Science Education Quarterly, 2025, Vol. **2**, Iss. 3, pp. 170–193 https://doi.org/10.55056/seq.962

Programmed learning in chemistry education: a critical review of theory, application, and effectiveness

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Abstract. This scoping review examines the historical trajectory, theoretical underpinnings, and efficacy of programmed learning in chemistry education from its behaviourist origins to contemporary adaptive learning systems. Through a systematic analysis of the literature following PRISMA-ScR guidelines, we mapped the field's evolution across secondary and tertiary education levels. Our findings reveal that programmed learning, when applied to specific chemistry domains such as stereochemistry and chemical bonding, shows moderate effectiveness in enhancing conceptual understanding and student achievement. The contemporary manifestations of programmed learning principles in technology-enhanced, adaptive learning environments demonstrate particular promise for personalising instruction and addressing diverse student needs. However, challenges persist in fostering higher-order thinking skills and in implementation contexts with limited resources. This review highlights the importance of balancing structured guidance with constructivist approaches, identifying a theoretical convergence that maintains programmed learning's systematic design while incorporating student-centred pedagogies. Critical gaps include limited longitudinal studies examining knowledge retention and insufficient research on teacher experiences and implementation fidelity. We present an integrative framework for future programmed learning applications in chemistry education that emphasises adaptive scaffolding, contextualised learning, and metacognitive development.

Keywords: programmed learning, chemistry education, adaptive learning systems, scoping review, higher-order thinking skills, educational technology

1. Introduction

Chemistry education faces persistent challenges in helping students grasp abstract concepts, develop problem-solving skills, and cultivate positive attitudes towards the subject [42]. Traditional lecture-based approaches often struggle to engage students actively and accommodate diverse learning needs, highlighting the necessity for exploring alternative pedagogical strategies [3]. The increasing integration of technology in education further prompts a re-evaluation of instructional methods to enhance learning outcomes, including deeper understanding and improved retention [26].

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Within this context, programmed learning (PL), also known as programmed instruction, represents a historically significant approach to structuring the learning process. Originating from the principles of behavioural psychology, particularly the work of Skinner [32], PL emphasizes individualized learning pathways, structured content delivery, and systematic reinforcement [30]. Its core premise involves breaking down complex material into manageable steps, requiring active learner participation, and providing immediate feedback to guide the learning process [13].

Despite its historical significance, the evolving landscape of educational theory and technology raises important questions about programmed learning's contemporary relevance, effectiveness, and optimal implementation in chemistry education. While some researchers argue that its structured approach provides necessary scaffolding for complex chemistry concepts [13, 39], others question whether PL's behaviourist foundations can adequately support higher-order thinking skills and conceptual understanding fundamental to modern chemistry education [8, 34].

The purpose of this scoping review is to provide a comprehensive and critical synthesis of the theoretical foundations and empirical research surrounding the application and effectiveness of programmed learning within chemistry education, spanning both secondary and tertiary levels. Through this review, we aim to:

1. Examine the theoretical evolution of programmed learning from behaviourist origins to contemporary adaptive implementations
2. Map the landscape of programmed learning applications across various chemistry domains
3. Critically analyze the evidence regarding programmed learning's effectiveness compared to other instructional approaches
4. Identify key challenges, opportunities, and research gaps in the field
5. Present an integrative framework for implementing programmed learning principles in contemporary chemistry education

The subsequent sections will delve into the historical foundations of PL, its specific applications and evaluation in chemistry, its strengths and weaknesses, examples of materials, the integration of technology, and finally, current trends and future directions for research and practice.

2. Theoretical framework

2.1. Evolution of learning theories in chemistry education

The theoretical landscape of programmed learning reflects a broader evolution in educational psychology, transitioning from behaviourism toward more cognitively oriented and constructivist approaches. When tracing the history of mind and learning theories relevant to chemistry education, we observe a transitioning course that traverses Cartesianism, Behaviorism, and eventually Functionalism [14]. This evolution provides an important context for understanding programmed learning's changing role in chemistry education.

Behaviourism, with its emphasis on observable behaviour changes in response to environmental stimuli, provided the initial theoretical foundation for programmed learning. Risi et al. [29] note that B.F. Skinner's approach to programmed instruction followed a Stimulus-Response-Reinforcement (S-R-R) model, where learning was conceptualized as a change in behaviour resulting from reinforcement. This theoretical perspective viewed free will as an illusion, suggesting that human action is determined by conditioning history.

However, as cognitive psychology gained prominence in the mid-20th century, greater attention was given to internal mental processes. This shift is reflected in the evolution of programmed learning toward approaches that incorporate principles of cognitive load theory, information processing, and schema construction. Crippen and Brooks [6] articulate this transition through the Interactive Compensatory Model of Learning (ICML), which emphasizes the critical roles of motivation, deliberate practice, and feedback in developing expertise in chemistry.

The constructivist turn in educational theory further transformed programmed learning approaches. Lamba [15] describes how constructivist principles in chemistry education emphasize scientific thinking and associated cognitive skills, challenging the rote memorization and recipe-following characteristic of traditional chemistry instruction. Similarly, Suaalii and Bhattacharya [33] advocates for a conceptual model of learning that reflects various learning theories, including student-centred, inquiry-based, collaborative, and contextual learning – elements increasingly incorporated into modern programmed learning implementations.

This evolution in theoretical influences on programmed learning in chemistry education from 1950 to the present is illustrated in figure 1, which depicts the relative prominence of behaviourism, cognitivism, constructivism, and adaptive learning approaches over time.

