

A Comparative Analysis of Robotics Integration in Chemistry Education: A Quasi-Experimental Study Across Two Schools

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Research Article

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Abstract

This study investigates the impact of robotics-based instruction on Grade 10 learners' understanding of stoichiometry and titration, addressing challenges in enhancing conceptual learning in diverse educational contexts. A quasi-experimental mixed-methods design was employed, combining pre- and post-test assessments with qualitative analysis of learners' knowledge construction. The sample included learners from a suburban, well-resourced school and a township, resource-constrained school. Findings indicate that learners exposed to robotics-based instruction significantly outperformed those receiving traditional teaching, demonstrating improved conceptual understanding and academic achievement. The results further reveal that robotics integration is adaptable across different school contexts, including those with limited laboratory resources. This study contributes empirical evidence to STEM education by highlighting the effectiveness of technology-enhanced instructional strategies in chemistry. It also provides practical implications for educators seeking innovative approaches to improve learner engagement, reduce educational disparities, and support meaningful learning in science education.

Introduction

The integration of robotics in chemistry education represents a promising avenue for transforming pedagogical practice in Science, Technology, Engineering, and Mathematics (STEM) subjects. Robotics-based instruction, which draws on multidisciplinary principles from mechanical, electrical, and computer engineering, offers learners opportunities for hands-on, experiential engagement with complex scientific concepts (Ouyang & Xu, 2024; Kurniawan et al., 2025). In the context of chemistry teaching and learning (CTL), robotics can serve as a tool for visualising and simulating abstract concepts such as stoichiometry and titration, areas often regarded as pedagogically challenging in traditional classrooms. However, despite a growing body of global research on educational robotics, its application within chemistry education, particularly in comparative school contexts with varying levels of infrastructural support, remains underexplored.

Within South Africa, persistent educational inequalities exacerbate this research gap. Suburban schools are often equipped with advanced laboratory facilities and digital resources, while township and rural schools continue to grapple with systemic resource limitations, including a lack of laboratories, underqualified teaching staff, and minimal exposure to emerging technologies (Amnesty International, 2020). These disparities raise critical questions regarding how educational technologies such as robotics can be equitably and effectively implemented across diverse school environments. Furthermore, existing studies (for example, Gavrilas, Kotsis & Papanikolaou, 2024; Ouyang & Xu, 2024) tend to generalise the impact of educational robotics without accounting for contextual distinctions such as school infrastructure, pedagogical training, and learners' prior knowledge. This study addresses this gap by evaluating the impact of robotics-based instruction across two secondary schools, one suburban and one township, thereby offering insight into how school context shapes pedagogical outcomes in chemistry education.

This research is theoretically grounded in a combination of constructivism (Piaget, 1972; Vygotsky, 1978) and constructionism (Papert, 1980), which posit that knowledge is actively constructed through interaction and the creation of tangible artefacts. Robotics-based activities, particularly when designed to simulate chemical reactions and titration processes, align with these theories by allowing learners to externalise abstract content through manipulation and observation. Moreover, the study draws on the Technological Pedagogical Content Knowledge (TPACK) framework (Koehler & Mishra, 2009), which highlights the intersection of content expertise, pedagogical strategy, and technological tools in effective teaching. Lastly, Cognitive Load Theory (Sweller, 1988) informs the study's analysis of how robotics can reduce extraneous cognitive demands, thereby enhancing learners' focus on core scientific principles.

The study also responds to calls for greater empirical attention to how educational innovations function across socio-educational contexts. While recent research supports the efficacy of robotics in STEM education (Darmawansah et al., 2023; Ching & Hsu, 2024), few studies have examined how such interventions translate into meaningful learning in under-resourced schools or how learners of differing academic levels engage with robotics in conceptual learning tasks. The present study contributes to this underrepresented area by investigating the role of robotics in fostering conceptual understanding in chemistry, with a particular focus on how contextual factors such as resource availability and instructional approach influence learning outcomes.

Employing a quasi-experimental design within an explanatory sequential mixed-methods framework, the study compares the academic performance and conceptual development of Grade 10 learners exposed to robotics-based instruction with those taught through conventional methods. The research is guided by the following question: *How does the use of robotics in chemistry education impact Grade 10 learners' conceptual understanding in stoichiometry and titration across two different school environments?* In answering this question, the study provides evidence-informed insights to support policy, curriculum development, and classroom practice aimed at promoting equitable and effective integration of robotics in South African science education.

Literature review

The integration of robotics into science education is increasingly recognised for its capacity to transform learning experiences by fostering engagement, enhancing conceptual understanding, and cultivating 21st-century skills (Ching & Hsu, 2024; Darmawansah, Abdullah, & Nugraha, 2023). In the context of chemistry education, robotics-based instruction presents an opportunity to bridge the persistent theory–practice divide, particularly in domains such as stoichiometry and titration, where learners often struggle with abstract conceptualisation (Burger et al., 2021; Lotriet & Gouws, 2024).

