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# Enhancing Chemistry Education Through Professional Development of Secondary School Chemistry Teachers Using Open Educational Resources

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**Abstract**

Chemistry, a core element of STEM education, fosters critical thinking and prepares students for higher education and careers. However, its teaching is challenging due to complex concepts, calculations, and laboratory safety concerns. Bhutanese students often struggle to comprehend chemistry and its practical application, relying heavily on rote memorisation. Research suggests that professional development can improve teaching and learning outcomes. This study assessed the impact of Open Educational Resources (OERs) on the professional development of Bhutanese secondary chemistry teachers, aiming to enhance their content knowledge, pedagogical skills, and inclusive practices. A mixed methods approach was used to evaluate the effectiveness of the OERs, using pre-test and post-test, lesson plans, reflections, classroom observations, and interviews. Additionally, a Community of Practice (CoP) network on Telegram was analysed to understand the dynamics of knowledge-sharing and learning within the community. The results indicated that the OERs and the CoP network supported the enhancement of teachers' knowledge, pedagogical skills, and inclusive practices. This suggests that educational institutions should leverage OERs and CoP platforms to promote equitable, high-quality professional development for teachers.

**Keywords:** Chemistry, secondary chemistry teachers, professional development, Open Educational Resources (OERs)

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## Introduction

Teaching chemistry to secondary school students is critical because it lays the foundation in Science, Technology, Engineering, and Mathematics (STEM) fields (Shidiq et al., 2020), fosters critical thinking, promotes understanding of everyday chemical science, and prepares students for higher education and future careers. Additionally, a deep understanding of chemistry plays a crucial role in various industries and in addressing global challenges such as climate change, environmental pollution, and sustainable future (Matlin et al., 2015), making chemistry a vital subject for preparing the next generation of informed and responsible citizens. However, students regard chemistry as a difficult (Johnstone, 2010) and “gatekeeper” subject that discourages them from pursuing science for higher education and future careers (Barr et al., 2008). According to Millar (1991), science subjects considered “hard” can be attributed to external (not within the student’s control) and internal (within the student’s control) factors. The external attributes that can make chemistry a challenging subject to teach and learn include the nature of chemistry, such as its experimental nature, abstract concepts, the interplay between macroscopic and microscopic levels of matter, symbolic and molecular representation, spatial representation, mathematic-intensive calculations, and laboratory work (Sirhan, 2007; Taber, 2002, 2019; Tsaparlis, 2009; van Berkel et al., 2009). Additionally, certain context-based extrinsic attributes could be curriculum design, resource availability, students’ socio-economic status, teacher-student ratio, qualifications and competencies of teachers, and the school’s location and culture. Selected student’s attributes that can contribute to poor chemistry performance include a lack of prior foundational knowledge, a negative attitude towards the subject, poor study habits, learning disabilities, language barriers, mathematical efficacy, and personal problems (Hassan et al., 2017; Moyo, 2018).

Bhutan, a small landlocked country situated in the Eastern Himalayas is known for its commitment to providing free, inclusive, and equitable education to all its citizens. This commitment begins with Early Childhood Care and Development (ECCD) Centres catering to children aged 3-5 years to formal education levels ranging from pre-primary to tertiary and post-graduate levels across various academic and professional fields. Bhutan also prioritises STEM education with significant emphasis. Considering the significance of chemistry and its relevance to students’ lives and future careers, the Bhutanese Education System (BES) introduces the teaching of chemistry as one of the mandatory science subjects starting from grade IX. Prior to that, several elements of chemistry are taught to students from grades IV to VIII within a general science subject, while at the higher secondary level (XI to XII), only science students study chemistry as a major subject. The science curriculum in Bhutan focuses on its ontology and epistemology, the foundational aspects of science education. It is organised into four themes: Life Processes; Materials and their Properties; Physical Processes; and Environmental Science, with Chemistry included under Materials and their Properties (Department of Curriculum and Professional Development [DCPD], 2022). The curriculum uses competency-based learning standards to provide students with a well-rounded understanding of the natural world, allowing them to make informed decisions and contribute to scientific advancement. Despite the importance of chemistry in providing students with a foundational understanding of the natural and chemical world, there have been reports of secondary students not performing well in chemistry.

The consecutive Pupil Performance Reports (PPR) from the national board examinations, Bhutan Certificate of Secondary Education (BCSE) for grade X and Bhutan Higher Secondary Education Certificate (BHSEC) for grade XII, show a consistently low mean performance in chemistry when compared to other science subjects. For instance, the mean chemistry mark in BCSE was 66.49 in 2022, 54.94 in 2021 and 61.60 in 2020, while the mean mark in BHSEA was 62.25 in 2022, 68.09 in 2021, and 66.15 in 2020 (Bhutan Council for

School Examinations and Assessment [BCSEA], 2021, 2022, 2023). Studies have reported that Bhutanese secondary students find chemistry abstract, difficult, have a negative attitude toward the subject, demonstrate low confidence in the subject, and have expressed fear and anxiety during chemistry assessments (Chogyel & Wangdi, 2021; Utha et al., 2021). As a result, teachers face a significant challenge in ensuring that secondary students are adequately prepared for future academic and professional opportunities requiring chemistry proficiencies. Therefore, it is crucial to determine and address the factors that contribute to poor performance and learners' dislike of chemistry among secondary school students in Bhutan to ensure that they develop a deeper understanding of chemistry concepts and applications and are adequately equipped to succeed in their academic and professional pursuits. Some potential contributing factors to this problem might include a lack of engagement with the subject due to limited practical applications or exposure to real-world scenarios, ineffective teacher preparation, insufficient teaching and learning resources, inadequate professional development (PD) support, and teacher-centred teaching methods. Above all, teachers' competency is an important factor in managing learning activities and student engagements, determining the success of a teaching session (Copriady, 2014), which ultimately determines students' performance in chemistry (Chogyel & Wangdi, 2021).

