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Using Educational Robotics in Chemistry Education: A Systematic Review

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Abstract

Although the value of educational robotics (ER) is recognised in science, technology, engineering, and mathematics (STEM) disciplines, limited research has been published that focusses on using ER to support and enhance chemistry education (CE). This article considers the existing body of scholarly knowledge related to the use of ER in CE published in scholarly literature by means of a systematic literature review. To structure the findings conceptually, a Robotics-Education-Chemistry Considerations (RECC) framework was developed and applied. The findings indicate that the use of ER in CE is understudied. ER is largely applied to enhance the operational and content aspects of traditional CE, rather than to exploit the affordances related to modern education theories and practices that using ER potentially offers to CE.

Introduction

Using educational robotics (ER) to enhance science, technology, engineering, and mathematics (STEM) education is an area of interest and research (Anwar, Bascou, Menekse & Kardgar, 2019; Sapounidis & Alimisis, 2020). It is believed that the use of robotics in education significantly supports modern educational approaches and practices (Benitti & Spolaôr, 2017) and engages learners (Anwar et al., 2019).

Chemistry and life sciences education lag in terms of transdisciplinary approaches and activities (including computing and robotics) compared to disciplines such as physics and mathematics, and it is considered important to address this gap (Gerber, Calasanz-Kaiser, Hyman, Voitiuk, Patil & Riedel-Kruse, 2017). Using ER for CE has also not been as extensively researched as in other STEM areas (see applications areas identified by Benitti & Spolaôr, 2017).

This paper examines the status of scholarly research related to the use of ER in CE. The following questions are considered:

- What is known in scholarly literature about the use of ER in CE?
- What insights can be gained from the interaction between considerations related to robotics, education, and chemistry (as a subject domain)?

The paper is structured as follows: (1) we present a theoretical framework to guide the review and classification of information from publications; (2) the details of the systematic review are provided; (3) findings and a discussion of results are presented; (4) we discuss the practical implications, and (5) research conclusions are presented.

The nature of educational robotics (ER)

ER has a history (since the 1960s) based on the realisation of the benefits of active, collaborative and constructivist learning to acquire high-level thinking and problem-solving skills (Sapounidis & Alimisis, 2020), while building social skills of learners (collaboration, communication, creativity) (Anwar et al. 2019). ER is applied at all educational levels, both in formal (schools, universities) and informal settings (summer camps, robotics competitions, and science clubs) (Anwar et al. 2019). For STEM topics, ER is meaningful for several reasons. Anwar et al. (2019) argue that the nature of robots has the potential to stimulate learner interest in STEM topics, leading to improved learner engagement. Furthermore, ER promotes development of thinking skills essential for STEM learners such as critical thinking, problem solving (Anwar et al., 2019) and computational thinking (Darmawansah, Hwang, Chen & Liang, 2023). The nature of ER requires integration of STEM disciplines (Anwar et al. 2019), thus enhancing transdisciplinary learning. The visual, tactile, and situated nature of robots allow improved understanding of abstract and theoretical STEM concepts applied in ’real world’ situations (Anwar et al., 2019).

In ER publications, STEM subjects are often treated as an encompassing entity. However, interest in and use of ER is not at the same levels for all STEM subjects. Some subjects have ‘intuitive’ matches with robotics, for example engineering, computing, and mathematics. Benitti and Spolaôr (2017) and Darmawansah et al. (2023) show that topics appearing in ER science and technology papers relate to technology (computational technologies, robotics, and coding), engineering, mathematics (mainly mathematical methods), with limited coverage of topics such as life and earth sciences, and no specific coverage of chemistry. Therefore, the need for a review to understand the status of ER in CE was identified and is the focus of this paper.

Conceptual (theoretical) basis

Figure 1 shows our conceptual framework that informed our research.