Several pedagogical frameworks justify the use of robotics in science classrooms. Constructivist theories posit that learners construct knowledge through active engagement (Piaget, 1972; Vygotsky, 1978), while Papert's (1980) constructionism extends this to learning through the design and creation of tangible artefacts. Robotics activities, especially those that model chemical reactions or titration

processes, enable learners to simulate, visualise, and manipulate phenomena in ways that reinforce conceptual reasoning. Furthermore, the Technological Pedagogical Content Knowledge (TPACK) framework (Koehler & Mishra, 2009) provides a structured approach to integrating technology with content and pedagogy, ensuring robotics is not treated as a standalone novelty but as a purposeful instructional tool. Studies suggest that robotics, when aligned with curricular goals, support both subject mastery and higher-order thinking skills (Arafat et al., 2024).

Additionally, robotics offers cognitive benefits by reducing extraneous processing and allowing learners to focus on core aspects of scientific reasoning (Sweller, 1988). For example, in titration simulations, learners can direct their attention toward pH curve interpretation rather than procedural mechanics, thus deepening analytical understanding (Alhashmi et al., 2021; Kurniawan et al., 2025).

However, despite the theoretical appeal, a critical gap persists in empirical work evaluating how these principles translate into practical gains across varied school contexts. Global meta-analyses report positive effects of robotics on STEM achievement (Ouyang & Xu, 2024), yet few studies undertake comparative investigations across school types or socio-economic settings. This is particularly true for the Global South, where systemic inequalities shape the feasibility and effectiveness of educational innovation. For instance, in South Africa, township schools continue to face constraints such as overcrowded classrooms, under-resourced laboratories, and limited teacher training in emerging technologies (Amnesty International, 2020). These conditions raise questions about the equitable implementation of robotics, and whether its benefits can be realised uniformly across socio-economic divides.

Equity-focused frameworks in STEM education argue for pedagogical strategies that are responsive to learners' contexts and prior experiences. In the case of robotics in chemistry education, equity extends beyond mere access to hardware; it includes instructional design, teacher agency, and the alignment of robotics tasks with curriculum outcomes. Studies in the Global South have shown that robotics can mitigate infrastructural deficiencies by offering experiential alternatives to traditional labs, particularly when supported by contextually relevant professional development (Lotriet & Gouws, 2024). However, such outcomes depend heavily on how robotics are embedded within the pedagogical process.

Comparative studies also offer important insights. Research contrasting urban and rural, or affluent and disadvantaged schools, has revealed substantial differences in how learners engage with robotics-enhanced STEM lessons (Keser & Guven, 2022). These differences are not solely attributable to resource gaps but also to variations in instructional quality and teacher beliefs about technology. For example, in a study conducted across Indonesian public schools, Darmawansah et al. (2023) found that learners' conceptual gains from robotics instruction were significantly mediated by teachers' ability to scaffold inquiry tasks. This implies that the impact of robotics is not universal; it is shaped by human and contextual factors.

In chemistry education specifically, emerging empirical work remains sparse but promising. Robotics kits have been used to simulate mole calculations, pH titrations, and reaction mechanisms (Burger et al.,

2021). While such interventions show potential, they often lack rigorous design or fail to address how robotics influence learners' deeper understanding. Moreover, the limited representation of African contexts in this literature leaves open questions about how robotics interacts with under-resourced school environments, diverse learner needs, and local curricular standards.

Thus, the present study seeks to address two intersecting gaps: the lack of comparative data on robotics use in divergent school settings, and the dearth of research on its application in core chemistry topics within Global South contexts. Anchored in constructivist and TPACK frameworks, this research evaluates not only whether robotics improves conceptual understanding in stoichiometry and titration, but how this improvement is shaped by instructional context, school infrastructure, and learner background. By doing so, it offers both theoretical and practical contributions to the equitable implementation of robotics in science education.

Methodology

Context and Participants

This study was conducted in two public secondary schools in Gauteng Province, South Africa, purposefully selected to represent contrasting educational contexts. School A, situated in a suburban area, is comparatively well-resourced with a functioning science laboratory and reliable access to digital technologies. School B, by contrast, is located in a township and experiences infrastructural limitations, including the absence of laboratory facilities, though it maintains a basic computer lab.

A total of 80 Grade 10 learners (40 per school) participated in the study. Within each school, learners were divided into an experimental group (robotics-based instruction) and a control group (traditional teaching), with 20 learners in each group. While the sample size is modest, it is consistent with classroom-based quasi-experimental designs in STEM education (Miller et al., 2020), and findings are interpreted with appropriate caution concerning generalisability.

Instruction at each school was delivered by a qualified subject specialist:

- The teacher at School A is a male educator with nine years of experience teaching physical sciences and holds a Master's degree in Education. He has previously participated in digital pedagogy workshops and ICT integration training programmes.
- The teacher at School B is a female educator with over fifteen years of experience teaching physical sciences and holds a Bachelor's degree in Education. She is recognised for her long-standing service in under-resourced environments and her commitment to learner-centred instruction despite infrastructural limitations.