Underpinning the concerns mentioned above, Samtse College of Education (SCE), under the Royal University of Bhutan, which trains secondary school teachers in the country, collaborated with teacher educators from Tanzania, Nigeria, and India as part of the IDRC (International Development Research Centre) Canada, funded consortium project CL4STEM (Connected Learning for Teacher Capacity Building in STEM) to support PD of secondary chemistry teachers through the OERs. The consortium partners curated OERs in three chemistry topics: Atomic Structure, Chemical Bonding, and Organic Chemistry aligned with respective country's national school curriculum frameworks. The primary objective of the OERs was to strengthen teachers' Subject Matter Knowledge (SMK), Pedagogical Content Knowledge (PCK), and General Pedagogical Knowledge (GPK) for promoting Higher-Order Thinking with Inclusion and Equity (HOTIE) in their classroom practices. Other designed benefits of the OERs included lesson planning using Universal Design for Learning (UDL) and writing reflection based on Borton's (1970) model for reflective learning.

Although the term "open educational resources" was coined in 2002 at a UNESCO conference in Paris in recognition of its potential to transform education (UNESCO, 2002), this initiative was the first of its kind in Bhutan. This article discusses the impacts of using OERs in chemistry to support the PD of selected secondary chemistry in-service and pre-service teachers in Bhutan. Considering the reported impacts of OERs presented in this article, relevant agencies may consider adopting OERs for teachers' PD due to their cost-effectiveness, and their ability to promote equitable, inclusive, and high-quality education, as well as lifelong learning opportunities for everyone.

## Research Questions

This study aimed to explore the impact of OER in supporting the PD of secondary chemistry teachers, guided by the primary research question: How does the PD programme using OER impact teachers' SMK, PCK, and GPK for fostering HOTIE in their teaching practices?

To comprehensively address this overarching question, the study was further structured around the following sub-questions:

(1) What changes in teachers' Knowledge, Attitudes, and Practices (KAP) are observed as a result of their engagement with OER?

(2) How do teachers' interactions within the CoP contribute to their ongoing PD, peer learning, and instructional practices?

## Materials and Methods

The study employed purposive sampling to recruit a sample of nine in-service and ten pre-service chemistry teachers from Samtse District, Bhutan. In-service teachers were further categorised into two groups based on their experience: In-service Focus Group or Newly Qualified Teachers (NQTs): This group comprised teachers with less than five years of teaching experience. In-service General Group: This group included teachers with more than five years of teaching experience. Pre-service teachers were post-graduate students enrolled in a Post-graduate Diploma in Education (PgDE) programme. All the participants were anonymised using a four-digit numerical code.

A mixed methods approach was employed to assess the impact of a PD programme on sample teachers' SMK, PCK, and GPK for fostering HOTIE in their practices. Quantitative data was collected through pre-test and post-test containing 20 multiple-choice questions each in all the OER modules, designed to assess changes in SMK. Qualitative data was gathered through semi-structured pre- and post-interviews with NQTs, focusing on their Knowledge, Attitudes, and Practices (KAP) in teaching chemistry. Classroom observations were conducted using a pre-determined protocol to analyse NQTs' teaching practices related to SMK, PCK, and GPK. Additionally, all the sample teachers submitted three lesson plans and written reflections for all the OERs, which were used to assess their developing competence in designing HOTIE-aligned lessons and self-reported changes in KAP.

To further examine teachers' engagement with the OERs and social learning interactions with peers and tutors during the PD programme, a Community of Practice (CoP) network was established on Telegram chat. Data on teachers' activity within the Learning Management System (LMS) was also continuously recorded and observed to track their progress and provide necessary support.

Quantitative data from the pre-test and post-test were analysed using paired-sample t-tests to identify statistically significant changes in scores. Qualitative data from interviews and reflections were analysed thematically using a coding scheme to identify patterns and recurring themes. The Social Network Analysis (SNA) was conducted with Gephi software to examine how the patterns of participation among members changed over time in the CoP. Additionally, thematic analysis of Telegram conversations was used to understand the social learning dynamics. Finally, findings from all data sources were integrated to provide a comprehensive picture of the PD's impact on teachers.

## Results

### Participant Demographics

A total of 19 teachers for the study were recruited in three categories. Table 1 presents the demographics of these teachers, detailing their gender, academic qualifications, subject specialisations, professional teaching experience, and ownership of electronic devices. The availability of ICT devices, including laptops and smartphones, was assessed to ensure teachers had access to the OERs whenever required.