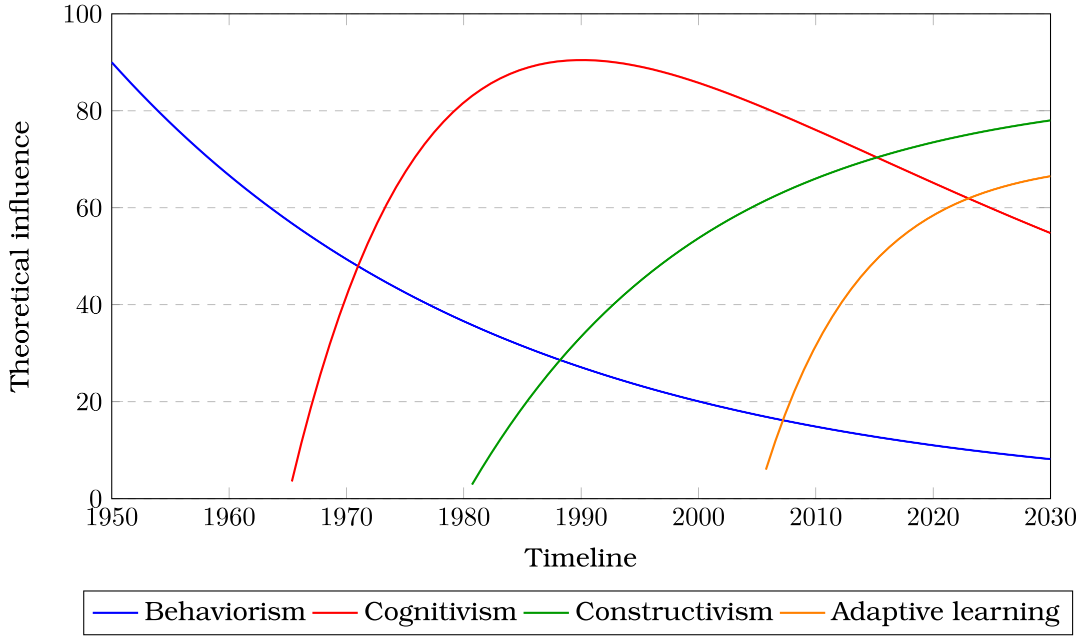

Figure 1: Theoretical influences on programmed learning in chemistry education (1950-2025).

2.2. Characteristics of programmed learning in chemistry

Programmed learning in chemistry education is characterized by several defining features that distinguish it from other pedagogical approaches. At its core, programmed learning involves:

1. *Micro-sequencing* – breaking chemistry content into small, sequential steps, allowing students to learn at their own pace [30].
2. *Active responding* – requiring students to actively engage with material rather than passively receive information [13].
3. *Immediate feedback* – providing prompt confirmation or correction following student responses [13].
4. *Self-pacing* – allowing students to progress through material at individual rates appropriate to their understanding [2].

5. *Mastery learning* – ensuring students demonstrate competence with current material before advancing to more complex content [39].

These features align with what García-Martínez and Serrano-Torregrosa [7] identify as critical elements for effective chemistry education: structured guidance, active engagement, and responsive feedback systems. Contemporary adaptations of programmed learning have evolved these core principles through technological innovation, leading to more sophisticated and adaptive implementations.

2.3. From programmed learning to adaptive learning systems

The evolution from traditional programmed learning to contemporary adaptive learning systems represents a significant theoretical and technological advancement. Osadcha et al. [22] describe adaptive learning systems as technological tools that facilitate the formation of individual educational trajectories based on learners' needs, abilities, and progress. This progression marks a theoretical shift from the standardized branching logic of traditional programmed instruction to more dynamic and responsive systems.

Hougen and Shah [12] highlight that this evolution mirrors natural adaptive processes, drawing parallels between biological evolution and reinforcement learning mechanisms. Both operate on different scales but employ similar feedback mechanisms, making their combined study synergistic in educational contexts.

Modern adaptive learning systems in chemistry education have integrated principles from various theoretical traditions. Vincent-Ruz and Boase [39] demonstrate how adaptive learning technology can activate discipline-specific thinking by personalizing learning pathways based on individual student characteristics. Similarly, Cinque et al. [5] describe adaptive learning modules designed to accommodate learner variability in terms of interest, background, and content knowledge.

The theoretical convergence in contemporary programmed learning is perhaps best exemplified by the focus on scaffolding learning processes. Liu et al. [17] describe multi-modal tutoring systems that scaffold language learning via pedagogical instructions based on four fundamental learning theories: knowledge construction, inquiry-based learning, dialogic teaching, and zone of proximal development. This approach illustrates how modern programmed learning incorporates constructivist elements while maintaining structured guidance.

Table 1 summarizes this theoretical evolution of programmed learning in chemistry education across different time periods, highlighting the shifting theoretical foundations, key characteristics, and chemistry applications.

This theoretical evolution has not been without tensions. Young et al. [43] report that peer-led team learning, a socially mediated pedagogy, shows no demonstrable effect on long-term retention of knowledge compared to traditional didactic instruction. This finding suggests that the integration of social constructivist principles with programmed learning structures presents ongoing theoretical challenges.

The contemporary theoretical framework for programmed learning in chemistry education thus represents a synthesis of multiple traditions. It maintains the systematic structure and immediate feedback mechanisms of behaviourism, incorporates cognitive considerations regarding information processing and schema construction, and increasingly embraces constructivist principles of active knowledge building and contextual relevance. This integrative approach provides the foundation for analyzing programmed learning's applications and effectiveness in chemistry education.

Table 1
Theoretical evolution of programmed learning in chemistry education.

Era	Theoretical foundation	Key characteristics	Chemistry applications
1950s-1960s	Behaviorist psychology (Skinner)	Linear sequencing, immediate reinforcement, teaching machines	Basic chemistry facts, nomenclature, simple procedures
1970s-1980s	Early cognitivism	Branching sequences, error analysis, cognitive task analysis	Procedural knowledge, problem-solving algorithms, basic concepts
1990s-2000s	Constructivism and social learning	Interactive multimedia, collaborative activities, context-based approaches	Conceptual understanding, laboratory procedures, real-world applications
2010s-present	Integrated adaptive approaches	Personalized pathways, AI-driven feedback, data-informed instruction	Complex problem-solving, misconception remediation, discipline-specific thinking

3. Methodology

3.1. Scoping review approach

This review employed a scoping methodology following the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) guidelines [25, 36]. A scoping review approach was selected as it provides a structured method to map the available evidence, identify key concepts, and examine how research has been conducted on a topic [20]. This methodology was particularly appropriate given our aim to characterize the breadth of literature on programmed learning in chemistry education, identify gaps in the existing research, and clarify key concepts rather than answer a specific effectiveness question, which would be more characteristic of a systematic review.

The review protocol was developed a priori following the JBI (Joanna Briggs Institute) methodology for scoping reviews [25], which outlines a structured approach including the formulation of clear objectives, development of inclusion criteria, search strategy design, data extraction, and synthesis. This methodological approach ensures transparency and reproducibility in the review process.