These teachers not only facilitated instruction but also collaborated in reviewing and validating the assessment tools used in this study, given their extensive experience and contextual knowledge of South

Research Design and Hypotheses

The study employed a quasi-experimental design within an explanatory sequential mixed-methods framework, suitable for real-world educational settings where random assignment is impractical. The quantitative phase evaluated the effectiveness of robotics-based instruction in improving learners' conceptual understanding of stoichiometry and titration. The qualitative phase provided insight into how learners interpreted and integrated these concepts.

Grounded in a pragmatic paradigm, the study draws upon constructivist and constructionist learning theories. Robotics was conceptualised as an epistemic tool that externalises and scaffolds learners' conceptual reasoning in chemistry.

The following hypotheses guided the quantitative inquiry:

- **H₀₁**: There is no statistically significant difference between pre-test and post-test scores within the experimental group.
- **H₁₁**: There is a statistically significant increase in post-test scores within the experimental group.
- **H₀₂**: There is no statistically significant difference in post-test scores between learners at School A and School B.
- **H₁₂**: There is a statistically significant difference in post-test scores between learners at School A and School B.

Statistical Analysis and Assumptions

To determine within-group gains in conceptual understanding, paired-sample t-tests were conducted separately for the experimental and control groups. Prior to this, two key statistical assumptions were evaluated:

- Normality was assessed using the Shapiro-Wilk test:
 - Experimental group pre-test: $p = .156$
 - Experimental group post-test: $p = .081$
 - Control group pre-test: $p = .097$
 - Control group post-test: $p = .113$
 - These values ($> .05$) indicated acceptable normality of distribution for parametric analysis.
- Homogeneity of variance was assessed using Levene's Test:
 - Between groups (School A vs School B, post-test scores): $F = 1.24, p = .270$

- Levene's test confirmed equal variance assumptions ($p > .05$), justifying the use of parametric comparisons.

The use of Levene's test in this context was necessary to ensure the appropriateness of independent-samples t-tests, which were subsequently conducted to examine inter-school differences in post-test performance. This additional analysis acknowledged the contrasting school environments and allowed for a comparative dimension beyond intra-group changes.

Cohen's d was calculated to determine the magnitude of observed effects, with thresholds interpreted as small (0.2), medium (0.5), and large (0.8).

Instructional Intervention

The robotics-enhanced instructional intervention spanned six weeks and incorporated Engino robotics kits, which learners used to simulate chemistry experiments. Students in the experimental group designed and programmed:

- Robotic arms to model stoichiometric mixing,
- Motorised burettes with embedded pH sensors to visualise titration processes.

This hands-on approach enabled real-time data collection and direct engagement with abstract chemistry concepts. The intervention followed a three-phase inquiry model:

1. Concept Introduction – Teachers conducted scaffolded discussions to elicit learners' prior knowledge.
2. Robotics Exploration – Learners programmed and ran robotic simulations to model chemical phenomena.
3. Concept Application – Students interpreted experimental data, drew connections to chemical theory, and presented their findings.

This progression aligns with constructivist principles, where learning is actively constructed through interaction with tools and phenomena.

Qualitative Analysis

Open-ended responses collected during the post-test phase were analysed using thematic content analysis to explore the depth and structure of learners' conceptual reasoning. An inductive coding strategy was initially applied, allowing themes to emerge from the data without preconceptions.

Subsequently, codes were refined and organised deductively around three guiding constructs: conceptual accuracy, integration of robotics, and explanatory coherence. Coding was peer-reviewed by two colleagues with qualitative expertise to ensure dependability and confirmability. Inter-coder

agreement was established through independent coding of 20% of the data and subsequent resolution of discrepancies.

Findings

The results are presented for each school, with each case providing a detailed analysis of the findings. This structured approach allows for clear comparisons across the different educational settings, highlighting the unique contributions of each school to the overall research outcomes. By examining the results on a case-by-case basis, the researcher can better understand how various factors may influence learner achievement in the differing contexts of robotics concept-based and traditional instructional methodologies (George & Mallery, 2018; Kaur, Stoltzfus & Yellapu, 2018). This nuanced analysis ensures that the researcher capture the distinct dynamics at play within each school, allowing for a comprehensive understanding of the efficacy of robotics in enhancing learners' conceptual understanding of complex topics such as stoichiometry and titration.

The research questions guiding this analysis are designed to elucidate how Grade 10 learners interpret and utilize their understanding of these foundational chemistry concepts through robotics-enhanced instruction. This ability to identify specific content related to stoichiometry and titration and to apply this knowledge effectively in learning chemical processes signifies a deeper comprehension of the subject matter.

Furthermore, the findings related to the learners are contextualized through their engagement with the instructional practices of the teachers implementing the robotic-based instructions. Teachers' agency, characterized by their content knowledge and pedagogical strategies, significantly influences what learners grasp and the ways in which they engage with the material. Thus, the insights drawn from the learners' assessments are juxtaposed with summarized findings concerning their respective teachers' instructional methods. This comparative analysis provides a nuanced understanding of how the integration of robotics in teaching can enhance learners' conceptual understanding and engagement in chemistry, highlighting the dynamic interplay between learner outcomes and teacher effectiveness in the chemistry classroom.