**Table 1**

*Background Information of Teachers (n = 19)*

| Particulars | Category (number and percentage) |
|---|---|
| Gender | Male (n = 9; 47%)<br>Female (n=10;53%) |
| Academic qualification and subject of specialisation | In-service:<br>BSc Chemistry (n=1)<br>PgDE Chemistry (n = 3)<br>PgDE, MSc Chemistry (n = 1)<br>BEd, MEd Chemistry (n = 1)<br>BEd Chemistry (n=3)<br>Pre-service:<br>PgDE Chemistry (n = 10) |
| Professional teaching experience | In-service Focus Group Experience < 5 years (n = 4; 21%)<br>In-service General Group Experience >5 years (n = 5; 26%)<br>Pre-service Undergoing PgDE (n = 10; 53%) |
| Electronic devices owned | Laptop (100%)<br>Smartphone (100%) |

There was nearly equal gender distribution with 9 (47%) male teachers and 10 female teachers (53%). Most teachers (95%) had formal education backgrounds, with PgDE in Chemistry being the most common qualification (13 teachers). In-service teachers (47%) were categorised by teaching experience (Focus Group or NQT < 5 years, Other General Group > 5 years), while the remaining teachers (53%) were pre-service teachers undergoing PgDE training. All teachers (100%) owned both laptops and smartphones, indicating strong electronic devices accessibility.

### Experience with OER for Professional Development of Teachers

The use of OERs in supporting the PD of secondary chemistry teachers was the first of its kind in the Bhutanese education system. Teacher educators appreciated the fact that OERs can be a resourceful pathway for supporting teachers' PD. Once the student teachers graduate from the education college, teacher educators normally lose contact with them, but this type of PD through the use of OERs connected them with in-service teachers in providing contextualised and need-based guidance and support. Teacher Educator 1 (TE1) emphasised that "the PD of in-service teachers should be supported by teacher education colleges to ensure effective teaching-learning and assessment practices by giving them insights into evidence-based reflective classroom practices." Likewise, Teacher Educator 4 (TE4) expressed that "OER can serve as adaptable resources that can support in-service teachers in augmenting their mastery of subject content, pedagogical skills, and technological proficiency." Additional benefits highlighted by teacher educators included the use of topic-specific PCK and technologies to pique students' interest and direct their attention to the lesson.

The sample teachers also appreciated the design of the OERs and the depth of content, along with the variety of inclusive pedagogies and technologies embedded in the OERs. According to in-service teacher participant 1503, "As an NQT, the OERs were very helpful to me in designing my lessons and teaching. I wish we had OERs for all the chapters of secondary chemistry textbooks." This view suggests that OERs were particularly useful for NQTs in deepening their understanding of the national curriculum framework content and fostering the application of appropriate pedagogical approaches and technologies. Teacher 1501 stated that the suggested PCK and technologies assisted her in making her classes more interactive and engaging. During the interview, teachers revealed that they were aware of the existence of students from diverse backgrounds and their different learning needs, but they were not conversant with dealing with them and supporting their learning needs. They stated that the introduction to UDL particularly prepared them to meet the learning needs of the students in the classroom.

However, both teachers and teacher educators acknowledged that time was a constraint. Teacher educators stated that they were unable to provide immediate feedback on the works (learning activities, lesson plans, and reflection reports) submitted by teachers. "Time was a challenge in supporting the PD because we couldn't visit the LMS to provide immediate feedback to the submitted works which might have demotivated them," explained TE2. Similarly, only four teachers' classroom teaching could be observed due to the teacher educators' time constraints. Likewise, teacher 1505 stated that focused time and resources such as internet data were required for effective learning from OERs. Another limitation mentioned by teachers was that the OERs' contents did not always align with the academic calendars of the schools.

### Change in Subject Matter Knowledge (SMK) of Teachers

The changes in SMK assessed through the scores of the pre-test and post-test in all three modules have been summarised as levels of performance, namely Novice (0-25%), Emerging (26-50%), Proficient (51-75%), and Accomplished (76-100%), as shown in Table 2.

**Table 2**

*Pre-test and Post-test Levels of Performance of Teachers*

| Levels of Performance | Pre-test Atomic Structure | Post-test Atomic Structure | Pre-test Organic Chemistry | Post-test Organic Chemistry | Pre-test Chemical Bonding | Post-test Chemical Bonding |
|---|---|---|---|---|---|---|
| Novice 0-25% (n) | 0 | 0 | 0 | 1 | 0 | 0 |
| Emerging 26-50% (n) | 0 | 1 | 11 | 6 | 7 | 4 |
| Proficient 51-75% (n) | 12 | 6 | 7 | 11 | 9 | 14 |
| Accomplished 76-100% (n) | 7 | 12 | 1 | 1 | 3 | 1 |
| Total (N) | 19 | 19 | 19 | 19 | 19 | 19 |

The pre-test results for the Atomic Structure module indicated that 63% of teachers had a proficient understanding of the concepts, while 37% demonstrated an accomplished understanding. Following the completion of the module, the post-test results showed a 26% increase in teachers with an accomplished understanding. The significant difference between the pre-test and post-test scores, evidenced by a p-value of 0.00 from the Wilcoxon test, indicates that the OER in Atomic Structure effectively addressed the initial knowledge gaps. The increase in the median score from 73 to 78.75 further supports this improvement. Conversely, the modules on Organic Chemistry and Chemical Bonding did not exhibit similar significant gains. The average score increases by only 5% in these modules, with non-significant p-values of 0.15 and 0.37 (paired t-test) respectively, suggests that these OER modules were less effective in enhancing teachers' SMK.

Teachers' SMK was also evaluated through lesson plans and reflections based on Borton's Reflection Model (1970), as shown in Table 3.