3.2. Research questions

The following research questions guided the review:

1. How has programmed learning evolved theoretically and practically in chemistry education from its behaviourist origins to contemporary adaptive implementations?
2. What are the main applications of programmed learning across various chemistry domains and educational levels?
3. What evidence exists regarding the effectiveness of programmed learning compared to other instructional approaches in chemistry education?
4. What are the key challenges, opportunities, and research gaps in implementing programmed learning in chemistry education?

3.3. Search strategy

The search was conducted in February 2025 using Scopus. Search terms were developed around three main concepts: (1) programmed learning and related approaches,

(2) chemistry education, and (3) educational outcomes. Keywords were combined using Boolean operators:

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TITLE-ABS-KEY(
  (
    "programmed learning" OR "programmed instruction" OR
    "programmed teaching" OR "programmed education" OR
    "programmed curriculum" OR "adaptive learning" OR
    "mastery learning" OR "computer-assisted instruction" OR
    "computer-aided instruction" OR "CAI"
  )
  AND
  (
    "chemistry education" OR "chemical education" OR
    "chemistry teaching" OR "chemistry learning" OR
    "chemistry instruction" OR "chemistry curriculum" OR
    "chemistry class*" OR "chemistry course*" OR
    "chemistry classroom*"
  )
  AND
  (
    "effectiveness" OR "efficacy" OR "achievement" OR
    "performance" OR "outcomes" OR "understanding" OR
    "conceptual understanding" OR "misconception*" OR "cognition" OR
    "attitudes" OR "perception*" OR "motivation" OR "engagement" OR
    "evaluation" OR "assessment"
  )
)
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Additionally, reference lists of included studies were manually searched to identify further relevant publications. Google Scholar was used to conduct forward citation searching of seminal articles to capture recent publications.

3.4. Eligibility criteria

Studies were included if they met the following criteria:

1. *Focus*: studies examining programmed learning, programmed instruction, or modern derivatives (e.g., adaptive learning systems) that maintain the core principles of programmed learning.
2. *Context*: application within chemistry education at secondary or tertiary levels.
3. *Study design*: empirical studies (quantitative, qualitative, or mixed methods), theoretical papers, reviews, or case studies.
4. *Timeframe*: published between 1950 and 2025.
5. *Language*: English-language publications.

Studies were excluded if they:

1. Focused solely on general educational technology without explicit connection to programmed learning principles.
2. Addressed chemistry education without discussing instructional approach.
3. Consisted only of program descriptions without theoretical foundation or evaluation.
4. Were published as abstracts only.

3.5. Selection process

The selection process followed a two-stage screening procedure. First, titles and abstracts of all identified records were independently screened by two reviewers against the eligibility criteria. Discrepancies were resolved through discussion and, when necessary, consultation with a third reviewer. Second, full texts of potentially eligible studies were retrieved and independently assessed by the same reviewers. The selection process was documented using a PRISMA flow diagram (figure 2).

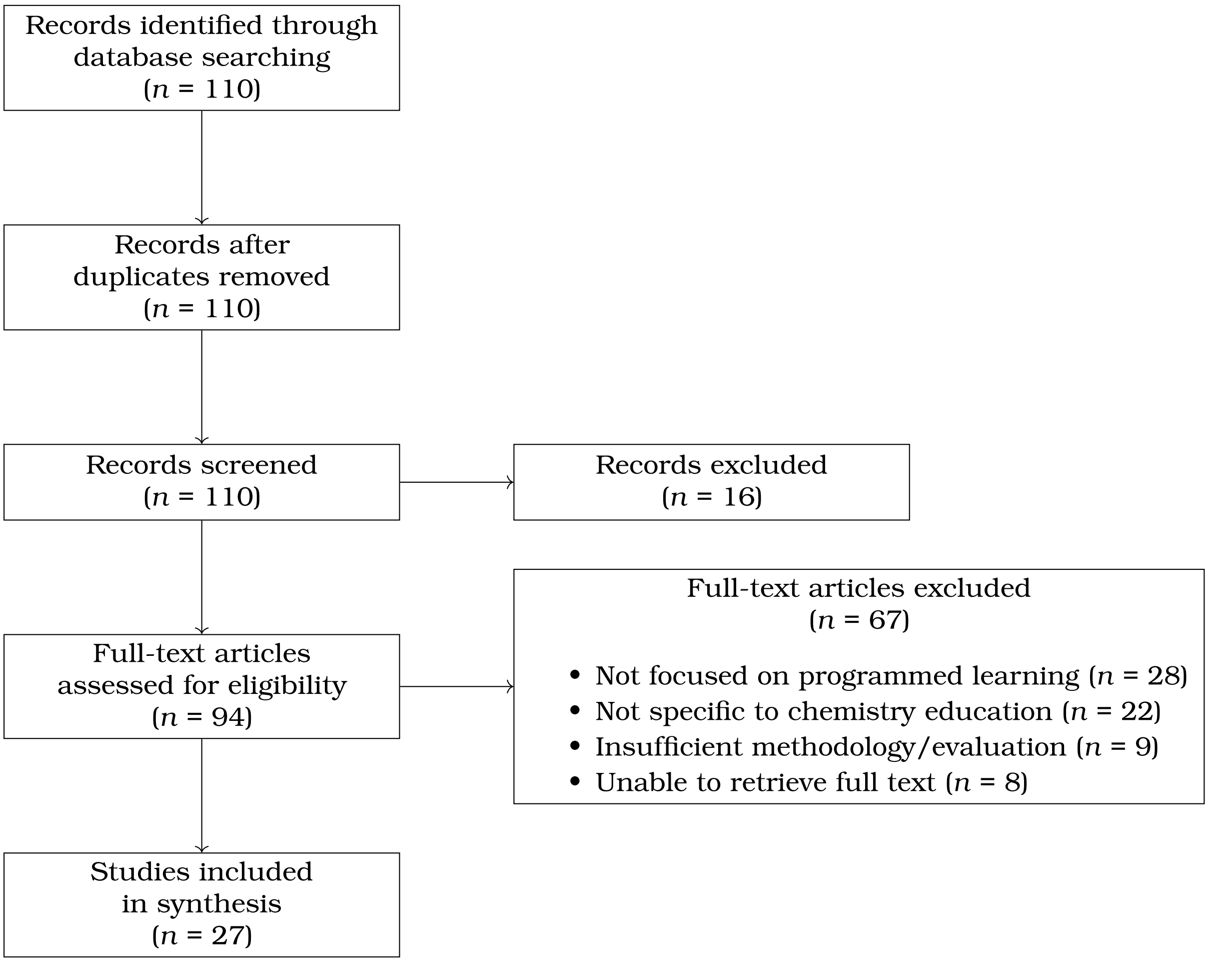

Figure 2: PRISMA flow diagram of the study selection process.

