workshop, teachers engaged in interactive activities, explored case studies, and participated in discussions on integrating UDL principles into chemistry topics. Practical sessions included examples of presenting content on some chemistry topics through various means, such as images, interactive simulations, videos, textual descriptions, physical models, songs, and locally available resources. Teachers were also trained to engage students in multiple ways and provide various opportunities to demonstrate their learning in diverse ways, such as presentations, drawings, role plays, writings, exit slips, question and answer sessions, etc.

2.4. Data Collection

After the orientation workshop, teachers returned to their schools and were given six weeks to complete one OER, during which they applied UDL principles in their classroom practices while teaching content related to the module. A combination of quantitative and qualitative tools was employed to measure the teachers' knowledge, understanding, and integration of the UDL principles in classroom practices. Quantitative data was collected through pre-tests and post-tests, comprised of fifteen multiple-choice questions in the OER modules designed to assess teachers' knowledge and understanding of UDL principles and their applications. Qualitative data were collected through pre- and post-interviews on teachers' perceptions, experiences, and challenges in implementing UDL. Additionally, teachers submitted two lesson plans per module incorporating UDL principles, along with a reflection report following the implementation of the lesson plans. These reflection reports provided insights into the teachers' understanding, strategies used during implementation, and challenges faced. Both the lesson plans and reflection reports were quantitatively assessed to evaluate how effectively teachers integrated UDL strategies into their instructional practices.

2.5. Data Analysis

Quantitative data from the pre-tests and post-tests were analysed using descriptive statistics to compare the mean and standard deviation between the pre-test and post-test. Cohen's *d* test was used to quantify the effect size between the pre-test and post-test scores. Likewise, scores from lesson plans and reflection reports were analysed using descriptive statistics, mean, and standard deviation. The interview data were transcribed, deductively coded, and thematically analysed using the approach outlined by Clarke and Braun (2017).

3. RESULTS

3.1. Teacher Participants Demographics

A total of 38 chemistry teachers teaching at middle (till class X) and higher (till class XII) secondary schools were recruited for professional development. Table 1 presents the demographics of these teachers, detailing their gender, academic qualifications, subject of specialisations, professional teaching experience, and ownership of electronic devices. The availability of ICT devices, including laptops and smartphones, was investigated to ensure teachers had access to the OERs and technology whenever required.

Among the 38 chemistry teachers who participated, eight were female, and 30 were male, indicating a gender imbalance. Of the 38 chemistry teachers, 17 teachers held Masters of Education (M.Ed.) in chemistry, eight held a Bachelor of Education (B.Ed.), seven held Postgraduate Diploma in Education (PgDE), five held a Master of Science (M.Sc.) in chemistry, and one had a Master of Arts (M.A.) with a B.Ed. in chemistry.

All the teachers had received formal teaching training within Bhutan. Around 29 teachers had school experience between six to fifteen years, while six teachers had five or less than five years of school experience. Only 3 had school experience of more than sixteen years. All the teachers (100%) owned both laptops and smartphones, indicating strong electronic device accessibility. Regarding the teacher

participants' proficiency in the use of ICT, 33 teachers were in the intermediate group, three teachers were just beginners, and two were proficient.

Table 1. Background Information on Teachers (n = 38)

Particulars	Category (Number and Percentage)
Gender	Male (n = 30; 79%)
	Female (n=8; 21%)
Academic qualification and subject of specialisation	In-service:
	PgDE Chemistry (n = 7)
	PgDE, M.Sc. Chemistry (n = 5)
	B.Ed., M.Ed. Chemistry (n = 17)
	B.Ed. Chemistry (n=8)
	B.Ed., Chemistry, M.A. (1)
Professional teaching experience	0-5 years: 6
	6-10 years:15
	11-15 years:14
	16-20 years: 2
	Above 20 years:1
Electronic devices owned	Laptop (100%)
	Smartphone (100%)
ICT Proficiency	Beginner:3
	Intermediate:33
	Proficient:2

3.2. Pre-Test and Post-Test Results

Table 2 below presents the results of the pre-tests and post-tests embedded within the OER modules. The module comprised 15 multiple-choice questions aimed at evaluating teachers' knowledge and understanding of UDL principles and their implementation.