**Table 3**

*Consolidation of Teachers' SMK Proficiency through Lesson Plans and Reflections*

| SMK subthemes | Modules | Novice 0-25% (n) | Emerging 26-50% (n) | Proficient 51-75% (n) | Accomplished 76-100% (n) |
|---|---|---|---|---|---|
| 1. Knowledge of the Subject Matter | Atomic Structure | 2 | 6 | 8 | 3 |
| | Organic Chemistry | 3 | 4 | 9 | 4 |
| | Chemical Bonding | 0 | 8 | 9 | 2 |
| 2. Nature of Science | Atomic Structure | 4 | 3 | 8 | 4 |
| | Organic Chemistry | 2 | 3 | 11 | 4 |
| | Chemical Bonding | 0 | 7 | 9 | 3 |

Despite the pre-test and post-test findings where some teachers displayed novice-level knowledge in Atomic Structure and Organic Chemistry, interview data revealed a more nuanced understanding. Teachers demonstrated a good grasp of the SMK in their teaching subjects, articulating key concepts and interconnections within the subject matter. They confidently applied appropriate pedagogies and designed effective activities to enhance students' understanding. For instance, teacher 1502 stated, "I planned my lesson on Atomic Structure from the students' point of view and applied PhET simulations and analogies to explain the concept and empowered students to make their concept maps of the taught concepts." The lesson plans and interviews also revealed that teachers were aware of the nature of science and provided opportunities for students to engage in scientific inquiry, observation, experimentation, and reasoning. For example, teacher 1506 asked her grade IX students to create a storyboard about the evolution of atomic models to help students understand how the atomic model changed over time as new evidence revealed flaws in earlier models. According to the teacher, "Students did this activity by putting themselves in the shoes of those scientists who devised models through their reasoning."

### Change in Pedagogical Content Knowledge (PCK) of Teachers

In this study, teachers' PCK development was facilitated by the OERs through: suggested topic-specific instructional strategies, discussions of some common misconceptions, multiple ways of representing content based on UDL, setting the context for learning, and their curriculum knowledge. The status of teachers' PCK development after completing the assigned OERs was determined by the grades obtained in their lesson plans and reflections categorised into Novice (0-25%), Emerging (26-50%), Proficient (51-75%), and Accomplished (76-100%), as shown in Table 4.

**Table 4**

*Consolidation of Teachers' PCK Proficiency through Lesson Plans and Reflections*

| PCK subthemes | Modules | Novice 0-25% (n) | Emerging 26-50% (n) | Proficient 51-75% (n) | Accomplished 76-100% (n) |
|---|---|---|---|---|---|
| 1. Instructional Strategies | Atomic Structure | 0 | 4 | 7 | 8 |
| | Organic Chemistry | 0 | 2 | 13 | 4 |
| | Chemical Bonding | 0 | 4 | 13 | 2 |
| 2. Students' misconceptions | Atomic Structure | 3 | 8 | 8 | 0 |
| | Organic Chemistry | 4 | 6 | 8 | 1 |
| | Chemical Bonding | 0 | 13 | 5 | 1 |
| 3. Representation of the Content | Atomic Structure | 0 | 4 | 10 | 5 |
| | Organic Chemistry | 0 | 1 | 9 | 9 |
| | Chemical Bonding | 0 | 1 | 13 | 5 |
| 4. The Context for Learning | Atomic Structure | 2 | 8 | 9 | 0 |
| | Organic Chemistry | 0 | 5 | 14 | 0 |
| | Chemical Bonding | 0 | 12 | 5 | 2 |
| 5. Curriculum knowledge | Atomic Structure | 3 | 7 | 9 | 0 |
| | Organic Chemistry | 3 | 5 | 9 | 2 |
| | Chemical Bonding | 2 | 7 | 9 | 1 |

The analysis of the Table 4 data revealed that the OERs were particularly effective in enhancing teacher proficiency in instructional strategies. In Organic Chemistry and Chemical Bonding, a significant portion (13 teachers each) reached the proficient level (51-75%). Notably, Atomic Structure showed even greater improvement, with 8 teachers achieving the accomplished category (76-100%). This suggests the OERs were most successful in equipping teachers with practical methods for delivering instruction in these specific chemistry topics. Likewise, teachers also demonstrated a positive shift in the use of learner-centred instructional strategies during interviews. Teachers stressed the importance of using a variety of instructional strategies to meet the needs of all learners. For example, teacher 1501 expressed, "I use activity-based learning, inquiry, simulations, team teaching, and digital tools to accommodate students of diverse learning abilities."

However, the OERs were less effective in equipping teachers to identify students' misconceptions. While some teachers achieved proficiency in this area (8 in Atomic Structure and Organic Chemistry and 5 in Chemical Bonding) a significant majority (7 Novice and 27 Emerging) still need support. This highlights a need for further resources or strategies within OERs to help teachers identify and address students' misconceptions.

The OERs were helpful in orienting teachers in using multiple ways of representing content based on UDL principles. Most of the teachers (10 in Atomic Structure, 9 in Organic Chemistry, and 13 in Chemical Bonding) reached proficient level. This was also evident during their classroom observations, as teachers were found using a variety of teaching aids and additional technological supporting devices such as laptops, smartphones, smart TVs, projectors, and so on to represent content. This shift towards UDL-aligned pedagogies suggests that the OERs effectively equipped teachers with strategies for catering to diverse learning styles.