3.6. Data extraction and synthesis

A standardized data extraction form was developed to capture relevant information from included studies. Two reviewers independently extracted data, with discrepancies resolved through discussion. Extracted data included:

- study characteristics (authors, year, country, study design);
- context (educational level, chemistry topic, learning environment);
- programmed learning implementation (type, features, technological components);
- comparison method (if applicable);
- outcomes assessed (achievement, conceptual understanding, attitudes, skills);
- key findings;
- theoretical framework;
- limitations.

Data synthesis employed a narrative approach supplemented by thematic analysis. We initially categorized studies according to chemistry domains, educational levels, and implementation types. Within these categories, we identified emergent themes related to effectiveness, challenges, and opportunities. This approach allowed us to map the landscape of programmed learning in chemistry education while identifying patterns and trends across the literature.

For studies reporting quantitative outcomes, we summarized effect sizes where available, noting statistical significance and confidence intervals. However, given the heterogeneity in outcome measures and study designs, a formal meta-analysis was not conducted. Qualitative findings were synthesized thematically to identify recurring perspectives, challenges, and contextual factors.

4. Applications of programmed learning in chemistry education

4.1. Overview of applications

Programmed learning has been implemented across various educational levels and chemistry topics, with applications ranging from traditional linear sequences to sophisticated adaptive systems. Research indicates the use of PL-based methods in chemistry teaching at both secondary/high school level and university/college level [30]. Its application extends beyond chemistry to other science subjects, suggesting a perceived suitability for domains characterized by structured knowledge and sequential concepts.

The specific chemistry domains where programmed learning has been most frequently applied reveal patterns in its perceived utility. Izzet Kurbanoglu, Taskesenligil and Sozbilir [13] demonstrated significant benefits of programmed instruction in teaching stereochemistry, while Cinque et al. [5] focused on topics including measurements, atomic theory, quantum mechanics, and molecular polarity. These applications suggest that programmed learning is often deployed for topics involving spatial visualization, hierarchical knowledge structures, or procedural algorithms.

Table 2 provides an overview of programmed learning applications across various chemistry domains, including specific implementation examples and their key features and findings.

The pattern of applications suggests that educators have primarily turned to programmed learning and its derivatives for two main purposes: first, to teach highly structured, rule-based content (like nomenclature or stoichiometric calculations) where mastery of procedures is key, and second, to tackle conceptually difficult and abstract topics (like bonding or stereochemistry) where the breakdown into small steps, coupled with immediate feedback, is thought to facilitate incremental understanding.

4.2. Implementation approaches

The implementation of programmed learning in chemistry education has taken various forms, reflecting both technological advancements and evolving pedagogical understandings. Historical implementations often relied on programmed textbooks and workbooks that presented information in sequential frames, required student responses, and provided immediate feedback [30]. These paper-based formats represented direct applications of Skinner's principles of programmed instruction.

As technology evolved, computer-assisted instruction (CAI) became a prominent vehicle for programmed learning principles. Batamuliza, Habinshuti and Nkurunziza [1] notes that simulations and interactive computer-based learning systems (ICBLS) have been perceived positively by chemistry teachers, who cite benefits such as enhanced safety, collaborative learning, and hands-on activities. Similarly, Wu and Lai [41] identifies the use of personal computers to deliver learning content as the main activity mode in technology-enhanced chemistry learning.

Table 2
Applications of programmed learning across chemistry domains.

Chemistry domain	Implementation examples	Key features and findings
Stereochemistry	Programmed instruction with sequential frames [13]	Students taught through programmed instruction performed significantly better than those taught through conventional approach; female students showed greater benefit
Chemical bonding	CAI incorporating PL principles [42]	Visual representations and interactive elements enhanced understanding of abstract concepts; improved attitudes toward chemistry
General chemistry concepts	Computer-Assisted Personalized Assignment (CAPA) system; Canvas Mastery Paths [5]	Individualized, network-delivered problem sets with immediate feedback; adaptive pathways based on student performance
Chemical nomenclature	Programmed modules for cyclic hydrocarbons [41]	Rule-based nature of naming chemical compounds suited to structured drill and practice; visual aids enhanced learning
Laboratory contexts	Computer programs for pre-lab preparation and data analysis [28]	Guided students through sequential calculations; virtual laboratories provided safe, flexible learning environments
Organic chemistry	Blended learning incorporating programmed elements [9]	Process-oriented, guided-inquiry learning (POGIL) showed positive impacts on student performance; enhanced higher-order thinking skills

Recent implementations have increasingly focused on adaptive learning systems that tailor instructional pathways to individual student needs. Vincent-Ruz and Boase [39] demonstrates how adaptive learning technology can effectively engage students in discipline-specific thinking by personalizing their learning pathway in chemistry education. This approach represents a sophisticated evolution of programmed learning that maintains its core principles while addressing individual differences more effectively than traditional "one-size-fits-all" approaches.

Process-Oriented Guided Inquiry Learning (POGIL) represents another contemporary implementation that incorporates programmed learning principles within a more collaborative framework. Hein [9] describes POGIL as a student-centred learning technique that facilitates collaborative and cooperative learning in chemistry classrooms. While maintaining structured guidance and immediate feedback characteristic of programmed learning, POGIL extends these principles through social learning mechanisms.

Figure 3 provides a visual comparison of different programmed learning implementations based on their level of adaptivity and the degree of student agency they afford, highlighting the evolution from traditional approaches toward more flexible and adaptive systems.