Table 2. Pre-Test and Post-Test Results in Atomic Structure

	UDL Competencies	Tests	Mean	SD	Change in Mean	Change in SD	Effect Size (d)
1.	Evaluating resources for multiple ways of representing content	Pre-test	0.70	0.13			Medium
		Post-test	0.76	0.11	0.06	-0.02	(0.5)
2.	Selecting instructional strategies to support multiple forms of student engagement	Pre-test	0.82	0.12			Medium
		Post-test	0.90	0.11	0.08	-0.01	(0.7)
3.	Choosing multiple tools of assessment to encourage multiple means of expression	Pre-test	0.83	0.11			Small
		Post-test	0.85	0.12	0.02	-0.01	(0.2)

Note: Cohen's d interpretation: $d<0.2$ (very small effect), $0.2 \leq d<0.5$ (small effect), $0.5 \leq d<0.8$ (medium effect), $d \geq 0.8$ (large effect).

The pre-test and post-test scores for UDL competencies in the OER on atomic structure are shown in Table 2. UDL competency 1, which investigated teachers' ability to evaluate resources for representing content in multiple forms, demonstrated a positive impact from the intervention. The mean score increased from 0.70 (SD = 0.13) on the pre-test to 0.76 (SD = 0.11) on the post-test, reflecting a meaningful medium effect size (0.5) as indicated by Cohen's d-test. UDL competency 2, which investigated teachers' ability to select instructional strategies that support various forms of student engagement, showed a positive impact from the intervention. The mean score increased from 0.82 (SD = 0.12) on the pre-test to 0.90 (SD = 0.11) on the post-test, indicating an improvement in this competency. Cohen's d test revealed a medium effect size (0.7), highlighting the effectiveness of the intervention in enhancing this skill. UDL competency 3, which investigated teachers' ability to select various assessment tools to support multiple means of student expression, showed a positive impact from the intervention. The mean score increased from 0.83 (SD = 0.11) on the pre-test to 0.85 (SD = 0.12) on the post-test, reflecting a small improvement in this

competency. Likewise, Cohen's d test also indicated a small effect size (0.2), suggesting that additional support may be needed to help teachers offer students more flexible options for expressing their learning.

Table 3. Pre-Test and Post-Test Results in Organic Chemistry

UDL Competencies	Tests	Mean	SD	Change in Mean	Change in SD	Effect Size (d)
1. Evaluating resources for multiple forms of representing content	Pre-test	0.58	0.14	0.07	0.12	Medium (0.6)
	Post-test	0.65	0.10			
2. Selecting instructional strategies to support multiple forms of student engagement	Pre-test	0.68	0.12	0.03	0.12	Small (0.3)
	Post-test	0.71	0.12			
3. Choosing multiple tools of assessment to encourage multiple means of expression	Pre-test	0.73	0.13	0.04	0.14	Small (0.3)
	Post-test	0.77	0.14			

The pre-test and post-test scores for UDL competencies in the OER on organic chemistry are shown in Table 3. UDL competency 1, which investigated teachers' ability to evaluate resources for representing content in multiple forms, demonstrated a positive impact from the intervention. The mean score increased from 0.58 (SD = 0.14) on the pre-test to 0.65 (SD = 0.10) on the post-test, indicating a medium effect size (0.6) as indicated by Cohen's d test. UDL competency 2, which investigated teachers' ability to select instructional strategies that support various forms of student engagement, showed a positive impact from the intervention. The mean score increased from 0.68 (SD = 0.12) on the pre-test to 0.71 (SD = 0.12) on the post-test. Cohen's d test revealed a small effect size of 0.3. UDL competency 3, which investigated teachers' ability to select various assessment tools to support students in expressing their learning in multiple ways, showed a positive impact from the intervention. The mean score increased from 0.73 (SD = 0.13) on the pre-test to 0.77 (SD = 0.14) on the post-test, reflecting a small improvement in this competency. Cohen's d test also indicated a small effect size (0.3).

The implementation of the three UDL principles was investigated using lesson plans and reflection reports, and the consolidated mean and standard deviation for these assessments are presented in Table 4.

