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From Knowledge to Literacy: Exploring the Theoretical Interface between Scientific Understanding and Chemistry Education

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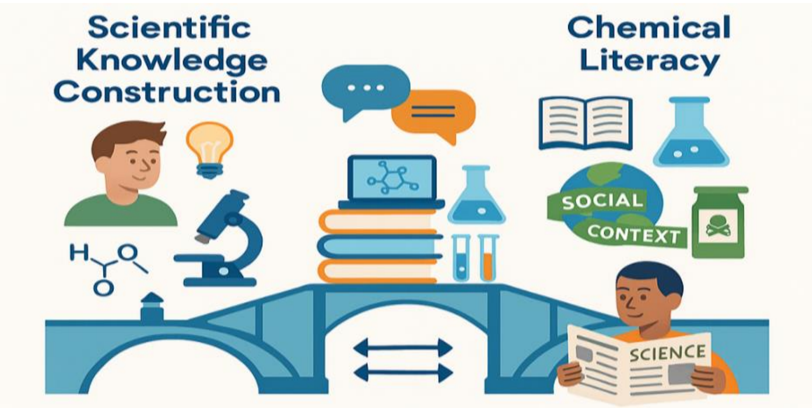
Students' scientific education in basic education has increasingly been examined from two complementary perspectives: the construction of scientific knowledge and chemical literacy. The former focuses on cognitive and formative processes involved in learning scientific concepts and practices while the latter emphasizes the ability to interpret, communicate, and apply chemical knowledge to social, environmental and technological contexts. This paper is a literature review which aimed at exploring interfaces, convergences and pedagogical potential of both perspectives in chemistry education. Eighty-five publications comprise a sample that was identified through searches in academic databases and institutional repositories. After preliminary screening and abstract review, 66 sources were selected for in-depth reading. Out of them, 45 papers were retained for the final analysis, based on their alignment with the theoretical axes of this study. Finally, 25 papers were selected to compose the Results and Discussion section due to their strong conceptual and methodological contributions. The analysis reveals that, although both perspectives have been frequently addressed by the literature, few studies explicitly integrate them. Findings suggest that fostering a more consistent articulation between scientific knowledge construction and chemical literacy may enrich pedagogical practices to make them more meaningful and contextualized and contribute to the development of scientific and critical citizenship in chemistry education.

Graphical abstract



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1. Introduction

In recent decades, objectives of science education have undergone significant transformation to reflect broad societal, epistemological and pedagogical changes [1]. Moving beyond traditional views that prioritize transmission

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of factual content, contemporary perspectives emphasize the importance of engaging students in processes that support both conceptual understanding and the development of competencies required to navigate an increasingly science- and technology-driven world [1, 2]. Therefore, chemistry education has increasingly been understood not only as a means to develop academic proficiency in the discipline, but also as a powerful tool for promoting active, critical and scientifically literate citizenship [3].

Two key constructs that have emerged as central to these discussions are the *construction of scientific knowledge* and *chemical literacy* [4, 5]. The former refers primarily to cognitive, epistemological and sociocultural dimensions of how students learn and make sense of scientific concepts while the latter centers on practical and contextual applications of that knowledge to real-life situations [4, 5]. Although these dimensions have been often addressed separately in research and policies, they are inherently interdependent, i. e., without meaningful conceptual understanding, literacy becomes superficial; without opportunities for application and contextualization, knowledge remains abstract and inert [4].

Construction of scientific knowledge in chemistry education is deeply rooted in constructivist learning theories, mainly those that emphasize active engagement, dialogic interaction and social negotiation of meaning [6, 7]. Piagetian and Vygotskian frameworks have long informed instructional design and highlighted the importance of prior knowledge, cognitive conflict and the role of language in shaping understanding [8]. More recent approaches extend this view by recognizing the importance of disciplinary discourse practices, model-based reasoning and the epistemic nature of science learning [9]. chemistry education benefits from pedagogical strategies that scaffold the construction of conceptual models (e.g., particulate representations), foster argumentation and promote engagement with the nature of scientific knowledge [6, 9].

On the other hand, the notion of *chemical literacy* has gained prominence as a response to the growing demand for science education to address socially relevant issues and prepare students for informed participation in democratic societies [2, 10]. Building upon the broader concept of scientific literacy, chemical literacy encompasses not only the ability to read, interpret and critically evaluate chemical information, but also to make decisions based on that knowledge in everyday contexts, from environmental issues and health-related decisions to ethical considerations in technological innovations [1, 10]. This perspective emphasizes the relevance of curriculum design that connects Chemistry contents to students' experiences and societal challenges, thus, reinforcing motivation and the perceived value of the discipline [10].