Blended learning approaches have also emerged as significant implementation vehicles for programmed learning principles. Lapitan Jr et al. [16] describes the design, implementation, and evaluation of an online flipped classroom with a collaborative learning model in chemical engineering. This approach combines pre-recorded lectures and self-assessment with synchronous collaborative activities, reflecting a hybrid model that incorporates programmed learning elements within a more flexible

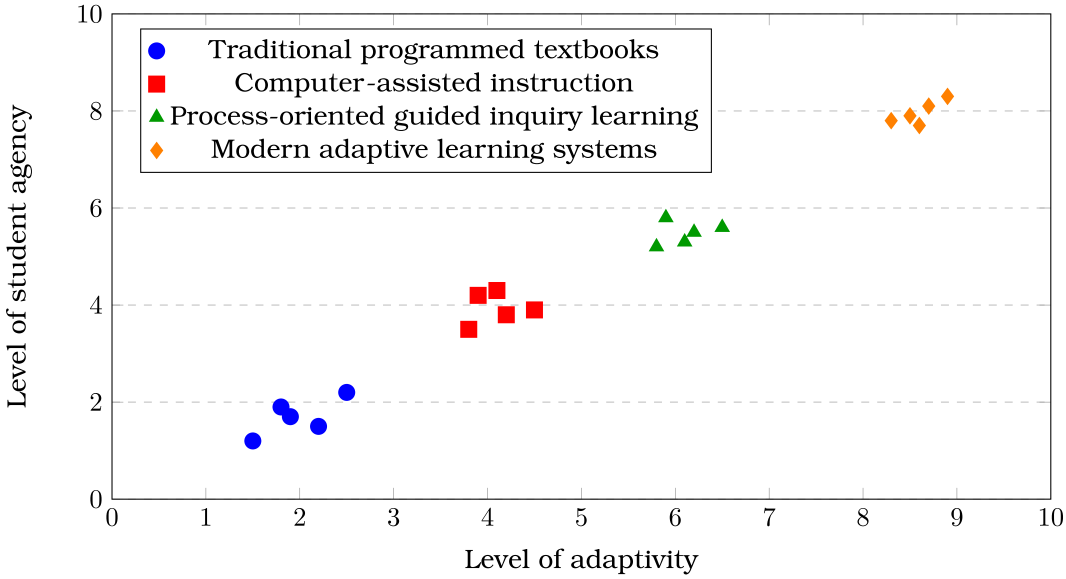

Figure 3: Comparison of programmed learning implementations by adaptivity and student agency.

structure.

The diversity of implementation approaches reflects a growing recognition that programmed learning principles need not be applied in isolation or their original form. Instead, they can be integrated with other pedagogical approaches and enhanced through technology to address the complex demands of contemporary chemistry education.

5. Effectiveness of programmed learning in chemistry

5.1. Evidence of effectiveness

The effectiveness of programmed learning in chemistry education shows considerable variation across contexts, implementations, and outcome measures. Numerous studies have compared PL-based approaches with traditional instruction, yielding a complex picture of relative efficacy.

Several studies report significant advantages of programmed learning in terms of academic achievement. Research using programmed instruction in stereochemistry found that students in the experimental group achieved significantly higher post-test scores compared to those taught via conventional lecturing, with female students particularly benefiting [13]. Similarly, Sadykov et al. [30] identified increased scores for college and secondary school students as a consistent benefit of programmed learning across multiple studies.

The effectiveness of programmed learning appears particularly pronounced for specific chemistry topics. Cinque et al. [5] found that adaptive learning modules on topics including measurements, atomic theory, quantum mechanics, and molecular polarity improved students' understanding of course material and enhanced their attitudes toward general chemistry. This finding suggests that programmed learning may be especially beneficial for abstract or conceptually challenging topics.

However, evidence regarding long-term retention of knowledge is more mixed. Young et al. [43] found no demonstrable effect of pedagogy (peer-led team learning compared with didactic instruction) on the long-term retention of knowledge about chemical equilibrium. This finding raises important questions about whether initial learning gains from programmed approaches translate into durable understanding.

Several factors appear to moderate the effectiveness of programmed learning. Nigon et al. [21] found that adaptive learning systems show differential effectiveness based on students' academic performance levels, with students in the middle GPA group showing the greatest improvement. This suggests that programmed learning may be particularly beneficial for students with moderate prior knowledge rather than those at either extreme of the achievement spectrum.

The implementation context also influences effectiveness. Treagust et al. [35] demonstrated that POGIL, which incorporates programmed learning principles, can be successfully adapted as a culturally relevant pedagogy in Qatar. This finding highlights the importance of contextual adaptation in determining the effectiveness of programmed learning approaches.

Table 3 summarizes key studies examining the effectiveness of programmed learning in chemistry education, highlighting the diverse contexts, methods, and findings across multiple investigations.

Table 3
Summary of studies on programmed learning effectiveness in chemistry education.

Study	Context	PL method	Comparison method	Key findings
Izzet Kurbanoglu, Taskesenligil and Sozbilir [13]	University stereochemistry	Programmed instruction (linear, print)	Conventional lecture	Significant advantage for PL group; females > males in PL group
Vincent-Ruz and Boase [39]	University chemistry (foundational)	Adaptive learning	Traditional instruction	Significant improvement in short and long-term outcomes; equitable benefits across student groups
Cinque et al. [5]	University general chemistry	Canvas Mastery Paths (adaptive)	Pre/post comparison	Improved understanding and attitudes toward chemistry
Hein [9]	University organic chemistry	POGIL	Traditional lecture	Higher final exam scores; positive impact across all proficiency levels
Young et al. [43]	University analytical chemistry	Peer-led team learning with PL elements	Didactic instruction	No significant difference in long-term retention of knowledge
Utami et al. [37]	Pre-service teacher chemistry	SMART-PBL (AR-enhanced)	PBL without AR	Greater impact on metacognitive and problem-solving skills

5.2. Impact on different learning outcomes

Programmed learning appears to affect different types of learning outcomes to varying degrees. Witherby and Tauber [40] found that making judgments of learning (JOLs) – a metacognitive element often incorporated into programmed learning – enhances both short-term performance and long-term learning for related information. This suggests that programmed approaches incorporating metacognitive elements may have broader benefits than those focusing solely on content delivery.

For conceptual understanding, the evidence is mixed. While some studies suggest that programmed learning can address specific misconceptions, particularly when enhanced with visual and interactive elements [23], others raise concerns about whether highly structured approaches adequately foster deep conceptual understanding. Lamba [15] warns that information overload and recipe-following in chemistry instruction can lead to memorization rather than understanding, potentially limiting the effectiveness of purely procedural programmed approaches.