Table 4. Evaluation of UDL principles through lesson plans and reflections

UDL Competencies	Lesson plans and reflection reports on atomic structure OER		Lesson plans and reflection reports on organic chemistry OER	
	Mean	SD	Mean	SD
1. Use of multiple representations of content	1.82	0.32	1.93	0.2
2. Use of instructional strategies for multiple forms of student engagement	1.89	0.26	1.87	0.2
3. Create opportunities for multiple means of expression	1.67	0.39	1.78	0.3

Note: Mean levels 1.00 - 1.24 Low; 1.25 - 1.74 Moderate; 1.75 - 2.00 High

The UDL competency, *'Use of Multiple Representations of Content'*, emphasises the importance of presenting content in diverse formats to accommodate various learning styles and foster a deeper understanding of concepts. Teachers exhibited a high level of proficiency in applying this competency, as reflected in their use of multiple representations of content in the OERs atomic structure (M = 1.82, SD = 0.32) and organic chemistry (M = 1.93, SD = 0.20). The UDL competency, '*Use of Instructional Strategies for Multiple Forms of Student Engagement'*, emphasises the importance of engaging students in active learning activities that foster critical thinking, problem-solving, and creativity. Teachers demonstrated a high level of proficiency in employing these strategies within the modules atomic structure (M = 1.89, SD = 0.26) and organic chemistry (M = 1.87, SD = 0.20). The UDL competency, *'Creating Opportunities for Multiple Means of Expression'*, emphasises the importance of allowing students to demonstrate their understanding through various means such as presentation, writing, drawing, problem-solving, question and answer, or conducting experiments. Teachers demonstrated a high level of proficiency in implementing this competency, as

evidenced by their use of multiple means of expression in the OERs atomic structure (M = 1.67, SD = 0.39) and organic chemistry (M = 1.78, SD = 0.30).

3.3. Selecting Resources for Content Representation

The findings from pre- and post-interviews conducted to examine teachers' application of UDL principles in their classrooms are organised into three key themes: selecting resources for content representation, engaging students in chemistry classes, and assessing students' learning. When selecting materials, teachers considered the availability of resources in the chemistry laboratory, locally accessible materials, and opportunities for technological integration. During baseline, teachers identified the chemistry laboratory as their primary source of teaching resources, while at the end line, they demonstrated a shift from focusing solely on laboratory materials to a broader and more practical and creative approach to selecting resources. Teachers improvised and utilised locally available resources to make abstract concepts more relatable and practical for students. For example, Teacher 5040 creatively used locally available fruits as shown in Figure 1 to teach the names of elements, providing a practical way for students to understand the arrangement of elements in the periodic table.

Figure 1. Locally Available Fruits Labeled as Elements

A key challenge identified by Teacher 5070 was the heavy reliance on textbooks as the primary source of teaching materials due to inadequately equipped chemistry laboratories. This limitation was attributed to the discontinuation of chemistry practical examinations in board assessments in class XII. Additionally, the teacher reported that the limited budget hampered the procurement of necessary equipment and chemicals.

The use of technology became more prominent by the end line. In the baseline, teachers mentioned using tools such as PowerPoint presentations, smart televisions, projectors, and curated videos. By the end line, they integrated advanced technologies such as virtual labs and online PhET simulations. For instance, Teacher 5044 stated, "I used video simulations to improve students' conceptual understanding to demonstrate how electrons fill orbitals according to the Aufbau principle, Hund's rule, and Pauli's exclusion principle." The practice of combining simulations and virtual labs with laboratory demonstrations was widely used to help students bridge the gap between theoretical knowledge and practical applications. Teacher 5073 at baseline described focusing on traditional visual aids like chart papers and sack bags with notes as teaching tools:

> *I often create teaching aids such as chart papers with notes that I hang in the classroom like a calendar […] I also use sack bags where I write notes and hang them in the classroom for easy reference.*

By the end line, Teacher 5073 started integrating digital tools, simulations, and interactive resources to teach abstract concepts.

3.4 Engaging students in chemistry classes

Teachers transitioned from simply managing classes to ensuring the active participation of students. At the baseline, Teacher 5040 relied on traditional methods such as storytelling and mnemonics to engage students while teaching abstract concepts like atomic structure. Class participation was monitored by ensuring students' physical presence and observing engagement during activities, such as walking around the classroom. By the end line, Teacher 5040 had adopted student-centred teaching strategies such as cooperative (Jigsaw method), integrated technology into lessons, asked open-ended questions to encourage critical thinking, and engaged students actively. Teacher 5040 added:

> *I started engaging students through presentations, experiments, creating models, visual representations, and drawing. I also started assigning extra tasks to high-achieving students and ensured that struggling learners received support during class activities from the teacher or peers.*

All the teachers encouraged peer tutoring by pairing high-achieving students with those who needed additional support, fostering collaboration and shared learning experiences.