Despite growing recognition of the importance of both domains, *research that integrates the construction of scientific knowledge with chemical literacy remains limited* [11]. Studies often focus on either epistemological framework for teaching and learning or on curriculum reforms aimed at societal relevance, but they rarely bridge both systematically [4, 11]. As a result, pedagogical practices may oscillate between abstract formalism and superficial contextualization and miss opportunities for meaningful learning [12, 13]. The articulation of these perspectives requires theoretical precision and practical strategies that enable Chemistry teachers to design learning experiences that are both intellectually rigorous and socially meaningful [11, 13].

This paper fills this gap by reviewing literature that addresses either or both paradigms and was published over the past two decades. It aimed to identify points of convergence, tensions and unexplored opportunities for synergy. It proposes that an integrative approach to chemistry education – grounded in both the construction of disciplinary knowledge and the development of chemical literacy – may enhance students' engagement, deepen conceptual understanding and ultimately contribute to develop critically and scientifically literate citizens [14, 15].

2. Material and Methods

Methodological Procedures

The methodology of this study is a *narrative literature review*, which is suitable for synthesizing theoretical frameworks and empirical findings across diverse sources, mainly in interdisciplinary fields, such as chemistry education. Since this approach enables the interpretation of trends, conceptual overlaps and theoretical gaps, it provides an analytical foundation to construct pedagogical insights and research guidelines [16].

The *literature search* was conducted on major academic databases, such as *Scopus*, *Web of Science*, *ERIC* and *SciELO*, to ensure broad coverage and academic rigor. Search terms included "chemical literacy," "scientific knowledge construction," "chemistry education," "science learning processes" and "critical chemistry education." Inclusion criteria were: **(i)** publications dating from 2015 to 2025; **(ii)** peer-reviewed journal articles, doctoral dissertations, master's theses and official educational policy documents; and **(iii)** direct relevance to the theoretical constructs under investigation. The initial sample comprised 85 publications. After a preliminary screening and full-abstract reading, 66 sources were selected for the in-depth analysis based on relevance and methodological consistency [17].

The initial sample consisted of 85 publications which were identified through searches in academic databases and institutional repositories with the use of descriptors related to science education, Chemistry teaching, scientific knowledge construction and chemical literacy. In the first stage, titles and abstracts were screened to assess thematic relevance and exclude duplicate entries; it resulted in 66 sources which were fully read. In the second stage, exclusion criteria included: **(i)** insufficient conceptual depth on either of both theoretical axes; **(ii)** superficial or merely descriptive methodological approaches; **(iii)** lack of peer review or academic legitimacy (in the case of non-indexed material); and **(iv)** absence of clear pedagogical implications for chemistry education. After this process, 45 studies that exhibited the strongest conceptual alignment and methodological robustness were selected for the final analysis (Figure 1).

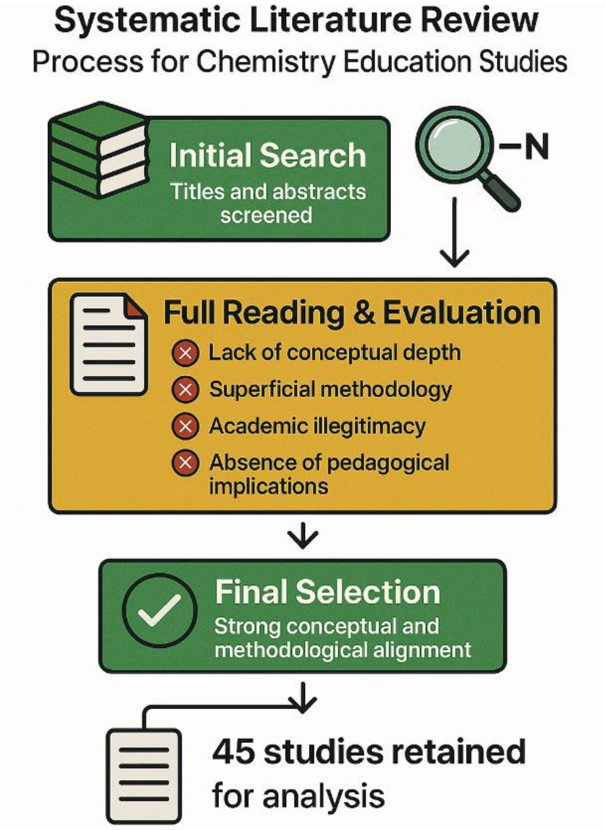

Figure 1. Flowchart of the stages of the systematic review process: initial screening of titles and abstracts (66 studies), full-text reading with application of exclusion criteria and final selection of 45 studies with the strongest conceptual alignment and methodological robustness.