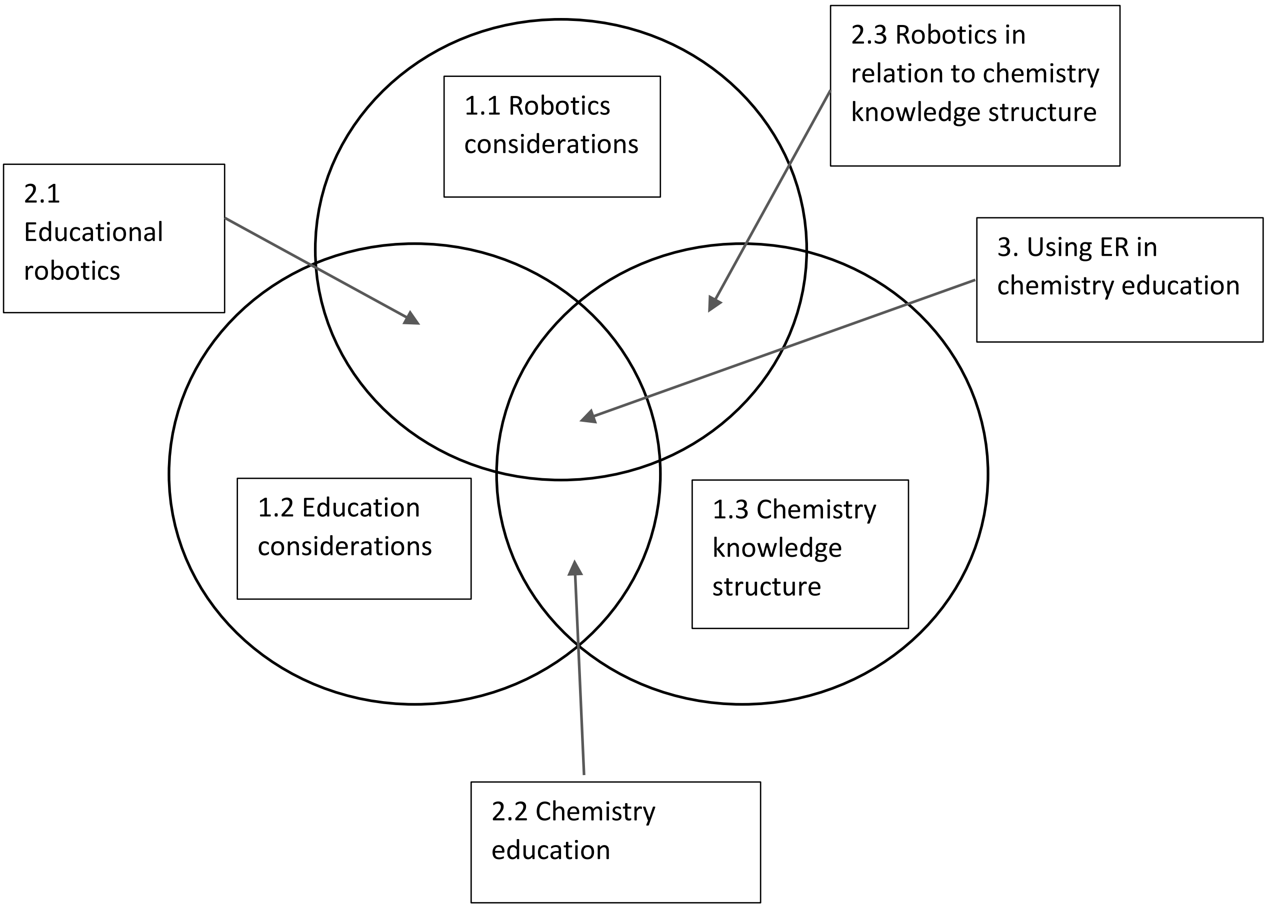

Figure: 1: Robotics-Education-Chemistry Considerations (RECC) framework

The research focusses on the intersection of considerations of robotics, education, and chemistry knowledge. The framework (Figure 1) is an analogy to the TPACK framework (Koh, Chai, & Lee, 2015), with adaptations. The proposed framework focusses on broader educational considerations of teaching and learning. The framework does not focus exclusively on knowledge (of, for example, teachers), and therefore we rather use the term 'considerations' related to the three areas of interest. The framework is directed at robotics as a technology and chemistry as a subject. The framework is named the Robotics-Education-Chemistry Considerations (RECC) framework and represents three levels: (1) a foundational level presents separate considerations of robotics, education, and chemistry content knowledge; (2) a second level presents the intersections between foundational considerations (robotics-pedagogy, robotics-chemistry, and pedagogy-chemistry); (3) a third level presents the intersection of three considerations (robotics-education -chemistry).

We briefly discuss each area and the relevant intersections.

Level 1: Robotics considerations (1.1 in Figure 1)

These considerations relate to the technical considerations of robotics as a technology and an understanding of its affordances and uses (Cox & Graham, 2009). A diverse range of robotics kits are available, representing variations in, for instance, cost, range of functionalities, and levels of assembly required (Sapounidis & Alimisis, 2020).