While the OERs demonstrably improved teacher proficiency in other areas, setting the context for learning seemed to have presented a challenge. The data suggests at least two teachers faced difficulty in contextualising Atomic Structure. Teacher 1503's quote highlighted the inherent challenge: "It's very difficult to contextualise the concepts on Atomic Structure as students find it difficult to imagine at the microscopic levels." This emphasises a potential gap in the OERs. Future iterations could benefit from including more resources or strategies specifically designed to help teachers bridge this gap and make Atomic Structure more relatable to students.

The majority of teachers' proficiency in curriculum knowledge at the proficient level (51-75%) suggests the OERs were helpful in deepening teachers' grasp of the curriculum content. This is likely as OERs were being aligned with the national curriculum framework, ensuring a clear connection between the provided materials and the learning objectives that learners were expected to achieve. Teacher 1502's experience further reinforces this point, who mentioned, "OERs were helpful in orienting NQTs to the curriculum, outlining the required instructional materials, and suggesting assessment strategies." This highlights the OERs' effectiveness in providing a comprehensive foundation for teachers to navigate the curriculum and ensure students' learning is aligned with learning outcomes. The lower proficiency levels in curriculum knowledge suggest the OERs, while helpful for many, might not be comprehensive enough, particularly for teachers new to the curriculum. While OERs have shown potential in enhancing chemistry teachers' PCK, their efficacy can be further optimised through the strategic integration of targeted support.

### Change in General Pedagogical Knowledge (GPK) of Teachers

To assess the GPK of teachers, lesson plans and reflections were evaluated through the lens of UDL by examining three key subthemes: promoting equity and inclusion, fostering a positive classroom environment, and ensuring assessments accurately measured learning for diverse needs. Before implementing the modules, teachers attended a workshop on UDL principles, which focused on orienting them on multiple means of representation, engagement, and action/expression. Evaluation solely focused on UDL principles to gauge teachers' growth in inclusion and equity, specifically their understanding of UDL, their ability to create equal participation opportunities, and their skill in designing UDL-based lessons, resources, and assessments that catered to diverse learners.

**Table 5**

*Consolidation of Teachers' GPK Proficiency through Lesson Plans and Reflections*

| GPK subthemes | Module | Novice (0-25%) (n) | Emerging 26-50% (n) | Proficient 51-75% (n) | Accomplished 76-100% (n) |
|---|---|---|---|---|---|
| 1. Equity and Inclusion | Atomic Structure | 3 | 8 | 5 | 3 |
| | Organic Chemistry | 4 | 3 | 5 | 7 |
| | Chemical Bonding | 0 | 6 | 10 | 3 |
| 2. Classroom Management | Atomic Structure | 0 | 6 | 9 | 4 |
| | Organic Chemistry | 0 | 4 | 10 | 5 |
| | Chemical Bonding | 0 | 4 | 13 | **2** |
| 3. Assessment | Atomic Structure | 0 | 8 | 8 | 3 |
| | Organic Chemistry | 0 | 8 | 10 | 1 |

| | | | | |
|---|---|---|---|---|
| Chemical Bonding | 0 | 7 | 9 | 3 |

While all teachers received training on fostering equity and inclusion, several areas for improvement were identified. Three teachers in the Atomic Structure module and four in Organic Chemistry demonstrated novice-level skills in fostering an inclusive classroom environment, which may have implications for students' learning. The OER on Chemical Bonding was especially effective in promoting inclusive teaching strategies. This is evident by 10 teachers reaching Proficient (51-75%) and 3 achieving Accomplished (76-100%) levels in addressing diverse learning needs. A few teachers (Table 5) were in the novice stage of managing classrooms. Group work and collaborative learning were common classroom management strategies implemented by the teachers. Instructions for grouping students for group activities emphasised mixed-ability student grouping. In the lesson plan of teacher 1517, it was mentioned that "students will be engaged in a Jigsaw group activity to discuss the types of chemical bonding. The groups will be heterogeneously mixed, with an equal number of low and high performers." Three teachers whose classes were observed were found to be using a variety of classroom interaction modes and activities to engage students in multiple ways while also managing their classes efficiently. During the interview, however, four in-service Focus Group teachers expressed difficulty in managing the classroom, as stated by teacher 1503:

> I make sure to include hands-on activities wherever possible. There are few students who do not cooperate with us in the class. They don't listen to us, or maybe they are not interested in the subject. The concept of inclusion from the CL4STEM was helpful in addressing disciplinary issues in my class.

Teachers reported that the interactive tools embedded in the module assisted them in capturing students' attention, effectively illustrating concepts, and engaging students in hands-on learning experiences, ultimately contributing to a more orderly and productive classroom environment. Strengthening teachers' capacity to use interactive technological tools in Bhutanese classrooms aligns with an inclusive classroom management approach that seeks to actively engage students in the learning process through higher-order thinking while reducing the likelihood of behavioural issues and disruptions.

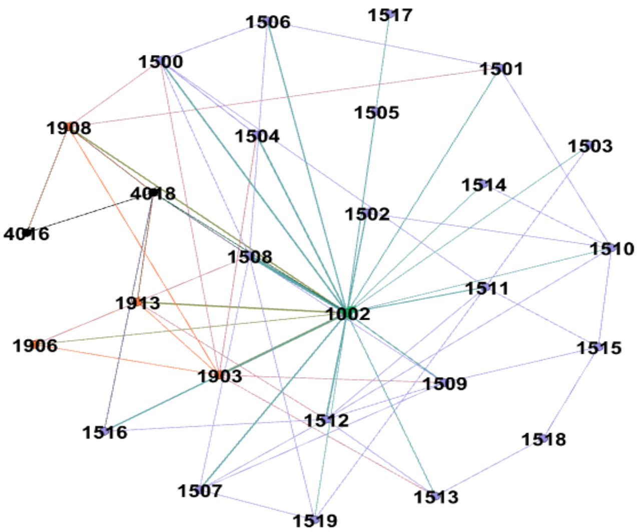
Teachers used continuous, formative, and summative assessments. They used a variety of assessment tools, including standardised tests and exams, quizzes, exit tickets, class discussions and presentations, homework, assignments, classwork, practical activities, and observation of students' progress. The teachers' competencies in assessing their learners ranged from emerging to accomplished, with most teachers falling in the proficient range (Table 5). Due to the large class size, the teachers indicated their preference for standardised summative assessments over formative assessments.