To reinforce replicability, the literature search was conducted between January and March 2025 in four academic databases: Scopus, Web of Science, ERIC, and SciELO. The following search strings were employed in different combinations: ("chemical literacy" OR "chemistry literacy") AND ("scientific knowledge construction" OR "science learning processes") AND ("chemistry education" OR "critical chemistry education"). The initial retrieval identified 85 publications: 32 from Scopus, 25 from Web of Science, 18 from ERIC, and 10 from SciELO. After removal of duplicates and preliminary abstract screening, 66 sources were retained for full-text reading. Following the exclusion criteria previously described, 45 publications were finally selected for detailed analysis.

The framework of the *qualitative content analysis* involved full-text reading, open coding of significant theoretical and pedagogical contributions and the organization of codes into broad thematic categories. Categories were developed iteratively and enabled the synthesis of key themes and relations between the concepts of scientific knowledge construction and chemical literacy. This interpretative process supported the identification of theoretical intersections, pedagogical strategies and research gaps [18].

Although this review did not involve empirical data collection with human participants, *ethical considerations* were maintained throughout. It includes the accurate citation of intellectual contributions, fidelity to the authors' original interpretations and transparency in the synthesis process [19].

3. Results and Discussion

Forty-five out of 66 sources identified throughout the narrative literature review were selected because they demonstrated the strongest alignment with the theoretical axes of this study: *the construction of scientific knowledge and the development of chemical literacy*. Choices were based on their citation relevance, empirical depth, theoretical innovation and alignment with international standards of research into chemical education. This curated corpus provides a solid foundation for critically examining intersections between knowledge acquisition and social functions of Chemistry teaching.

A central finding across the selected literature is the growing consensus that chemical literacy should be regarded as a multidimensional construct involving critical thinking, socio-environmental awareness and ethical judgment, rather than the mere ability to read and write chemical symbols and equations [20, 21]. This perspective moves beyond traditional didactic models and aligns with the notion of *critical chemical literacy* which emphasizes the ability to engage with and act upon chemically-relevant issues in personal, societal and global contexts [22].

Innovative pedagogical strategies have emerged as essential tools for advancing chemical literacy. For instance, technology-enhanced learning environments have shown promising results in promoting conceptual understanding and learners' autonomy. Ardyansyah and Rahayu [23] emphasize how augmented reality, virtual simulations and adaptive digital platforms increase students' motivation and comprehension, mainly when they are aligned with inquiry-based learning principles. Similarly, integration of socio-scientific issues (SSI) into Chemistry curricula has proven to be a powerful approach to contextualize learning and foster decision-making competencies among students [24, 25].

Several authors also advocate explicit incorporation of *systems thinking* into chemistry education and reinforce the role of Chemistry as a "central science" only when it is contextualized within broader societal and ecological frameworks [26]. Orgill et al. (2019) argue that a systems-oriented curriculum equips students to understand chemical phenomena as part of dynamic and interconnected systems, a skill which is crucial for addressing complex challenges, such as climate change and sustainable development [27].

The connection between knowledge construction and scientific citizenship has gained much attention. Empirical studies conducted by Kohen and collaborators [28] showed that promoting online scientific dialogues and engaging students in authentic communication with scientists may significantly improve their understanding of the nature of science and foster their civic engagement. Other studies have proven that participatory approaches, such as project-based learning and community-based science interventions, enhance both conceptual mastery and socio-political awareness [29–31].

Despite these advances, challenges persist. Teacher education remains a key barrier to integrate both frameworks effectively. Some studies show that many educators feel unprepared either to implement SSI or to adopt interdisciplinary approaches and mention lack of institutional support and insufficient training [32,33]. Furthermore, the literature highlights the need for curricular reform to balance epistemological rigor and social relevance and to promote chemistry education that is both intellectually robust and socially transformative [34].