The main considerations in the selection of robots (Sapounidis & Alimisis, 2020) relate to cost, artefact attractiveness, simplicity of all aspects of assembly and operation, and whether the software is proprietary or open source.

Level 1: Education considerations (1.2 in Figure 1)

Considerations relate to conceptual educational approaches (independent of subject matter), and all aspects of structuring of tuition and learning and activities, learner interaction, and use of specific methods and techniques (Cox & Graham, 2009).

Level 1: Chemistry knowledge structure (1.3 in Figure 1)

This refers to the representation of chemistry as a subject (Cox & Graham, 2009). Our foundation is the widely accepted and adopted chemistry ‘triplet’ proposed by Johnstone in 1982 (Taber, 2013). The triplet allows for conceptualisation of the chemistry knowledge field at three levels: (1) descriptive and functional (experiences and sensory perceptions of chemistry), (2) representational (semiotic and communicative aspects), and (3) explanatory (Taber, 2013). Talanquer (2011) expands the triplet by adding dimensions (time, energy, and structure), and scales (ranging from subatomic to macroscopic). Thus, a complex picture emerges of chemistry knowledge (Talanquer, 2011).

Level 2: ER considerations (2.1 in Figure 1):

This refers to general considerations when using robotics for educational purposes.

ER may improve learning results, engagement, and interest of learners (Anwar et al., 2019). ER supports strategies such as constructivist and constructionist learning and collaborative learning methods such as project-based and inquiry-based learning (Altin & Pedaste, 2013).

ER research has focused on the evaluation of ER benefits, learning-related aspects, learner creativity and motivation, broadening access, and teacher development (Anwar et al., 2019). Although the potential for ER is recognised (Alimisis, 2013), the impact and effectiveness of ER to achieve outcomes, such as improving learning outcomes, is questioned (Anwar et al., 2019).

Education practices should take cognisance of the development of automation in professional practice and the availability of cost-effective robotic technologies (Fuhrman et al., 2021), especially liquid handling robotic technologies (Gerber et al., 2017).

Level 2: Chemistry education (CE) (2.2 in Figure 1)

For chemistry education, there is a perception that chemistry as a subject domain is complex and therefore difficult to master. The diversity of levels in chemistry concepts that need to be grasped (that is, macro-, molecular, and symbolic) by learners and students provides a plethora of challenges for chemistry educators (Garcia-Martínez & Serrano-Torregrosa, 2015).

Excessive chemistry content leads to disconnected information and contributes to low learner motivation and engagement with chemistry learning materials (Gilbert, 2006; Mahaffy, 2015). Students thus do largely rote learning and do not connect the learnt chemistry concepts to real-life problems beyond the teaching context. Thus, chemistry learners often fail to see the relevance of chemistry to real life, and this (in conjunction with low motivation and enthusiasm) contributes to many students choosing not to continue with chemistry for tertiary studies (Gilbert, 2006; Mahaffy, 2015).

Practical aspects of CE in laboratories pose a range of challenges, including safe and efficient experimental procedures and use of chemicals (Lu, Xu & Zhu, 2021), and access to such experiments for all chemistry learners, even those with disabilities (Khnykin, Laletin & Uglev, 2021).

Discourses on the adoption and use of novel education practices in CE emphasise aspects, including viewing CE as human activity, the importance of context-based education (Gilbert, 2006), visualisation, innovation in pedagogies and curriculum design, and teacher development and support.

Understanding CE as human activity implies designing curriculum with the learner (rather than subject content) at the core (Mahaffy, 2015). This approach highlights the links between chemistry and ‘real life’, thus enhancing sense making and communication with learners about the nature of science (Mahaffy, 2015, op. cit.). The contexts of teaching chemistry become important (Avargil, Herscovitz & Dori, 2013; Gilbert, 2006; Parchmann, Broman, Busker & Rudnik, 2015), enabling learners to link content with contexts, contributing to improved conceptualisation (Gilbert, 2006) and enhancing student interest and motivation (Middlecamp, 2015; Chiu & Chou, 2015). Gilbert (2006, op. cit.) argues that understanding of context also contributes to the reduction of excessive learning content, although Avargil et al. (2013) point out that time spent on core topics is not reduced when innovative and context-based approaches are adopted. An aspect of contextual teaching is related to the effective merging of chemistry with other disciplines, which is appealing to students (Avargil et al., 2013).