Table 1
Descriptive Statistics and Paired-Sample T-Test Results

School	Group	Pre-test Mean	Pre-test SD	Post-test Mean	Post-test SD	t-value	p-value
1	Robotics	54.7	12.2	80.4	7.2	12.98	< 0.001
1	Traditional	39.5	14.0	55.9	12.8	7.18	< 0.001
2	Robotics	50.4	8.2	76.5	6.5	11.68	< 0.001
2	Traditional	37.4	11.0	40.5	7.2	2.58	0.021

The robotics group in the two schools exhibited a substantial increase in post-test scores, consistently outperforming the control group. In School 1, the robotics group demonstrated a mean improvement of 25.7 points, with a highly significant difference ($p < 0.001$), highlighting the intervention's efficacy in promoting conceptual understanding. Similarly, School 2 recorded a mean increase of 26.1 points in the robotics group, with the control group showing only minimal progress. The significant p-value ($p < 0.001$) reaffirmed the positive impact of robotics instruction.

The varying levels of conceptual comprehension observed across different stages of learning highlight the progressive nature of cognitive development and the significant impact of interactive instructional tools. The robotics-based instruction provided learners with opportunities to actively engage with abstract chemical concepts, fostering visualization and practical application. This hands-on, experiential process not only deepened their conceptual understanding but also facilitated individualized interpretations of stoichiometry and titration. These findings reinforce the potential of robotics as an effective tool for enhancing comprehension of complex scientific processes, offering meaningful contributions to the integration of technology in contemporary chemistry education.

Table 2
Learners' knowledge representations for *School A*

Section	Topic	Group	Learner Level	Learner Response	Analysis
Section 2: Problem Solving	Stoichiometry	Experimental Group	L1:Highest	"The reaction of 5.0 grams of sodium produces 12.8 grams of NaCl. First, I calculated the moles of sodium ($5.0 \text{ g} \div 23 \text{ g/mol} = 0.217 \text{ mol}$). Then, using the mole ratio (2:2), I determined the moles of NaCl were the same. Finally, I converted moles of NaCl to mass ($0.217 \text{ mol} \times 58.5 \text{ g/mol} = 12.8 \text{ g}$). The robotics simulation showed this visually, helping me understand the process better."	Experimental group responses included robotics tools, emphasizing visualization and understanding of mole-to-mass relationships.
			L2:Middle	"The reaction produced 12.8 g of NaCl. I used the mole ratio to determine this, but I wasn't sure why I needed to calculate moles first. The robotics activity was helpful but a little confusing."	Middle learners attempted to apply robotics-based strategies but lacked complete understanding of mole conversions. They demonstrated moderate reliance on visual aids.
			L3:Lowest	"The answer is 12.8 g. I don't understand how the calculations work. The robotics activity didn't make sense to me."	Lowest learners struggled with mole conversions and integrating robotics into problem-solving. They expressed limited conceptual understanding.

Section	Topic	Group	Learner Level	Learner Response	Analysis
		Control Group	L4:Highest	"Moles of Na = $5.0 \div 23 = 0.217$. Moles of NaCl = 0.217. Mass of NaCl = $0.217 \times 58.5 = 12.8$ g."	Responses were accurate and concise but lacked references to applied learning tools or visual aids.
			L5:Middle	"I calculated the mass of NaCl as 12.8 g, but I don't fully understand the process."	Middle learners showed partial accuracy but lacked confidence in their calculations, highlighting gaps in understanding theoretical foundations.
			L6: Lowest	"I got the answer as 12.8 g, but I don't know if it's correct."	Responses lacked depth and confidence, with limited understanding of stoichiometry.
	Limiting Reagent	Experimental Group	L1:Highest	"H and O ₂ react in a 2:1 ratio. Moles of H = $50 \div 2 = 25$ mol; moles of O ₂ = $50 \div 32 = 1.56$ mol. Since O ₂ runs out first, it's the limiting reagent. Water produced = $2 \times 1.56 = 3.12$ mol. The robotics simulation used a bar graph to show the reaction progress."	Experimental group demonstrated greater conceptual clarity, explaining the rationale for selecting the limiting reagent. Robotics visualizations aided comprehension.
			L2:Middle	"The limiting reagent is oxygen, and water is 3.12 mol. I used the ratio and a graph, but I don't understand why O ₂ is the limiting reagent."	Middle learners displayed partial understanding of limiting reagents, relying heavily on robotics visuals without fully grasping theoretical underpinnings.
			L3:Lowest	"I just followed the ratio and used the	Lowest learners focused on