It was learned that students were given autonomy in choosing their roles and responsibilities when completing assigned group tasks. Teacher 5069 engaged students by assigning topics for discussion, and while preparing presentations, the teacher allowed the group to decide individual roles, such as who would write on the chart paper and who would present. By the end line, Teacher 5069 adopted more hands-on and interactive strategies, such as conducting experiments in small groups of three to four, ensuring active participation from all students, and encouraging everyone in the group to ask questions to the teacher.

The changes in how Teacher 5070 engaged students in organic chemistry classes reflect a significant shift towards more interactive, real-world, and hands-on approaches. At the baseline, Teacher 5070 primarily relied on syllabus-prescribed hands-on experiments like identification of functional groups in organic compounds in the laboratory and asserted, "Students understand the concept better when they conduct experiments themselves." By the end line, Teacher 5070 broadened engagement strategies by integrating real-life examples and field visits. In addition to testing functional groups of organic compounds in the laboratory, the teacher organised field trips and explained how the characteristic smells and flavours of fruits during ripening result from esterification and specific esters formed as a result of the oxidation of carboxylic acids with alcohols.

However, teachers reported that engaging students in multiple ways during chemistry lessons was not always feasible due to the bulky syllabus and the limited time of just three hours per week allocated to science classes. Additionally, organising outdoor experiential learning in chemistry classes posed significant challenges. These included managing large numbers of students (35 to 40 in one section), ensuring adherence to safety protocols, securing necessary permissions, and arranging transportation. Teachers also highlighted that the lack of adequate resources, such as equipment and laboratory materials, further limited them from implementing diverse and interactive teaching strategies effectively. Despite their willingness, logistical constraints often prevented them from providing more hands-on and field-based chemistry learning experiences.

3.5 Assessing Students' Learning

Although the BES places greater emphasis on summative assessments, with 80% of the total weighting in higher secondary levels (Classes XI and XII) and 70% in middle secondary levels (Classes IX and X), teachers tend to prefer formative approaches over summative assessments. Teacher 5044 initially prioritised group assessments, where students worked collaboratively, allowing high achievers to support low achievers, and focused on presentations and learning new chemistry vocabulary, stating, "*I do not prefer class tests because I feel they might not always reflect students' true learning.*" By the end line, Teacher 5044 incorporated a variety of assessment strategies, including question and answer methods, quizzes, writing tasks, and exit tickets to evaluate student learning. Likewise, during the baseline, Teacher 5070 highlighted the use of formative as well as summative assessments to track student learning, but the approaches evolved significantly in the end line, demonstrating greater variety and responsiveness to students' needs. The

approach incorporated classroom questioning, discussions, and opinion sharing to reinforce concepts while scaffolding students' learning.

Due to the higher emphasis on summative assessments, rote memorisation remains a deeply rooted practice among Bhutanese students, with some teachers even providing tips on memorising learning materials (Rai et al., 2025). However, Teacher 5073 reported a shift from encouraging rote memorisation and traditional testing to adopting a more learner-centred approach, focusing on scaffolding, topic-specific formative assessments, and continuous feedback to promote deeper understanding.

In addition to allowing students to express what they have learned, teachers also reported leveraging technology to provide real-time feedback and diagnostic reports that specify specific areas in which students were having difficulty. At the baseline, Teacher 5064 talked about administering tests at the end of each chapter, using rubrics to evaluate learning, conducting question and answer sessions, and organising debates. By the end line, there was a significant shift towards a more diagnostic, interactive, and formative assessment approach to enhance learning outcomes. Teacher 5064 began conducting pre-tests to understand students' prior knowledge before introducing new topics, and also integrated interactive tools like Kahoot, Quizlet, and Nearpod for providing real-time feedback and generating diagnostic reports to find out specific areas where students faced challenges.