It is important to use innovative approaches in curriculum and teaching (Goedhart, 2015) and to ensure that CE research informs these (Cole, 2015). Innovative approaches incorporate aspects of constructivist learning (Goedhart, 2015), and appropriate approaches for CE include active learning (problem-based learning/community-based (service) learning) (Poë, 2015), inquiry-based learning (Lamba, 2015), flipped classroom approaches (Goedhart, 2015) and innovative community-engaged approaches (McDonnell, 2015).

Level 2: Using robotics in relation to chemistry knowledge (2.3 in Figure 1)

This refers to the use of robotics in relation to aspects of chemistry knowledge (analogous to Cox and Graham, 2009). Although situated in the context of tuition and learning of chemistry, this consideration is not specifically linked to pedagogical considerations.

Level 3: Use of ER to teach chemistry (3 in Figure 1)

At this level, the intersection between all three areas of consideration takes place. As indicated previously, research on the use of ER for CE is limited, and lags compared to research in other STEM areas (Benitti & Spolaôr, 2017).

Use of a systematic review as research approach

A systematic review was used, as it allows a holistic picture to emerge through the collation of academic research on the use of ER in CE. Systematic reviews for education (Newman & Gough, 2020) have the characteristic of an ‘aggregative synthesis logic’ (Newman & Gough, 2020, p.5), with a predefined protocol that specifies the methodological aspects of the study.

The process followed corresponds to the process set out by Newman & Gough (2020, p.6), which includes the development of a conceptual framework to guide the study, the steps taken to identify and select a comprehensive set of publications related to the research question, applied quality measures to assess the inclusion or exclusion of publications for analysis in the study, and qualitative coding of selected papers for elements of interest. Aspects of the process that could introduce bias are listed and partially addressed through the explicit description of the processes followed.

A qualitative aggregative analysis was performed and is presented. The quality assessment process (Greenhalgh & Taylor, 1997) involved ensuring that the studies were related to the research topic, with appropriate use and execution of research methods. Studies without empirical evidence to support findings (descriptive studies) were excluded. The first author reviewed, and second author moderated the process. The ethics committee approval number for this project is 091/PMG/2019/CSET_SOC.

The Boolean search strings are listed in Table 1.

Searches were carried out on Web of Science, ERIC (ProQuest version), Ebsco, ACM, and IEEE. No filters were used in searches performed across all fields.

Table 1: Boolean search

Topics	Strings
Chemistry	‘Chemistry’ OR ‘chemical AND science*’
Education	‘Education’ OR ‘Educate’ OR ‘Educator*’ OR ‘Educational’ OR ‘Teaching’ OR ‘Teacher’ OR ‘Teach’ OR ‘Teachers’ OR ‘Learn’ OR ‘Learning’ OR ‘Learner’ OR ‘Learned’ OR ‘Learns’ OR ‘Learnt’ OR ‘Engag*’ OR ‘Mentor*’ OR ‘assess*’
Robotics	‘Robot*’ OR ‘educational AND robots’ OR ‘educational AND robotics’

Table 2 presents the search carried out on the open Internet. Note that full search strings are impossible to paste into the search engine. No timelines were specified; thus, included papers represent an open timeline up to the date of last search (2023-05-15).

Table 2: Search strategy for Google Scholar (2023-05-15)

Topics	Strings
Chemistry	‘Chemistry’ OR ‘chemical AND science*’
Education	‘Educat*’ OR ‘Teach*’ OR ‘Learn*’ OR ‘Engag*’ OR ‘Mentor*’ OR ‘assess*’
Robotics	‘Robot*’ OR ‘educational AND robots’ OR ‘educational AND robotics’

The Google Scholar (2023/05/15) yielded 83300 pages of which 49x20 were viewable. A further search (2023/05/15) included terms ‘robotics’ AND ‘chemistry’ AND ‘education’, yielded 279000 pages, of which 49x20 were viewable. The applicable inclusion and exclusion criteria are listed in Table 3.

Table 3: Inclusion and exclusion criteria

Included	Excluded
English-language publications	Non-English publications
All dates	No full-text access
Published articles	Grey literature
Conference papers	Systematic reviews
	Meeting notes

To verify the completeness of included articles, a snowball search (Wohlin, 2014) was performed as a complementary approach.

The Prisma diagram is shown in Figure 2.