Section	Topic	Group	Learner Level	Learner Response	Analysis
		Control Group		robotics graph. The answer is 3.12 mol of water."	robotic outputs without connecting the visual tools to conceptual reasoning, showing minimal independent understanding.
			L4:Highest	"Moles of H = $50 \div 2 = 25$ mol. Moles of O ₂ = $50 \div 32 = 1.56$ mol. Limiting reagent = O ₂ . Water produced = 3.12 mol."	Responses were concise and correct but lacked integration of applied or visualized learning strategies.
			L5:Middle	"Oxygen is the limiting reagent, and the water produced is 3.12 mol. I don't get why the ratio works that way."	Middle learners demonstrated procedural accuracy but lacked a clear understanding of the concept of limiting reagents.
		Experimental Group	L6:Lowest	"I think the limiting reagent is O ₂ , but I'm not sure how to calculate it."	Responses reflected limited conceptual understanding and procedural errors.
			L1:Highest	"Volume of NaOH = 50 mL = 0.050 L. Moles of NaOH = $0.050 \times 0.10 = 0.005$ mol. HCl concentration = moles $\div$ volume = $0.005 \div 0.025 = 0.20$ M. Using robotics, I learned to track equivalence visually."	Learners highlighted how robotics clarified titration endpoints and mole relationships, suggesting enhanced engagement and understanding.
			L2: Middle	"I calculated the HCl concentration as 0.20 M. The robotics tool helped show the endpoint, but I didn't get how the	Middle learners displayed moderate procedural understanding but struggled to integrate

Section	Topic	Group	Learner Level	Learner Response	Analysis
		Control Group		moles and volumes fit together."	robotics-assisted visualizations with theoretical concepts.
			L3:Lowest	"The HCl concentration is 0.20 M. I didn't understand how the robotics helped."	Lowest learners relied solely on procedural steps and did not effectively integrate robotics tools or visualize titration concepts.
			L4:Highest	"Moles of NaOH = 0.005. HCl concentration = $0.005 \div 0.025 = 0.20 \text{ M}$."	Responses were correct but lacked references to any hands-on or visual learning tools.
			L5:Middle	"I calculated 0.20 M for the concentration of HCl, but I don't understand the reasoning behind the formula."	Middle learners displayed procedural knowledge but lacked deeper conceptual understanding.
			L6:Lowest	"I followed the steps to get 0.20 M, but I don't know why I used those numbers."	Responses were superficial, reflecting gaps in understanding both the procedure and the concept.

Table 3
Learners' knowledge representations for *School B*

Section	Topic	Group	Learner Level	Learner Response	Analysis
Section 2: Problem Solving	Stoichiometry	Experimental Group	L7:Highest	"5.0 g of Na produces 12.8 g of NaCl. Moles of Na = $5.0 \text{ g} \div 23 \text{ g/mol} = 0.217 \text{ mol}$. Using the stoichiometric ratio of 1:1, the moles of NaCl produced equals 0.217 mol. Mass of NaCl = $0.217 \text{ mol} \times 58.5 \text{ g/mol} = 12.8 \text{ g}$. The robotics provided a visual graph that clarified resource allocation."	The highest achievers in the experimental group effectively utilized both calculations and visual aids from robotics, demonstrating a sophisticated understanding of stoichiometric relationships.
			L8:Middle	"I found that 12.8 g of NaCl is produced but I'm puzzled about why calculating moles is necessary. The robotics tools were somewhat confusing."	Middle achievers utilized robotics but expressed uncertainty about the significance of mole calculations, indicating a superficial grasp of stoichiometry that could be enhanced through further instruction on the conceptual basis of mole conversions.
			L9:Lowest	"The answer is 12.8 g. I don't understand how to get to that number. The robotics made no sense to me."	Lowest achievers struggled significantly with understanding stoichiometric calculations and robotics integration, suggesting a need for a more scaffolded approach in teaching these concepts.

Section	Topic	Group	Learner Level	Learner Response	Analysis
		Control Group	L10: Highest	"Calculated moles: $\text{Na} = 5.0 \text{ g} \div 23 \text{ g/mol} = 0.217 \text{ mol}$; the same amount of NaCl is produced. Therefore, NaCl is 12.8 g."	Though this response is correct and concise, the lack of reference to robotics limited insight into the learning process for the highest achiever in the control group. A more interactive approach may enhance understanding.
			L11: Middle	"I got 12.8 g of NaCl, but I'm unclear about how I arrived at it."	Middle achievers demonstrated procedural accuracy but expressed hesitations and uncertainties, highlighting the need for strengthening connections between theoretical understanding and problem-solving procedures.
			L12: Lowest	"My answer is 12.8 g, but I don't know if that's right."	Responses in this level indicated a lack of depth in understanding stoichiometry, reinforcing the idea that hands-on learning, such as robotics, could provide significant benefits in enhancing confidence and comprehension.
	Limiting Reagent	Experimental Group	L7: Highest	"In reaction, H and O_2 have a 2:1 ratio. Moles of H = $50 \text{ g} \div 2 = 25$; moles of O_2 = $50 \text{ g} \div 32 = 1.56$. O_2 is the	Highest achievers in the experimental group demonstrated a strong command of the concept of