4. DISCUSSION

4.1 Teachers' Understanding of UDL Principles through OER

The pre-test and post-test results for both modules demonstrated improvement in teachers' understanding of UDL principles following their engagement with the OER modules over six weeks per module. Test results showed the intervention improved teachers' UDL competencies, with considerable gains in content representation in both the modules (0.70 to 0.76, d=0.5 in atomic structure; 0.58 to 0.65, d=0.6 in organic chemistry) and student engagement through multiple strategies in atomic structure (0.82 to 0.90, d=0.7). However, the improvement in multiple forms of student engagement in organic chemistry (0.73 to 0.77, d=0.3) and using diverse assessments in both modules (0.83 to 0.85, d=0.2; 0.73 to 0.77, d=0.3) was smaller, indicating a need for further support. These results suggested that the OER modules successfully addressed key aspects of UDL, including multiple means of representation, engagement, and expression. The OERs on atomic structure and organic chemistry were developed in alignment with UDL principles to give hands-on practice to teachers on these principles for fostering inclusion and equity in their classroom practices. This aligned with the work of Craig et al. (2022) and Lee and Griffin (2021), who have emphasised that targeted professional development significantly enhances teachers' ability to understand and implement UDL principles in their teaching practices.

Teachers reported that the design of the OER modules, which included interactive content, reflective exercises, interactive assessments, audio-visual aids, and reading materials, played a critical role in deepening their conceptual understanding of UDL principles and translating them into effective classroom practices. Teachers also reported that OER designed on UDL principles increased their awareness of addressing learner variabilities. Israel et al.(2022) posit that UDL is a responsive framework that helps teachers adapt strategies to cater to diverse students' needs. Teachers also demonstrated increased awareness in addressing students' variability through multiple means of representation, engagement, and expression. This finding aligned with Sharma et al. (2023), who stated that UDL provides a robust framework for designing learning environments that are more inclusive and equitable.

Furthermore, teachers' growing awareness of UDL principles was evident in their ability to apply these concepts in lesson planning and instructional strategies. Such progression has also been reported in previous studies by Craig et al. (2022) and Unluol Unal et al. (2022), which emphasised teachers' understanding and implementation of UDL principles through targeted support. The observed improvement is also consistent with the findings of Craig et al. (2022) and Saliba (2019), who reported that structured professional development on UDL leads to meaningful changes in teachers' perceptions and practices governed by inclusion and equity. Teachers also transitioned from a basic understanding of UDL to a more nuanced understanding and application of its principles, particularly in the context of representing content in multiple ways for diverse learners. Lee and Griffin (2021), have also reported the effectiveness of online modules in enhancing teachers' knowledge and skills for designing and implementing UDL-based

lesson plans for fostering inclusive teaching practices. Since UDL principles can reduce learning barriers by enhancing accessibility, inclusivity, and engagement (Capp, 2017; King-Sears & Johnson, 2020), OERs can be tailored using UDL principles to support teachers in accommodating various learning styles and the needs of diverse learners. The findings emphasise the importance of integrating professional development initiatives on UDL with opportunities for contextualised designing of lesson plans, implementation, and reflection. Such initiatives not only strengthen teachers' conceptual understanding of UDL principles but also foster their ability to translate these principles into inclusive and equitable classroom practices.

While the findings from this study are encouraging, limitations such as small sample size and context-specific study should be acknowledged, as they might potentially affect the generalisability of the results. Future studies could expand the sample across different educational contexts and subject areas to gain broader insights. Moreover, smaller gains observed in assessment strategies in both the modules and student engagement within the organic chemistry module indicate that teachers may require additional support in engaging students in multiple ways and designing multiple assessment techniques. Likewise, future research could investigate the specific features of OER that facilitate the implementation of each principle of UDL.

4.2 The Impact of UDL-based OERs on Teachers' Instructional Practices

Besides theoretical understanding, the OERs facilitated teachers to apply UDL principles in lesson planning and classroom practices. As reported in Table 4, lesson plans and reflection reports showed high proficiency in content representation (M=1.82, SD=0.32 in atomic structure; M=1.93, SD=0.20 in organic chemistry) and student engagement in both modules (M=1.89, SD=0.26 in atomic structure; M=1.87, SD=0.20 in organic chemistry), and creating multiple means of expression in organic chemistry (M=1.78, SD=0.3) but moderate proficiency in creating diverse opportunities for expression in the atomic structure module (M=1.67; 0.39). Teachers also demonstrated creativity in improvising the representation of content in multiple ways. For instance, Teacher 5040 creatively used locally available fruits to teach the names of elements, providing a practical way for students to understand the arrangement of elements in the periodic table. Likewise, Teacher 5070 enhanced students' engagement by combining laboratory experiments on functional groups in organic chemistry with fieldtrips. Such practices demonstrated teachers' understanding of creating inclusive and engaging learning experiences. Further, interview responses revealed teachers' growing understanding of UDL principles and their applications in fostering inclusivity and equity in their classrooms. Teachers actively strived to incorporate instruction, learning, and assessments aligned with UDL's principles.