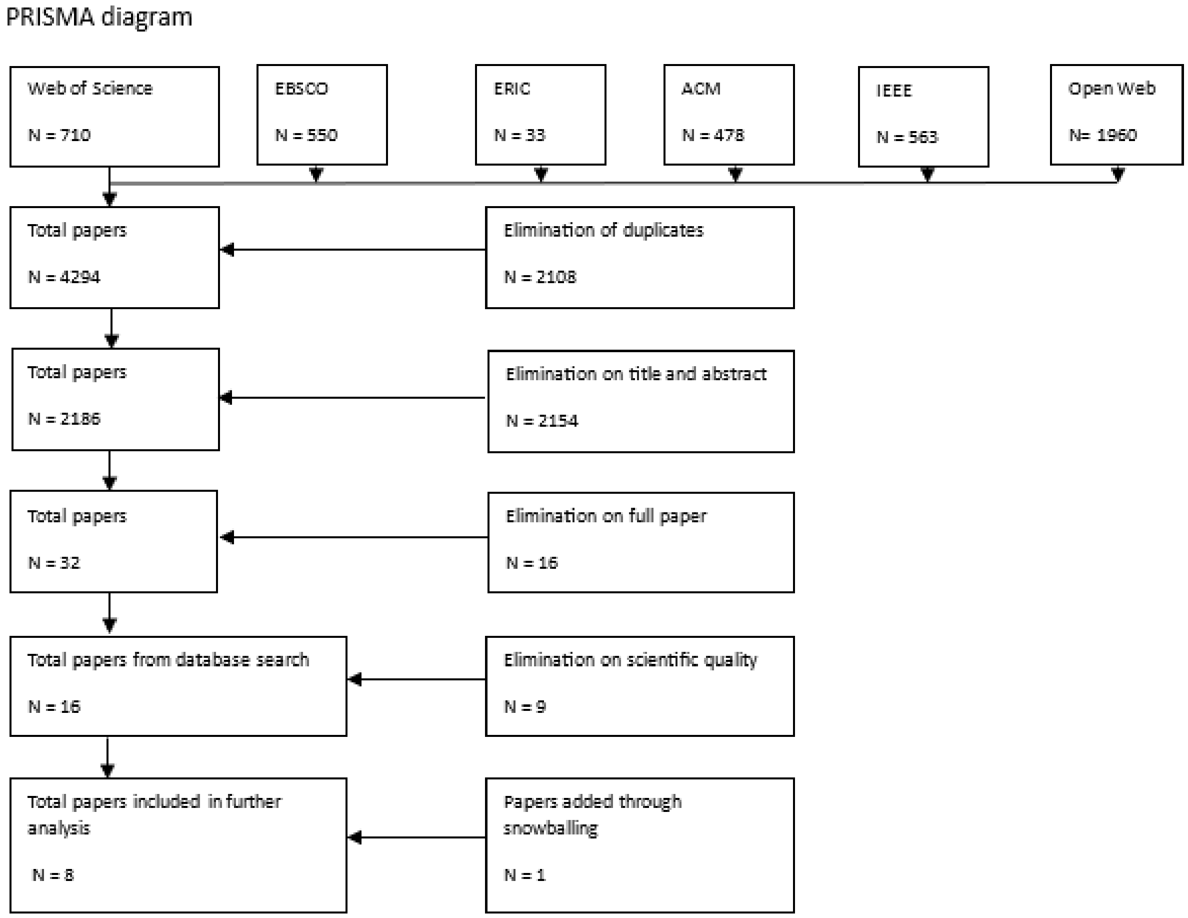

Figure 2: Prisma diagram

The eight studies selected are shown (Table 4). The publications appeared in years 2010-2023.

Table 4: Included studies

No.	Paper	Research Category	Nature of research
1	Fuhrmann et al. (2021)	Non-experimental	Pre- and post-test evaluation of learners.
2	Gerber et al. (2017)	Non-experimental	Post-use evaluation of learners' experiences.
3	Randall, Klingner & Correll (2016)	Descriptive	Principles and system of swarm robots for the simulation of chemical reactions and feedback on student reactions after use.
4	Soong et al. (2019)	Descriptive	System description with a focus on accessibility for disabled students
5	Tarrés-Puertas et al. (2022)	Non-experimental	Post-use evaluation of learner experiences
6	Tarrés-Puertas et al. (2023)	Non-experimental	Post-use evaluation of learner experiences
7	Verner & Revzin (2017)	Qualitative	Assessment of student engagement during automated chemistry learning
8	Verner & Revzin (2010)	Non-experimental	Assessment of activity and post-course questionnaire for student feedback

Findings

The findings were analysed and synthesised using a qualitative approach. The presentation of findings and discussion are structured using the RECC diagram (Figure 1), together with supporting information (such as aspects of chemistry covered, and school levels of learners).