### Community of Practice (CoP) Network

The CoP hosted on the Telegram chat provided a valuable platform for teachers to engage in social learning and knowledge sharing. It facilitated access to expertise and help, enabling them to enhance their KAP. Additionally, the platform promoted resource sharing and collaboration, while also fostering professional networking opportunities beyond the PD programme. Data from the CoP was extracted only after all three modules had been completed and teachers' participation had concluded. Figure 1 shows the SNA of the CoP during the implementation of chemistry modules. SNA utilised three parameters to illustrate the dynamics of interactions: density (the number of interactions that happen between the teachers at a given time), average degree (the average number of interactions per participant), and maximum degree (the participant with the most interactions).

**Figure 1**

*Community of Practice (CoP) Network Evolution*




SNA revealed a density of 0.23, which is lower than the maximum possible density of 1. This indicated that not all teachers actively interacted with each other but must have benefited from being part of the community by passively following the conversations. This finding aligns with the statement provided by the teacher 1506:

> Usually in the CoP, I don't send messages, I just go through the messages that other members have sent. I do sometimes ask my friends here for help solving some questions and I also ask them about their progress in the CL4STEM modules. If I face a problem in completing any activity online, I ask them for help by asking them how it should be done.

The average degree at 6.07, suggests that teachers typically interacted with around 6 other members suggesting a moderately interactive environment. The maximum degree score of 25 for teacher educators aligns with their leadership role in implementing OERs within the network, suggesting their central role in facilitating communication and collaboration among teachers.

Further, thematic analysis of the conversations revealed three main types of interactions in the CoP: Teacher educators supporting teachers with technical issues; teachers sharing resources and practice; and teacher educators supporting teachers' practice. Since the OER-enabled PD support was implemented for the first time in Bhutan, many teachers encountered problems such as being unable to log in, forgetting their passwords, and being unable to proceed with the next lessons or activities due to restrictions set by the teacher educators for completing given tasks, as well as incorrect progress rates. Whenever teachers faced such issues, teacher educators were notified through the CoP and help was provided immediately.

Teachers shared a variety of educational resources, such as lesson plans and multimedia materials to promote collaborative learning. Teacher educators encouraged the sharing of best practices and provided additional resources, fostering a culture where teachers sought help and exchanged experiences, ultimately enhancing their professional growth. For instance, teacher 1502 expressed "I watched YouTube videos posted in the CoP and used in teaching and I also used to post for others." This contributed to a collaborative learning culture where teachers could benefit from the experiences of their peers. Another teacher 1504 shared that "If I face a problem in completing any activity online, I ask my peers for help by asking them how it should be done." Teachers also shared photos of their practices, examples of resources for other teachers to use, experimental setups, and evidence of students' participation in lesson plans.

Teacher educators continuously supported the teachers' professional growth through a mentor-mentee relationship, with the teachers divided among the five chemistry teacher educators. When at times teachers were not progressing or submitting evidence of their practice, they were reminded by being tagged in the CoP. Additionally, teachers approached the educators to discuss relevant PCK, subject matter, and misconceptions related to the content. TE1 expressed that it was a valuable learning experience to support the PD of teachers using OER, emphasising that teachers' PD should be conducted by the teacher educators, as they are in a better position to understand their professional needs. Similarly, the CoP not only served as a platform for PD but also extended its impact beyond the programme's formal sessions, thereby fostering long-term professional growth and community building. For instance, TE2 expressed:

> It has been almost a year since the implementation of OER was completed, but we continue our contacts even today. I often receive calls from teachers seeking information related to subject matter and other resources. At times, I also reach out to them when I need information from the schools, such as research data and other information.

This aspect underscores the sustained value and impact of the community in supporting teachers beyond the structured programme.

## Discussion

### Practice-based Professional Development

This study evaluated a PD programme designed to leverage OERs for situated teacher learning within a practice-based framework. Teacher educators enjoyed supporting teachers' PD, noting that they could provide real time guidance based on individual needs. Teachers also acknowledged the design of the OERs as instrumental in providing them with practical strategies for improving their classroom practices. This aligns with the growing recognition of the importance of OERs and practice-based PD. OERs offer educators access to diverse online resources, which can be seamlessly integrated into their teaching practices, supplementing traditional textbooks (Carlson & Meadows, 2020). Further OERs bridge the gap in accessing educational materials benefiting both students and teachers as a cost-effective alternative (Robinson et al., 2014; Tang, 2020). Although OERs in education align with UNESCO's mission to promote equitable, inclusive, and quality education for all, and support UN Sustainable Development Goal 4 for lifelong learning opportunities (Demirbağ & Sezgin, 2021), it was implemented for the first time in Bhutan. This initiative advances UNESCO's efforts to enhance educational access, improve teaching practices, and foster global educational collaboration. However, both teacher educators and teachers reported that the primary limitation of the OERs was the prescribed time duration. Teachers found it challenging to progress on the OER platform while managing their regular duties. This disconnects between the time needed for effective progress and the constraints of daily workloads highlighted the need for solutions to bridge the gap. Teachers recommended that the ministry should reduce the teaching load for those participating in such practice-based PD programmes. Future research could explore ways to design OER platforms that fit within teachers' time constraints while still supporting effective learning. Additionally, investigating the impact of various support mechanisms on teachers' engagement with OERs and their impact on student outcomes would be valuable.