Section	Topic	Group	Learner Level	Learner Response	Analysis
				limiting reagent as it runs out first; water produced = $2 \times 1.56 = 3.12$ mol. Robotics simulation visualized this effectively."	limiting reagents and utilized robotics aids, showcasing deeper conceptual understanding reinforced by visual tools.
			L8:Middle	"It's O ₂ that limits the reaction and produces 3.12 mol of water. I'm unsure about why O ₂ is limiting; I just used the graph."	The middle achievers expressed reliance on robotics for visual support but struggled to articulate the theoretical basis for their conclusions, emphasizing the potential gap in understanding limiting reagents.
			L9: Lowest	"I used the graph to get that O ₂ is limiting and water produced is 3.12 mol."	The lowest achievers' reliance on robotic outputs without any conceptual reasoning underscores a need for better instructional strategies focusing on theory to improve overall comprehension.
		Control Group	L10:Highest	"Moles of H = $50 \div 2 = 25$; O ₂ = $50 \div 32 = 1.56$; O ₂ is the limiting reagent, and water produced is 3.12 mol."	Responses were accurate but distinctly lacked engagement with learning tools or visual methods, suggesting a missed opportunity for enhancement through interactive resources.

Section	Topic	Group	Learner Level	Learner Response	Analysis
			L11:Middle	"O ₂ limits the reaction, and 3.12 mol of water is produced. I don't see why the ratio works the way it does."	Middle achievers displayed procedural correctness but failed to grasp the concept of limiting reagents clearly, indicating the need for targeted instructional strategies to bolster understanding.
			L12:Lowest	"I think O ₂ limits, but I'm unsure how to calculate it."	Responses reflected a fundamental lack of understanding and procedural errors, reinforcing the necessity for more remedial resources to solidify foundational knowledge in chemistry.
	Titration	Experimental Group	L7:Highest	"Volume NaOH = 50 mL = 0.050 L. Moles NaOH = $0.050 \times 0.10 = 0.005$ mol; HCl concentration = $\text{moles} \div \text{volume} = 0.005 \div 0.025 = 0.20$ M. The robotics helped visualize tracking the equivalence."	Learners were able to integrate calculations with insights from robotics effectively, suggesting that robotics enhanced their learning experience and comprehension of titration concepts.
			L8:Middle	"I found 0.20 M for HCl. The robotics tool was of help to visualize, but I still don't see how moles and volumes relate."	Middle learners exhibited moderate understanding, though their struggle to integrate calculated values with robotics highlights the need for deeper exploration of theoretical

Section	Topic	Group	Learner Level	Learner Response	Analysis
					principles behind titration.
			L9:Lowest	"HCl concentration is 0.20 M. I don't see how the robotics helped."	Responses demonstrated procedural dependency with minimal conceptual integration, indicating learners might benefit from targeted instructional practices focusing on both calculation and conceptual frameworks.
			L10:Highest	"Moles of NaOH = 0.005; HCl concentration = $0.005 \div 0.025 = 0.20 \text{ M}$."	Despite being correct, this response missed opportunities to reference any interactive learning methods, highlighting an ongoing gap between knowledge and application in practical contexts.
			L11:Middle	"0.20 M for HCl. I don't understand why the formula is used."	Middle achievers expressed factual knowledge but lacked clarity on the underlying principles, suggesting a need for strategies that enhance theoretical instruction alongside practical application.
		Control Group	L12:Lowest	"I got 0.20 M, but I don't understand why those numbers were used."	Responses at this level indicated superficial engagement with the problem-solving process,

Section	Topic	Group	Learner Level	Learner Response	Analysis
					reflecting the urgent need for instructional strategies to develop deeper understanding in chemistry education.

In this comparative study, learners from two schools were assessed on their understanding of stoichiometry and titration, comparing the impact of robotics-based instruction (experimental group) and traditional methods (control group). The analysis revealed both similarities and differences in how these instructional approaches affected learners' engagement, understanding, and academic achievement, with notable variations between the two schools' contexts.

At School A, the experimental group showed a broad range of performance levels. Learner 1, the highest performer, demonstrated strong understanding and practical application of stoichiometric calculations using robotics simulations. In contrast, Learner 2, with a middle-level understanding, displayed partial comprehension of the mole calculations, relying on robotics for visualization but failing to connect these with underlying chemistry concepts. Learner 3, the lowest performer, showed minimal engagement, struggling to apply both the theoretical and practical aspects of stoichiometry despite using robotics. These patterns indicate that, although robotics can engage learners, its impact is contingent on the learner's existing grasp of the material.

In comparison, School B's experimental group had some noteworthy differences. Learner 7, the highest performer, showcased exceptional integration of robotics and theoretical concepts, suggesting a deeper understanding facilitated by the hands-on nature of robotics. Learner 8, at the middle level, demonstrated correct outcomes but struggled to understand the necessity of mole calculations, highlighting a similar issue to School A's Learner 2, where procedural knowledge was not fully linked with conceptual understanding. Learner 9, at the lowest level, faced significant challenges integrating both robotics and stoichiometric calculations, showing the same type of difficulty as School A's Learner 3, where robotics did not significantly enhance understanding.