Aspects of chemistry covered

Table 5 shows areas of application of robotics in CE. Numbering of included studies are as per Table 4.

Table 5: Robotics application in CE

Chemistry aspects	Studies
Basic liquid handling experiments	Titration [4],[7],[8] Dilution [2],[5] pH [1],[2] Density layers [5] Mixing [5],[6] Sedimentation [7]

	Neutralisation of dangerous materials [7] Spectrophotometry [2]
Simulations in CE	Chemistry reactions [3] Industry 4.0 processes [5]

The focus of most experiments requires the handling of liquids. Simulations of chemical reactions and chemical processes represent interesting applications of robotics.

Educational levels for the included studies are shown in Table 6.

Table 6: Educational levels and studies

School level	**Studies**
Pre-school	[5],[6]
Primary school	[3],[9][2],[5],[6]
Middle school	[1],[2],[6]
High school	[1],[3],[6],[7],[8]

Like robotics studies in other disciplines, the focus is largely on high-school learners.

Table 7: Robots used (1.1 in Figure 1)

Robotic platform selected for use	**Studies**
Lego (Mindstorms)	[2],[5],[6],[7]
Own constructions	[8]
Arduino	[1],[4]
Open-Source Droplet Swarm Robotic Platform	[3]

As Table 7 shows, Lego Mindstorms kits and Arduino are mostly preferred. An innovative application is using open-source swarm robotics to simulate chemistry reactions in a visual manner (Randall et al., 2016).

In terms of the chemistry education triplet, most applications are related to descriptive and functional (laboratory experimental) work, while Randall et al. (2016) demonstrate the use of robotics for representational and explanatory purposes.

Tables 8-10 show considerations and intended outcomes of robotics use in terms of the RECC framework (Figure 1).

Table 8: Level 1 considerations informing the use of robots and intended outcomes

Category	**Considerations**
Robotics (1.1 in Fig. 1)	
Hardware characteristics	Liquid handling abilities [1],[2] System cost [2],[3],[4],[5],6],[7],[8] Ease of construction [4] System memory requirements [4] Use of commonly available components and equipment [5] Use of standard Lego parts [2] Hardware customisations [6]
Software and protocols	Reproducibility of robot [2] Use of open-source software and protocols [5]

	LHR selection conveys characteristics such as speed, throughput, and reproducibility to learners [1] Software customisations [6]
Interfaces	Customisations of interfaces [6] Construction of non-gender stereotypical interfaces [6] Accessibility features [6]
	Self-construction by learners [7] Enabling activity spaces through combining low-cost household consumables with modified robot designs and programming pipetting routines [1],[2]
Education (1.2 in Fig. 1)	
Novel approaches to teaching	Affordances of constructivist learning [7] Use of inquiry-based project learning with the Next Generation of Science Standards [1]

Table 8 shows the significance of the cost of using robotics for CE. Furthermore, limited attention was paid to the conceptualisation of new teaching approaches that could potentially be applied (1.2 in Figure 1).

Table 9: Level 2 considerations (ER, CE, robotics-chemistry knowledge structure interaction)

Category	**Consideration**
CE (2.2 in Fig. 1)	
Computational thinking and chemistry	Computational thinking as a fundamental skill in chemistry [1] Mapping aspects of computational thinking to science topics [1] Introduction to encoding of scientific procedures [1]
The need for hands-on engagement	Hands-on activities for more positive perceptions of learning [1]
Robotics and chemistry as a subject (2.3 in Fig. 1)	
Automation of manual laboratory operations	Support for automation and programming in chemistry (wet science) [1],[4],[7],[8] Safer practical work [5] Safer simulation of industrial processes [5] Diversity of experiments and topics is possible [2]
Representation of chemistry using robotics	Simulation of the basic rules of chemistry [3]
Improved efficiency	Reduction of experimental errors [8] Better time efficiency through automation [8]
Accessibility	Improving access to chemistry experiments (experiential learning) for all, including learners with disabilities [4]

Table 9 shows a significant focus on the link between robotics and chemistry knowledge. From an educational perspective, the importance of computational thinking in terms of chemistry knowledge is highlighted, and the importance of hands-on experiences is mentioned. The interaction between innovative educational practices and chemistry is limited.