These findings contribute to the growing body of research on inclusive STEM education by providing evidence that UDL-based OERs can strengthen teachers' instructional practices through the promotion of inclusivity, accessibility, reflective teaching, and pedagogical adaptability (Rusconi & Squillaci, 2023). It also highlights the importance of supporting teachers' professional development by integrating UDL into resource developments such as OERs for supporting teachers in designing instruction that meets diverse learner needs. This aligns with the study by Chee and Weaver (2024), which asserts that embedding UDL in the development of OERs ensures the creation of accessible and inclusive learning materials, thereby fostering equitable learning materials. Teachers aligned instruction, learning activities, and assessments with UDL principles, reflecting a shift from awareness to inclusive instructional practices. Similarly, Lowrey et al. (2023) and Lambert et al. (2023)concluded that integrating UDL principles into teacher education programmes fosters the development of inclusive teaching practices. Their study reported that teacher participants experienced a significant shift toward more constructive, reflective, and responsive teaching to learners' needs.

Additionally, the integration of technology was frequently mentioned by teachers as a key tool for teaching difficult and abstract concepts. This statement aligns with the view of Bray et al. (2024) that technology serves as a powerful enabler of UDL in offering flexible tools and activities for representing content and engaging learners. Teachers' adoption of such technology for promoting inclusion, equity, and enhancing learning outcomes indicated a transformative shift towards more dynamic and inclusive pedagogical practices and accommodation of diverse learners, also emphasised by Eden et al. (2024) and Tang et al. (2024). Findings were also consistent with previous studies by Craig et al. (2022) and Unluol Unal et al. (2022), which reported that professional development focused on UDL significantly improved teachers' capacity to make lesson plans more accessible and create more responsive learning and teaching

environments. Overall, the evidence revealed the effectiveness of OER designed using UDL principles in equipping teachers with knowledge, skills, and attitudes to apply in their teaching. However, further research could explore the scalability of such initiatives across diverse educational settings.

A major limitation of this study lies in its exclusive focus on changes in teachers' instructional practices without assessing corresponding student learning outcomes. While effective instructional practices are expected to facilitate learning and support students in achieving academic goals, this study evaluated students' understanding, engagement, and means of expression based on teachers' reflections and lesson plans, rather than direct measurement of students' achievements. Specific assessment tools or standardised testing instruments were not employed to evaluate the learning enhancements and academic achievements of students. Future research should consider incorporating robust methods to assess student learning outcomes to evaluate the impact of UDL-based instructional practices.

5. CONCLUSION

This study highlighted the effectiveness of OER modules in enhancing secondary school chemistry teachers' understanding and applications of UDL principles through practice-based professional development. The OER modules on atomic structure and organic chemistry embedded with UDL-aligned interactive activities, assessments, reading contents, audio-visual resources, and reflective exercises demonstrated significant improvement in their ability to design lesson plans and foster inclusion and equity in their classroom practices. The findings emphasised the strength of integrating UDL principles into professional development programmes for empowering teachers in designing lesson plans and instructional practices that address the needs of diverse learners in chemistry classes.

Furthermore, lesson plans and classroom practices demonstrated practical applications of UDL principles, such as the representation of content with locally available fruits and meaningful engagement with various digital technologies. Teachers also revealed their enhanced understanding of the UDL principles during the interviews and increased competencies in using technologies while teaching complex and abstract concepts. Most importantly, this study proved that well-designed OER bridges the gap between theoretical understandings of the UDL principles to address challenges encountered in diverse classrooms. This study recommends scaling the use of UDL-based OER modules for supporting the professional development of teachers to enhance their instructional competencies and foster inclusion and equity. Future studies should also examine the impact of UDL-based professional development on students' learning outcomes in chemistry education.

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Research Ethics. This study adhered to the ethical guidelines specified by the IDRC's Advisory Committee on Research Ethics. The research design was reviewed and approved by the Department of School Education, Ministry of Education and Skills Development (MoESD), Bhutan. In addition, all individual participants provided informed consent through signed consent forms, which also granted them the flexibility to withdraw from the study at any stage, should they wish to do so.

Data Availability Statement. All data can be obtained from the corresponding author.

Conflicts of Interest. The author declares no conflicts of interest. The views expressed herein do not necessarily represent those of IDRC or its Board of Governors.

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