When comparing the control groups, both schools exhibited patterns of surface-level understanding. At School A, Learner 4, the highest achiever, demonstrated proficiency in stoichiometric calculations but lacked engagement with interactive tools, indicating that while traditional methods supported basic content knowledge, they did not foster deeper learning. Similarly, Learner 5 exhibited some accuracy in calculations but expressed uncertainty about the conceptual underpinnings, while Learner 6 demonstrated a lack of confidence and understanding. In School B, Learner 10, the highest achiever, displayed accurate calculations without using interactive methods, similar to Learner 4 at School A, suggesting a comparable reliance on traditional learning methods that did not fully leverage hands-on activities for deeper understanding. Learner 11 in School B, like Learner 5 in School A, showed correct

calculations but struggled with the process, indicating that the absence of visual aids and interactive learning tools in the control group hindered the ability to grasp the underlying concepts of stoichiometry. Learner 12 in School B, similar to Learner 6 at School A, exhibited minimal understanding and lacked confidence, underscoring the need for improved pedagogical strategies that engage learners at all levels of understanding.

Cross-analyses of the two schools reveal significant differences in how the learning environments influenced the outcomes of robotics-enhanced instruction. In School A, robotics appeared to have a more mixed impact on learners, with some benefiting from the visual aids while others struggled to make meaningful connections between the robotics and conceptual understanding. The differences in engagement levels within the experimental group suggest that additional scaffolding and support could help bridge gaps in conceptual understanding. In contrast, School B's experimental group showed more consistent integration of robotics, with higher achievers benefiting more from the practical visualizations offered by the technology. However, similar to School A, even within the experimental group, lower-achieving learners struggled with connecting robotics to the core concepts, indicating that robotics alone may not be sufficient to overcome foundational gaps in knowledge.

The control groups in both schools exhibited similar limitations, with a reliance on traditional methods failing to engage learners in ways that promoted deep conceptual understanding. Learners in both schools showed proficiency in calculations but lacked engagement with interactive learning tools, which could have enhanced their ability to apply theoretical knowledge in real-world contexts. The similarities in the control group performances across both schools suggest that traditional methods alone may not be sufficient to address the complex nature of topics like stoichiometry and titration, which require more active, hands-on engagement for deeper comprehension.

While both schools demonstrated variability in their learners' responses, the cross-school comparison reveals that robotics-based instruction can lead to better conceptual understanding and engagement in stoichiometry and titration, especially when combined with structured instructional support. However, the differences in outcomes between the two schools also suggest that the effectiveness of robotics-enhanced instruction is influenced by contextual factors such as school resources, teaching methodologies, and the level of prior knowledge. These findings highlight the importance of tailoring educational interventions to the specific needs and contexts of learners to optimize the impact of robotics on chemistry education.

Discussion

This study set out to evaluate the impact of robotics-based instruction on learners' conceptual understanding of stoichiometry and titration across two schools with contrasting educational contexts. The findings confirm that robotics-enhanced pedagogy can significantly improve conceptual performance, particularly when paired with structured instructional support. However, the effectiveness

of this approach varied based on learners' prior knowledge, the fidelity of implementation, and contextual factors such as school resources and pedagogical culture.

These findings are consistent with constructivist and constructionist learning theories, which suggest that meaningful learning occurs when learners actively manipulate materials and construct artefacts (Piaget, 1972; Papert, 1980). In this study, the use of programmable robotic arms and titration tools allowed learners to externalise abstract chemical concepts, facilitating active engagement and reinforcing understanding through iterative exploration. High-performing learners in the experimental groups demonstrated the ability to connect robotic simulations with stoichiometric reasoning and chemical calculations. This is in line with Ching and Hsu's (2024) work, which found that robotics supported scientific inquiry and conceptual comprehension in high school science classrooms.

However, mid- and low-performing learners, particularly in School A, struggled to fully internalise the theoretical underpinnings, even when robotics tools were present. This reinforces Vygotsky's (1978) theory of the Zone of Proximal Development, which holds that learners require scaffolding to bridge the gap between what they can do independently and what they can accomplish with support. The absence of consistent scaffolding may explain the limited conceptual gains among some learners, despite access to robotics. These observations echo Sullivan and Umaschi Bers (2023) and Lin et al., (2024), these authors highlighted that the effectiveness of educational robotics is highly dependent on the pedagogical strategies that accompany them.

The comparative design revealed a more consistent impact of robotics in School B, where robotics integration was more explicitly scaffolded and aligned with chemistry learning outcomes. This suggests that robotics alone is insufficient; its impact is amplified when supported by well-sequenced inquiry-based instruction (Verner & Revzin, 2024; Vilela, Morais & Paiva, 2025). Teachers in School B appeared to embed robotics within the learning trajectory more effectively, allowing learners to contextualise the simulations within broader chemical principles.

Another important dimension is the cognitive efficiency introduced by robotics. Based on Cognitive Load Theory (Sweller, 1988), robotics tools reduced extraneous load by automating titration delivery and enabling real-time visualisation of equivalence points and pH changes. Learners could then focus on interpreting data rather than manually executing complex procedures. This aligns with Naghsh and Bechtold (2024) and Kaelbling et al., (2022), the authors noted that robotics-assisted instruction in chemistry allows learners to concentrate more on analysis than on procedural mechanics.