Table 10: Level 3 considerations

Consideration	Aspects
(Using ER in CE (Level 3 Figure 1)	
Expand and focus learner laboratory experiences	Automation in wet sciences education [1],[2] Integration of chemistry and computing [1] Improved scientific procedures enabled by technology [1] Programming robots to execute scientific experiments [1],[2] Learners build their own tools [2] Learners experience technology-based acceleration of scientific research [1]
Impact of advanced learning environments	Provision of an advanced learning environment improves learner motivation for chemistry [8]
Enhancing engagement and experiential learning	Improving learner engagement [2],[5],[7] Automating chemistry experiments [2],[5],[8] Enabling engaging experiments [2] Using the innate curiosity of learners for experiments [5] Harnessing learner enthusiasm to play with robots [5] Improved visible and tangible interaction between learner and chemistry [3] Motivating students in chemistry through experimentation [8]
Diversity and inclusivity in chemistry education	Using ER to increase interest in STEM [5],[6], and specifically chemistry [3] Reduction of the gender gap [6] Reduction of the digital divide [6] Stimulating the interest of female learners (computational science through chemistry applications [5]
Improving and promoting cognition and meta-skills:	Computational thinking [1],[5] Design thinking [4] Creativity [5] Problem solving skills [5] Sequential thinking [1] Systems thinking [3] Visual-spatial cognition of chemical processes [3] Improved understanding of chemistry [3]
Improved chemistry teaching and learning opportunities	Merging the accurate representation of physical systems with educational requirements [3] Alignment with UN SDGs [5],[6] Universal access to experiential learning [4] Reduction of the gender gap in STEM [5],[6] Improved interactivity [3] Integrating RE and CE [2] Improving knowledge and skills for chemistry and technology [5],[7]

Considerations at level 3 (Figure. 1) (Table 10) show the intention to enhance learners' laboratory experiences (using robotics, provision of advanced learning environments, improving diversity and inclusivity, and the intention of having a positive impact on cognitive aspects of CE). This includes efforts to improve laboratory practices and introduce cognitive aspects of learning associated with ICT use (for example computational thinking). However, a more human-centred educational approach is lacking.

Scholarly findings on the use of robotics in CE

The actual (research-based) findings reported in included studies are shown using the RECC model. The findings of all studies are preliminary, and more in-depth research is needed. No scholarly findings related to Level 1 considerations were reported.

At level 2 (2.3 in Figure 1) Verner and Revzin (2010) report that a comparison of automated and manual titration in a high school experimental laboratory showed that the automated system led to better time efficiency and fewer experimental errors, especially in the case of inexperienced learners.

Table 11: Level 3 considerations (Using ER in CE Part 3 in Figure 1)

Consideration	Specific aspects
Combining chemistry and computing related work	Learning reflects a combination of scientific and computational aspects [1]
Learner engagement and enjoyment	Students find robotics-based experiments interesting, engaging, and exciting [2],[5],[7] Learners enjoyed activities and were motivated and interested [2],[6] Learners repeat robotics activities [6] Learners enjoyed robotics and liquid experiments [2]
Learning outcomes and perceptions of learning outcomes	Students learn both robotics and chemistry [2] Activities are experienced as non-trivial [6] In early childhood, the learner-robot interaction is the same for boys and girls [6] Learners perceive experiments as simpler, faster, safer, and more accurate [8] Learners prefer experimental environments with state-of-the-art technology [8]
Teaching methodologies and teaching environments	Learning experience is appreciated in terms of open-endedness, cohesion among learners, and saving of time and effort [8] Learners considered the industry-like experience as relevant [8] Swarm-based simulations are adequate for introductory chemistry modules [3]
Cognitive considerations	Chemistry learning takes place [7] LHR work significantly improved algorithmic thinking of learners [1] Learners understand advantages of robotics (precision, time savings, convenience, and debugging opportunities) as benefits for experimentation [8] Experiments are faster, therefore more time is spent on inquiry-focused activities [8]

Table 11 indicates using ER created a positive learning experience. Learning occurred in both chemistry and computational thinking. As indicated in Table 4, findings are mostly based on pre/post evaluations. Evaluation studies in education raise concern (Marsden & Torgerson, 2012) in terms of context and learner maturation. Learning experience findings should therefore be considered indicative (rather than definitive). Extensive and formal studies are required to verify the evaluations. No findings are reported that indicate to what extent the use of ER may impact student decisions to pursue chemistry at tertiary levels.

Discussion of findings

Research on the use of ER for CE is limited. Reported work seeks ways in which 'robotics technology can benefit traditional CE' (Lu et al. 2021, p. 2720), rather than explicitly examining educational affordances presented by the available technology.