Recent studies have attempted to operationalize chemical literacy through empirical instruments, rubrics and diagnostic tools [35,36]. These efforts aim to establish measurable benchmarks for assessing students' literacy levels across cognitive, affective and socio-political dimensions. Notably, Syahr et al. (2024) suggest a model of reflective Chemistry teaching that integrates knowledge of pedagogical content and commitment to democratic and sustainability-oriented education [37].

Finally, relevance of chemical literacy in post-pandemic education has emerged as a vital theme. The COVID-19 crisis underscored the urgency of equipping students with the ability to critically evaluate scientific information, discern misinformation and make informed health-related decisions [38,39]. As Fotou (2024) argue, chemical literacy in the 21st century must extend to competencies in media literacy, risk communication and public reasoning [40].

These findings underscore the urgent need for chemistry education that bridges cognitive development with critical engagement – education that not only teaches what Chemistry is, but also the meaning of being chemically literate in an increasingly complex and interconnected world. In support of this view, several Brazilian scholars have argued that fostering chemical literacy involves promoting epistemic, sociocultural and political dimensions of science education, mainly in contexts marked by social inequalities and environmental urgency [41].

Research developed within the Brazilian context highlights the importance of pedagogical practices that connect Chemistry contents with students' experiences and critical reflection on socio-environmental issues [42]. Furthermore, studies published in national journals advocate the inclusion of SSI's and the development of didactic strategies that empower students as agents of transformation in their communities [43]. This perspective aligns with the call for a curriculum that is not only conceptually rigorous but also ethically and culturally relevant, as emphasized by Brazilian researchers committed to a transformative approach in science education [44]. Thus, the Brazilian literature offers significant contributions to the debate on chemical literacy and reinforces the idea that chemistry education must move beyond content transmission and toward the development of critical, reflective and scientifically literate citizens [45].

In this sense, the integration of scientific knowledge construction and chemical literacy demands pedagogical approaches that move beyond abstract content transmission by incorporating socio-scientific issues to foster ethical and environmental decision-making, employing technology-enhanced environments to support conceptual understanding and autonomy, adopting systems thinking and participatory strategies to connect Chemistry with broader societal and ecological contexts, and investing in teacher education programs that prepare educators to design lessons where epistemological rigor and social relevance converge.

4. Conclusions

This review has critically examined the conceptual and pedagogical interplay between scientific knowledge construction and chemical literacy within the field of chemistry education. Through a narrative synthesis of international and Brazilian literature, the study has demonstrated that, even though both domains share common goals, such as meaningful understanding, critical thinking and informed citizenship, they often operate in parallel, with limited explicit integration. This fragmentation poses challenges to educators who strive to design learning experiences that are both epistemologically grounded and socially responsive.

Evidence reveals that traditional models which merely focus on content transmission are increasingly inadequate to address the multifaceted demands of 21st-century science education. Robust chemistry education must go beyond cognitive acquisition; it must cultivate the capacity to interpret and act upon scientific information in real-world contexts. This requires a paradigm shift, from teaching Chemistry as an isolated body of knowledge to embracing it as a cultural, political and ethical endeavor. Convergence between knowledge construction and chemical literacy opens new pathways for a more holistic, inclusive and socially engaged pedagogy.

Furthermore, this integrative perspective is vital to face global challenges, such as climate change, technological innovation and public health crises since all demand chemically literate citizens who are capable of critical analysis and responsible decision-making. The synthesis of international frameworks with insights from Brazilian scholarship enriches this vision, mainly by highlighting the value of contextualized education rooted in students' realities and local sociocultural dynamics.

From a Brazilian standpoint, this reflection gains even greater urgency. In a country marked by regional disparities, environmental vulnerabilities and persistent educational inequalities, chemistry education must take on a transformative role. Brazilian authors have argued that fostering chemical literacy is inseparable from promoting social justice, environmental awareness and democratic participation. Thus, embracing a critical and emancipatory view of science education not only aligns with global imperatives but also resonates deeply with Brazil's educational and societal needs. In doing so, Chemistry teaching becomes a profound act of citizenship and collective responsibility, rather than mere academic endeavor.

Author Contributions

M.L.D.M. outlined the whole research project, conducted the systematic literature review, wrote the manuscript and submitted it to *Orbital: The Electronic Journal of Chemistry*.

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