### Teachers' Subject Matter Knowledge (SMK)

SMK, which refers to a teacher's comprehensive understanding of a subject's core content, principles, and theories and their application in real-world contexts, is essential to teaching proficiency. Teachers must have a deep understanding of the subject they teach, a necessity emphasised by Pitjeng-Mosabala and Rollnick (2018) and van Driel et al. (2002). A solid foundation in chemistry SMK is crucial for shaping teachers' instructional strategies and their ability to create meaningful learning experiences. This proficiency enables teachers to clearly explain concepts, address students' questions and misconceptions, effectively adapt to curriculum changes, and incorporate innovative teaching methods.

Overall, the findings indicate that all teachers recognise the importance of having deep subject knowledge and tried to convey the content to students through various strategies and activities. The study found that the OER in Atomic Structure significantly enhanced teachers' SMK, while the Organic chemistry and Chemical bonding OERs showed minimal improvement and non-significant impact. Findings also revealed a discrepancy in SMK assessment: formal tests and lesson plans indicated that some teachers had novice-level SMK, while interviews showed they had a good grasp of the subject matter and employed effective teaching practices. The reliance on formal tests and lesson plans for assessing SMK may not fully capture the depth of teachers' understanding or their effectiveness in teaching the subject matter.

Findings also suggested that teachers do not put much effort into lesson planning due to lack of time but teach effectively in practice. Hence, it is critical to ensure that all teachers are given adequate time to plan their lessons. Lesson planning is a reflective process that assists teachers in developing a structured plan for teaching in a particular learning environment (Nagro et al., 2019). Therefore, when designing a lesson, the teacher must make deliberate judgments based on an in-depth understanding of the subject matter that will have a direct impact on students' learning and engagement. Furthermore, according to Iqbal et al. (2021), effective lesson designs can improve student engagement and active learning in the classroom. Lesson planning is essential for effective teaching and learning because it helps teachers organise their thoughts, set clear objectives, create engaging activities, understand students' learning, achieve learning outcomes, and promote purposeful classroom engagement (Moh'd et al., 2022).

### Teachers' Pedagogical Content Knowledge (PCK)

PCK refers to a teacher's ability to effectively teach the specific subject matter by integrating content knowledge (CK) and pedagogical knowledge (PK). According to Shulman (1986), PCK entails knowing how to present content in a way that is appropriate for students' developmental levels and prior knowledge, using effective teaching strategies, and assessing student learning. PCK is required for effective teaching because it allows teachers to translate their subject knowledge into meaningful learning experiences for students. Teachers' PCK should be improved through PD to develop their content knowledge, use of appropriate pedagogies, teaching experience, beliefs about teaching and learning, and knowledge of student understanding and assessment (Schiering et al., 2023).

This study demonstrated the potential of OERs to enhance PCK development among chemistry teachers. The OERs were particularly effective in equipping teachers with instructional strategies, UDL-based content representation methods, and deepening their understanding of curriculum content. However, findings also revealed areas where additional resources or strategies are required within the OERs, or potentially alongside them, to effectively identify and address students' misconceptions. This is particularly crucial for challenging topics, as evidenced by the lower proficiencies in this area. Additionally, teachers need support in contextualising content, particularly for topics like Atomic Structure, where teachers faced difficulties.

The use of appropriate instructional strategies is crucial for teachers to create a conducive learning environment that promotes student engagement, critical thinking, problem-solving skills, and the acquisition of knowledge and skills. Instructional strategies for teaching chemistry should be differentiated based on the context, learners' needs, and types of chemistry concepts. Common instructional strategies used in chemistry teachings, such as active learning methods, stimulating learning materials, assessment practices, inquiry and constructivist approaches, problem-solving, collaborative learning, problem-based learning, case study, and laboratory investigations, have been shown to improve academic performance in the subject (Reyes, 2017; Salleh et al., 2022) and can enhance students' abilities to analyse data, construct scientific explanations, and communicate scientific procedures and reasoning (Rahayu, 2017).

Misconceptions are common in chemistry classes that can present significant challenges for both students and teachers. Understanding the sources of these misconceptions and putting effective mitigation strategies in place are critical steps toward promoting meaningful learning in chemistry education. Misconceptions in chemistry can arise from students' initial prejudices, incompetent teachers, unclear textbooks, different contexts of student daily experience, traditional instructional strategies, learners' failure to understand the emergent nature of chemical entities, their properties, and interactions, and learners' inability to connect the macroscopic, microscopic, and symbolic levels of chemical representation (Mondal & Chakraborty, 2013; Tumay, 2016). Misconceptions impede students' understanding and can result in incorrect predictions and interpretations of chemical phenomena. It is therefore important to identify and address students' misconceptions using effective instructional strategies, learning resources, and activities.