Student motivation and engagement with learning materials

Preliminary evidence shows that students are interested and motivated when doing robotics-based experiments. This needs to be confirmed by more in-depth research.

Evidence is also required to determine the extent to which learners see the real-life relevance of chemistry and choose to continue with CE. Although learners reported positive experiences in using high-tech environments and equipment that simulate industrial processes, the literature presents limited evidence that the introduction of robotics-based experiments is inspiring high school students to continue with CE. The introduction of robotics while retaining traditional teaching methods may be ineffective in achieving inspiration.

Connecting chemistry concepts to real-life and other contexts

Adding robotics to chemistry experimentation provides students with connections to real-life in preparation for industrial and research laboratory processes. Tarrés-Puertas et al. (2022) suggest that chemistry experiments conducted should be contextualised in engaging ways.

Using innovative approaches to curriculum and teaching

ER potentially supports innovative collaborative learning approaches in STEM. Limited research has been conducted on the benefits of combining innovative teaching practices with robotics in a chemistry curriculum. Fuhrmann et al. (2021) describe an inquiry-based project learning curriculum considering the Next Generation of Science Standards (NGSS). Verner and Revzin (2017) consider the context of educational potential afforded by constructivist learning and describe a learning event that is constructivist in nature, concluding that such an approach holds potential, especially where traditional teaching is ineffective.

Implementing innovative teaching and learning approaches using ER remains unexplored, with potential for extensive research to inform improved teaching and learning practices.

Without understanding the human-activity systems of modern CE practices, the use of ER in chemistry laboratories will have limited educational impact. Understanding the role and impact of context in defining the appropriate use of ER in CE is crucial. An important missing context is the use of robotics to teach chemistry in developing countries. Insights gained from research in these contexts may inform efforts to overcome existing CE divides.

Teacher support and professional development

This aspect is not covered in included studies, despite the recognition in literature of the importance of professional development of teachers to support robotics in educational settings

(Chalmers, 2017). Without visionary teachers equipped with the necessary knowledge and skills, the field will remain limited, despite its potential.

Practical implications

Given the nature of the chemical industry, it is important to introduce computational aspects to learners, and doing this through the implementation of robotics has the benefit of impacting positively on learner attitudes and experiences.

Implementing ER in CE can lead to significant educational benefits when combined with modern teaching theories and approaches. Teachers must understand the educational foundations of ER, related to constructivism and constructionism (Ronsivalle et al., 2019), and inquiry-based and project-based learning (Schina, Esteve-González, & Usart, 2021). These foundations represent a departure from 'traditional' teaching practices for many teachers, requiring pedagogical changes to teaching practices. Furthermore, chemistry teaching using ER requires skills (or access to skills) related to fundamentals of robotics, computer science and technology, coding, and multimedia (Ronsivalle et al., 2019). Caution is required when ER is included in a curriculum, to ensure that adequate planning of learning opportunities and strong appropriate guidance of learners take place; furthermore, educators must select appropriate robotics technology carefully, taking factors such as age and gender into account (Sapounidis & Alimisis, 2020). More research is needed on practical aspects related to the implementation of ER in educational institutions (Anwar et al., 2019).

Teacher training (both updating pedagogical skills and using ER) for those wishing to pursue the ER option is essential (Alimisis, 2019). Ideally, teacher training programmes should be collaborative, provide teachers with materials for classroom use, and provide some post-training interaction with teachers who participated (Schina et al., 2021).

Using ER in CE allows for contextual and visionary aspects. By using contextual elements (materials, case studies), learners relate the curriculum to their own situations, thus improving the relevance of both chemistry and its automation, while demonstrating chemistry to students using high-tech robotics environments, thus creating “authentic environments (Hackling, 2015) may provide a vision of the future and inspire learners to continue with CE studies.

Conclusions

This paper considered existing publications that focus on the use of ER for CE. There is general agreement in the literature analysed that operationally using ER ensures safer and more efficient experiments in educational laboratories, leaving more time for aspects such as planning and analysis of experiments.

However, limited knowledge has been published on the educational impact of ER in CE and the extent to which ER can contribute to innovative educational practices, contextual teaching, motivation of students to continue with chemistry studies, and best practices to support educators who wish to implement robotics-related activities in their teaching practice. It is implied that research on the use of ER in CE will have to be within the context of examining and researching the employment and use of modern human-centred education practices in chemistry. Such research can inform the theory and practice of the use of ER in CE.

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Note: The references marked with * were analysed as part of the review.

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