Moreover, the study provides contextual insight into educational inequality, showing that robotics can serve as a bridging tool in under-resourced environments. While suburban schools have traditionally benefited from better infrastructure, this study shows that even township learners, when provided with modest technological access and instructional support, can derive cognitive gains from robotics-enhanced chemistry instruction. This supports the work of Jackson et al., (2021) who emphasise the need for equity-oriented interventions in STEM education.

Despite the positive outcomes, several limitations must be acknowledged. The sample size ($n = 80$), though sufficient for exploratory classroom-based research, limits generalisability. Furthermore, teacher fidelity in implementing robotics-based instruction may have introduced variation in learner outcomes, as suggested by discrepancies in scaffolding quality between the two schools. Future studies should include classroom observations and teacher interviews to triangulate findings and better understand the mechanisms behind observed effects.

Conclusion

This study examined the comparative impact of robotics-based instruction on Grade 10 learners' conceptual understanding of stoichiometry and titration across two schools with divergent resource contexts. The findings suggest that robotics-enhanced instruction can significantly improve conceptual understanding when it is thoughtfully integrated within a structured pedagogical framework. Learners in both schools demonstrated improved academic performance and cognitive engagement, with more pronounced gains observed in the experimental groups. However, the variability in learner outcomes, particularly among lower-performing learners, underscores the importance of instructional scaffolding, contextual responsiveness, and teacher training.

The success of the intervention reinforces the value of constructivist and constructionist learning environments, where learners actively build knowledge through manipulation, visualisation, and inquiry (Papert, 1980; Vygotsky, 1978). Robotics served not only as a technological aid but also as a pedagogical catalyst that enabled learners to visualise complex chemical processes and interact with them in a meaningful, embodied manner. This supports recent calls for the integration of hands-on digital tools in STEM education, particularly in underserved contexts (Darmawansah et al., 2023).

Nevertheless, the effectiveness of robotics integration is conditional. It does not inherently guarantee deeper understanding unless aligned with well-sequenced curriculum goals, supported by teacher facilitation, and responsive to learners' cognitive and contextual needs. As the literature suggests, the intersection of content knowledge, pedagogy, and technology (TPACK framework) must be deliberately cultivated for technology to achieve its intended educational outcomes (Koehler & Mishra, 2009).

In terms of practical implications, the successful implementation of robotics-enhanced chemistry instruction requires teacher training that extends beyond technical competence. Educators must also be equipped with pedagogical strategies for scaffolding, inquiry facilitation, and formative assessment. Without such instructional mediation, the robotics tools risk becoming superficial or underutilised (Reyes Mury et al., 2022; Bano & Mehdi, 2024). Policymakers should therefore prioritise investment in sustained and contextually relevant professional development focused on the pedagogical use of educational robotics.

Furthermore, robotics activities must be carefully aligned with curriculum outcomes. Inquiry-based learning structures that include explicit concept introduction, guided robotics exploration, and structured reflection, such as those applied in this study, have been shown to support deeper conceptual learning

(Keser & Guven, 2022; Chang & Tsai, 2023). The instructional design must foreground conceptual clarity while enabling learners to explore and apply their knowledge through meaningful interactions with technological artefacts.

In under-resourced schools, robotics can serve as a viable alternative to traditional laboratory experimentation. While such schools often lack wet-lab infrastructure, the use of programmable kits offers a scalable and cost-effective route to experiential learning in chemistry. However, success in these settings is contingent on system-level support, including mobile STEM centres, open-source robotics platforms, and professional learning networks for teachers. Ensuring equity in robotics integration thus requires both strategic investment and systemic planning.

From a research perspective, the current study indicates several avenues for further investigation. Future research should examine the long-term effects of robotics-based instruction on learners' retention of conceptual knowledge and their sustained interest in STEM subjects. Longitudinal and multi-site studies will help to determine whether observed gains are persistent and generalisable across diverse educational contexts.

Additionally, further work is needed to explore how teacher mediation affects the implementation fidelity and learner outcomes of robotics-enhanced lessons. Classroom observations, teacher interviews, and process evaluations could provide more granular insights into the pedagogical mechanisms underlying effective integration. This would enrich understanding of the dynamic interplay between robotics, instructional practices, and learning outcomes.

Finally, given the observed variation in learner responses, differentiated instructional strategies should be explored. Learners with limited prior knowledge or lower performance levels may benefit from robotics tasks that are scaffolded through stepwise guidance, visual supports, and collaborative learning. Future studies could investigate how personalised or adaptive robotics interventions might better support diverse learner profiles, ensuring that educational robotics promotes inclusivity as well as innovation.

Declarations

Ethics Approval Statement This study was conducted in accordance with University of South Africa ethical standards for research involving human participants. Ethical approval was obtained from the College of Science, Engineering and Technology_ School of Computing ethics committee, and permission to conduct the study was granted by the participating schools and relevant educational authorities. **Participant Consent Statement** Informed consent was obtained from all participants involved in the study. For participants under the age of 18, consent was obtained from their legal guardians, and assent was obtained from the learners. Participation was voluntary, and all data were anonymized to ensure confidentiality.

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