Regarding affective outcomes, several studies report positive impacts on student attitudes and motivation. Sadykov et al. [30] identified increased student interest as a consistent benefit of programmed learning across multiple studies. Similarly, Cinque et al. [5] found that adaptive learning modules improved students' attitudes toward general chemistry. These findings suggest that programmed learning, when well-designed, can enhance engagement and interest in chemistry.

The evidence for higher-order thinking skills is particularly nuanced. Traditional programmed learning, with its focus on sequential steps and predetermined pathways, has been criticized for potentially limiting the development of critical thinking and problem-solving abilities. However, modern adaptations that incorporate inquiry elements show more promise. Utami et al. [37] found that SMART-PBL (Strategy Meets Augmented Reality Technology-using Problem Based Learning) improved both metacognitive and problem-solving skills in chemistry students.

5.3. Contextual factors affecting effectiveness

The effectiveness of programmed learning in chemistry education is highly dependent on contextual factors. Key influencing variables include:

1. *Topic complexity and type* – programmed approaches appear more effective for structured, rule-based content and topics requiring spatial visualization [5, 13].
2. *Implementation quality* – the design of programmed materials, feedback mechanisms, and technological infrastructure significantly influences outcomes [1].
3. *Student characteristics* – prior knowledge, learning preferences, and metacognitive abilities moderate the effectiveness of programmed approaches [21, 39].
4. *Educational level* – different age groups and educational levels may respond differently to programmed approaches, with secondary students potentially showing different patterns of benefit compared to university students [30].
5. *Cultural context* – the cultural relevance and adaptability of programmed materials influence their effectiveness in diverse settings [35].
6. *Integration with other methods* – how programmed learning is combined with other pedagogical approaches affects its overall impact [9, 16].

The inconsistent results across different studies underscore that programmed learning is not a universally superior method in chemistry education. Rather, its effectiveness depends on the specific implementation context, the nature of learning goals, the characteristics of learners, and its integration into the broader instructional environment.

6. Advantages and limitations in chemistry education

6.1. Reported advantages

Programmed learning offers several distinct advantages for chemistry education, particularly in addressing specific challenges associated with the discipline. These advantages stem directly from PL's core principles and have been consistently identified across multiple studies.

The most frequently cited advantages are individualization and self-pacing. In chemistry courses with diverse student populations and varying levels of prior knowledge, this feature allows learners to progress at their own rate without being rushed or held back [39]. As Cinque et al. [5] note, this is particularly valuable in large enrollment courses where accommodating learner variability is otherwise challenging.

The active engagement required by programmed learning represents another significant benefit. Unlike passive lecture formats, PL necessitates constant student interaction with the material, requiring them to formulate responses rather than merely observe [30]. This aligns with broader evidence regarding the effectiveness of active learning in science education [3].

Immediate feedback and reinforcement constitute a third major advantage. The provision of instant confirmation or correction allows students to identify and address misunderstandings before they become entrenched, particularly valuable when learning intricate chemical rules or procedures [13]. As Vincent-Ruz and Boase [39] demonstrate, this feedback mechanism can be further enhanced through adaptive technologies that provide personalized guidance.

Programmed learning also facilitates mastery learning, requiring successful completion of foundational concepts before advancing to more complex topics. This structured approach helps ensure students build a solid understanding of prerequisite knowledge in chemistry, where concepts are highly interconnected and hierarchical [31].

Additionally, programmed approaches offer efficiency for specific content types. Wu et al. [42] note that technology-enhanced learning is particularly effective for delivering structured information and definitions, allowing more classroom time for higher-level activities. This efficiency extends to laboratory preparation, where programmed modules can prepare students for hands-on activities [28].

Finally, programmed learning can increase motivation and interest in chemistry. Sadykov et al. [30] identified raised student interest as a consistent benefit across multiple studies, while Cinque et al. [5] found that adaptive learning modules improved attitudes toward general chemistry. This motivational impact may be particularly important in a discipline often perceived as challenging and abstract.

6.2. Identified challenges and limitations

Despite its advantages, programmed learning in chemistry education faces several significant limitations and challenges. These challenges reflect both inherent characteristics of PL approaches and practical implementation barriers.

A primary limitation concerns the potential rigidity of highly structured approaches. The predetermined sequence of traditional programmed learning may stifle student curiosity, limit exploration of alternative solution pathways, or fail to adapt to unexpected learning needs [23]. This rigidity contrasts with inquiry-oriented approaches increasingly advocated in science education.

Related to this rigidity is the risk of promoting surface-level learning. Lamba [15] warns that chemistry instruction often emphasizes memorization and recipe-following rather than conceptual understanding, a risk potentially exacerbated by highly structured programmed approaches. The focus on discrete steps and correct answers may encourage students to adopt superficial strategies aimed at progression rather than deep engagement with chemical concepts.

Limited opportunities for social interaction represent another significant challenge. Traditional programmed learning is primarily an individualistic experience, lacking the collaborative discussion, peer feedback, and negotiation of meaning that occur in well-facilitated group settings [9]. While modern implementations increasingly incorporate collaborative elements, this tension between individual progression and social learning remains a challenge.

From a practical standpoint, technical and resource barriers present substantial challenges to implementation. Batamuliza, Habinshuti and Nkurunziza [1] identify limited access to computers and insufficient professional training as key obstacles faced by teachers attempting to implement computer-based programmed learning in chemistry classrooms. These challenges are particularly acute in resource-constrained educational settings.

The development of effective programmed materials also requires significant time and expertise. Creating well-designed sequences, anticipating misconceptions, and developing appropriate feedback mechanisms demands both subject matter knowledge and instructional design skills [8]. This development burden may limit widespread implementation, particularly for specialized chemistry topics.

Finally, the rapid pace of technological change presents ongoing challenges for technology-enhanced programmed learning. Holme [11] questions whether the current chemistry curriculum, even with technology enhancements, can adequately prepare students for future workplace demands. Similarly, Sweeder, Herrington and Crandell [34] notes that the COVID-19 pandemic has forced a global rethinking of chemistry education, raising questions about the adaptability of programmed approaches to changing educational contexts.

Figure 4 illustrates the relationship between structure and adaptivity in chemistry education, positioning various programmed learning approaches within this framework and highlighting both the historical evolution of PL and the constructivist push toward more flexible approaches.