Teachers need to have a clear understanding of the prescribed chemistry curricula (Chen & Wei, 2015) as this will influence adaptations of effective instructional strategies and planning appropriate learning experiences. However, research indicates that teachers may have gaps in their comprehension of some chemistry topics and concepts (Ozdemir, 2023). As a result, PD in chemical literacy and context-based chemistry instruction is necessary to strengthen teachers' grasp of the curricula. By enhancing teachers' knowledge and understanding of the chemistry curricula, they may better support students' learning and engagement in the subject. Likewise, it is very important to communicate the curricula using multiple means of representing the content since students have to navigate their thoughts and comprehension in macroscopic, sub microscopic, and symbolic levels of chemical representation, and real-world applications. According to Nyachwaya and Wood (2014), representing chemistry content in multiple ways allows for a deeper comprehensive understanding, helps students make connections between different levels of representation, and enhances their ability to apply knowledge in different contexts.

### Teachers' General Pedagogical Knowledge (GPK)

The evaluation of teachers' GPK through UDL principles revealed mixed results across three themes: promoting equity and inclusion, fostering a positive classroom environment, and ensuring diverse assessments. While the Chemical Bonding OER effectively enhanced inclusive teaching, with many teachers reaching Proficient or Accomplished levels, some teachers in the Atomic Structure and Organic Chemistry modules struggled to promote equity and inclusivity. Novice-level skills in fostering an inclusive classroom environment may have some implications for students' learning. Bhutan's national convention "Education for All" resulted in the development of an inclusive education policy draft (Schuelka, 2012), which has increased teacher awareness of inclusive education in Bhutan. A growing body of research on inclusive education in Bhutan has contributed to understanding of inclusive education and suggests a transition to a more inclusive education system. Dorji et al. (2021) investigated teachers' attitudes toward inclusive education in Bhutan and found that teachers play a critical role in the successful implementation of educational change. Chhetri et al. (2023) have emphasised the importance of providing comprehensive teacher education programmes that address the specific needs of inclusive education in Bhutan. Dorji and Schuelka (2016) have identified that challenges in implementing quality inclusive education in Bhutan include teacher quality, personnel and administration issues, curriculum, pedagogical knowledge, student physical access, and a lack of resources. As a result, all teachers must be equipped with the knowledge and skills to facilitate an equitable and inclusive classroom environment in which every student feels welcomed, respected, and supported in their educational journey, or else some students may fall behind.

Classroom management varied with successful use of group activities and interactive tools, yet challenges with students' cooperation persisted. Teacher's knowledge of multiple modes of classroom interaction, multiple ways of engaging learners in higher-order thinking with the necessary resources and space, and the ability to manage students' behaviour are critical components of classroom management. A study by Dorji (2020) has identified that the predominant use of the traditional "chalk and talk" method, limited student participation, and lower-order thinking questions in Bhutanese classrooms underscore the importance of proactive classroom management. In classrooms where students are primarily passive recipients of information, classroom management challenges may arise, such as maintaining student engagement, addressing disruptions, and fostering a positive learning environment.

Assessments were varied, though large class sizes led to a reliance on standardised summative methods, highlighting the difficulty in consistently implementing formative assessments despite their motivational benefits for the students. While standardised tests can provide a uniform measure of student performance, they may not fully capture the individual learning progress and needs of each student. Balancing standardised summative assessments with formative assessments in large classes is crucial for a comprehensive understanding of students' progress and needs. This approach ensures both overall class performance evaluation and personalised student support, fostering a more effective learning environment.

### Social Learning

The Telegram-based CoP significantly enhanced social learning and knowledge sharing. Despite low interaction density (0.23), many teachers benefited from passively following conversations. The average degree of 6.07 interactions per participant indicated a moderately active environment, with teacher educators playing a central role in facilitating collaboration. Interactions focused on technical support, resource sharing, and professional practice guidance. Teachers exchanged lesson plans, multimedia materials, and best practices, while educators provided mentorship and addressed pedagogical challenges. The CoP's impact extended beyond the formal programme, fostering long-term professional growth and sustained community engagement.

## Conclusion

This study aimed to assess the enhancement of teachers' SMK, PCK, and GPK through the use of contextualised OERs hosted on Moodle and a CoP on Telegram chat. This is the first study to implement PD support through OERs and CoP for chemistry teachers in Bhutan. The findings indicated that OERs can be a powerful tool to support practice-based professional development, facilitated by teacher educators through LMS and CoP. Although the quantitative enhancement of SMK was not significant in two OERs, qualitative data provided evidence that the modules improved teachers' SMK. OERs have shown potential in enhancing chemistry teachers' PCK and GPK, and their efficacy can be further optimised with targeted support. The Telegram-based CoP significantly enhanced social learning, knowledge sharing, and fostered long-term professional growth and sustained community engagement.

The main limitations of this study were the small sample size, its implementation in just one district with only seven schools, and its focus on short-term impact, which restricts generalisability. Despite these limitations, the findings offer valuable insights, indicating that OERs can be effective with targeted support for enhancing teachers' professional growth. This study also provides evidence that teacher educators are in a better position to support practice-based PD by scaffolding teachers' needs through social learning platforms. Future research involving larger, more diverse populations and long-term impact assessments can confirm the effectiveness of contextualised OERs curated by teacher educators for the PD of secondary school chemistry teachers.

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## Disclaimers

The views expressed herein do not necessarily represent those of IDRC or its Board of Governors. No potential conflict of interest was reported by the authors.

## Ethics Statement

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.

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