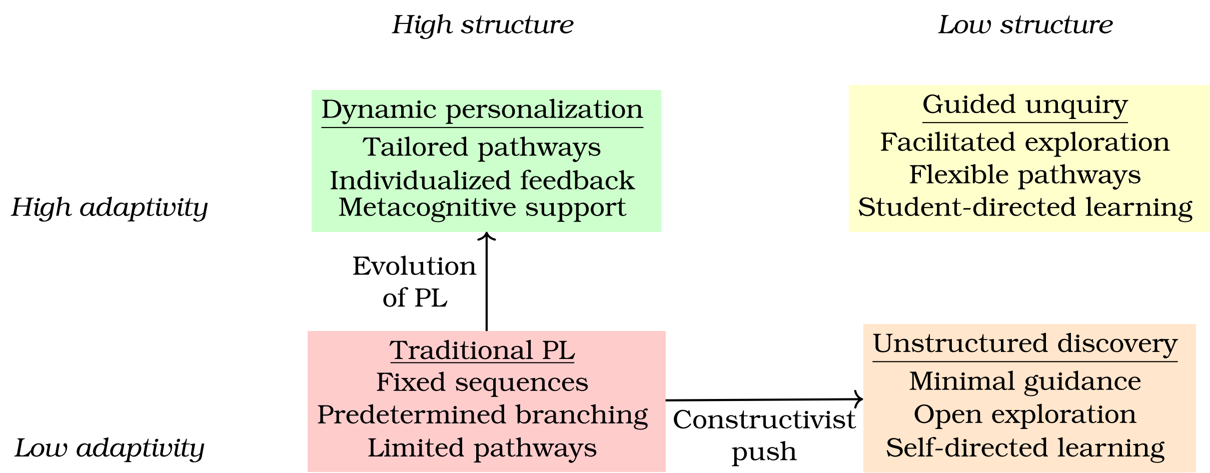

Figure 4: Programmed learning in relation to structure and adaptivity in chemistry education.

7. Contemporary implementations of programmed learning in chemistry

7.1. Technology-enhanced programmed learning

Technology has fundamentally transformed programmed learning in chemistry education, enabling implementations that far exceed the capabilities of traditional teaching machines or programmed textbooks. These technological enhancements have addressed some historical limitations of programmed learning while introducing new possibilities for personalization, visualization, and engagement.

The evolution from mechanical teaching machines to computer-assisted instruction (CAI) represents the first major technological leap in programmed learning. Pribush [26] traces this transition, noting how computers overcame many limitations of mechanical devices by enabling complex branching logic, multimedia integration, and sophisticated progress tracking. This technological advancement allowed for more responsive and engaging programmed learning experiences in chemistry.

Digital technologies have remarkably enhanced the visualization capacities of programmed learning in chemistry. Wu and Lai [41] describes the use of videos, pictures, and animations within CAI frameworks for teaching chemical concepts. These visual elements are especially valuable for chemistry topics involving molecular structures, reaction mechanisms, or laboratory procedures where spatial understanding is crucial.

The integration of virtual and remote laboratories represents another significant technological enhancement. Reyes et al. [28] examines the role of virtual laboratories in enhancing experiential science learning, noting their potential to provide safe, accessible environments for chemistry experimentation. These virtual environments allow students to observe molecular-level phenomena and practice laboratory techniques within a structured, programmed framework.

Perhaps the most transformative technological development is the emergence of adaptive learning systems powered by artificial intelligence. Vincent-Ruz and Boase [39] demonstrates how adaptive learning technology can effectively engage students in discipline-specific thinking by personalizing their learning pathway based on individual performance patterns. Similarly, Cinque et al. [5] describes the implementation of Canvas Mastery Paths as an adaptive instructional system that improves student learning outcomes through flexible, aligned content-assessment sequences.

Mobile learning represents another frontier in technology-enhanced programmed learning. The ubiquity of smartphones and tablets provides new opportunities for delivering programmed instruction in chemistry, enabling learning in diverse contexts beyond the traditional classroom or laboratory [42]. These mobile applications can deliver microlearning modules, interactive simulations, and assessment tools with immediate feedback.

Intelligent tutoring systems incorporating programmed learning principles represent a sophisticated synthesis of educational theory and artificial intelligence. Liu et al. [17] examines scaffolding language learning via multi-modal tutoring systems with pedagogical instructions, demonstrating principles that could be applied to chemistry education. These systems can mimic human tutors by providing customized guidance based on student needs and responses.

7.2. Integration with constructivist approaches

Contemporary programmed learning in chemistry education increasingly incorporates constructivist elements, representing a theoretical convergence that maintains structured guidance while encouraging active knowledge construction. This integration addresses some traditional criticisms of programmed learning while preserving its core benefits.

Process-oriented guided inquiry learning exemplifies this integration, combining structured activities characteristic of programmed learning with collaborative inquiry approaches reflective of constructivism. Hein [9] describes POGIL as a student-centred learning technique that facilitates collaborative and cooperative learning in the chemistry classroom, enhancing both higher-order thinking skills and process skills.

Context-based learning represents another constructivist approach increasingly integrated with programmed elements. Broman, Bernholt and Christensson [4] examines the affective aspects of context-based chemistry problems, noting how connecting chemistry to personal dimensions increases student interest and relevance. This contextual embedding can provide meaningful frameworks for programmed sequences, helping students connect abstract chemical concepts to real-world applications.

Problem-based learning (PBL) has also been integrated with programmed approaches to create hybrid models that balance structure and inquiry. Utami et al. [37] describes SMART-PBL, which combines problem-based learning with augmented reality technology to improve metacognitive and problem-solving skills in chemistry learning. This approach maintains the scaffolding benefits of programmed learning while encouraging deeper inquiry and application.

Blended learning models represent another important integration path, combining programmed elements with face-to-face instruction. Lapitan Jr et al. [16] examines an online flipped classroom with a collaborative learning model in chemical engineering, where pre-recorded lectures and self-assessment questions provide programmed preparation for subsequent collaborative activities. This approach leverages programmed learning for knowledge acquisition while using constructivist approaches for application and synthesis.

New Inquiry-Based Learning (NIBL) similarly combines structured guidance with inquiry approaches. Mitarlis et al. [19] demonstrates how NIBL can improve multiple higher-order thinking skills of prospective chemistry teachers, including critical, analytical, creative, and practical thinking. This model provides scaffolded support for inquiry processes, maintaining elements of programmed sequencing while encouraging more open exploration.

These integrated approaches reflect a growing recognition that programmed learning need not be implemented in isolation or its original behaviourist form. Rather, it can be combined with constructivist elements to create balanced instructional models that provide structured guidance while encouraging active knowledge construction, critical thinking, and real-world application.

7.3. Exemplars of modern programmed learning in chemistry

Several exemplary implementations illustrate the evolution and potential of programmed learning in contemporary chemistry education. These examples demonstrate how core programmed learning principles have been enhanced through technology, integrated with complementary pedagogical approaches, and adapted to address specific chemistry learning challenges.

Adaptive learning modules for general chemistry developed at the University of Central Florida exemplify the personalization potential of modern programmed learning. Cinque et al. [5] describe four Canvas Mastery Paths modules covering measurements, atomic theory, quantum mechanics, and molecular polarity, designed to accommodate learner variability and enhance student success. Student responses indicated improved understanding and attitudes toward chemistry, highlighting the motivational benefits of adaptive programmed approaches.

The Compute-to-Learn (C2L) pedagogy represents an innovative adaptation of programmed learning principles to computational chemistry. Hendrickson et al. [10] describes this semester-long, active-learning experience where students learn basic programming skills applied to coding demonstrations of chemistry concepts. Students work collaboratively within a studio learning environment, combining structured programming instruction with creative application to chemistry visualization.

Process-oriented guided inquiry learning implementations in organic chemistry provide another exemplar of integrating programmed and constructivist approaches. Hein [9] demonstrates how POGIL has been successfully employed to enhance higher-order thinking skills and improve examination performance in organic chemistry courses. This approach maintains structured guidance while fostering collaborative learning and deeper conceptual understanding.

Virtual laboratories incorporating programmed learning principles have emerged as powerful tools, particularly during the COVID-19 pandemic. Reyes et al. [28] examines the merits, challenges, and implementation strategies of virtual labs in science education, noting their potential to enhance experiential learning when physical laboratories are inaccessible. These virtual environments provide structured guidance through complex procedures while allowing safe experimentation.

Recent developments in chemistry education exemplify the integration of artificial intelligence with programmed learning principles. Velázquez-García et al. [38] examines AI-based applications enhancing computer science teaching with principles applicable to chemistry education. These systems can analyze student responses, identify misconceptions, and provide personalized feedback at a scale impossible with traditional programmed materials.

Context-based learning implementations incorporating programmed elements represent another important example. Löffler, Pozas and Kauertz [18] analyzes students' context-based problem-solving in thermodynamics, examining how they coordinate context information with their own knowledge. This approach embeds programmed sequences within meaningful contexts, helping students connect abstract chemical principles to real-world applications.

These exemplars demonstrate the diversity and sophistication of modern programmed learning implementations in chemistry education. They illustrate how the core principles of structured guidance, active responding, and immediate feedback have been enhanced and integrated with other approaches to address the complex demands of contemporary chemistry learning.

8. Future directions and research needs

8.1. Emerging trends in programmed learning research

The most significant trend is the increasing integration of artificial intelligence and machine learning into programmed learning systems. Velázquez-García et al. [38] examines how AI-based applications can support teaching and learning in higher education, identifying key applications, including intelligent tutoring systems, assessment, performance prediction, and adaptive learning. These technologies enable programmed learning systems to analyze patterns in student responses, identify misconceptions, and personalize instruction at unprecedented scales.

The development of more sophisticated adaptive learning models represents another important trend. Bekaulova et al. [2] describes adaptive learning as a process using special algorithms to build individual learning paths with selected resources meeting the unique needs of students. This approach shifts from the predetermined branching of traditional programmed instruction toward more dynamic, responsive systems that continuously adjust to learner characteristics and performance.

Programmed learning is increasingly being integrated with immersive technologies such as virtual reality (VR) and augmented reality (AR). Pellas [24] investigates the impact of AI-generated instructional videos on problem-based learning in science teacher education, demonstrating potential applications for chemistry visualization and laboratory simulation. These immersive technologies can make abstract chemical concepts more concrete and provide safe environments for experimental exploration.

Another emerging trend is the focus on developing higher-order thinking skills through programmed approaches. While traditional programmed learning has been criticized for emphasizing recall and procedural knowledge, modern implementations increasingly target critical thinking, problem-solving, and metacognitive skills. Qi et al. [27] examines strategies for enhancing critical thinking in vocational chemistry education, including problem-based learning, simulations, and collaborative projects that incorporate programmed elements.

The integration of programmed learning with culturally responsive pedagogy represents a growing area of interest. Treagust et al. [35] examines POGIL as a culturally relevant pedagogy in Qatar, demonstrating how structured guidance can be adapted to diverse cultural contexts. This cultural responsiveness is increasingly important as chemistry education becomes more globalized and diverse student populations engage with programmed learning materials.

Finally, there is growing attention to the role of programmed learning in preparing students for rapidly changing workplace demands. Holme [11] questions whether today's chemistry curriculum can produce tomorrow's adaptable chemist, highlighting the need for instructional approaches that foster adaptability alongside structured knowledge acquisition. This tension between structure and adaptability will likely shape future programmed learning implementations.

8.2. Critical research gaps

Despite extensive research on programmed learning in chemistry education, several critical gaps remain that limit our understanding of its optimal implementation and effectiveness. Addressing these gaps through targeted research would significantly advance the field and inform evidence-based practice.

A primary research gap concerns the long-term retention of knowledge gained through programmed learning approaches. Young et al. [43] found no significant difference between peer-led team learning and didactic instruction in terms of long-term knowledge retention, raising questions about the durability of learning from different pedagogical approaches. More longitudinal studies examining knowledge retention over extended periods would provide valuable insight into the lasting impact of programmed learning.

Another critical gap involves understanding how programmed learning affects diverse student populations. While Vincent-Ruz and Boase [39] found that adaptive learning can equitably meet the needs of all students, more research is needed to examine how different demographic groups respond to various programmed learning implementations. This includes students from different cultural backgrounds, socioeconomic statuses, prior achievement levels, and those with learning disabilities.

Research on the development of higher-order thinking skills through programmed learning remains limited. While traditional programmed approaches have been criticized for emphasizing recall and procedural knowledge, contemporary implementations increasingly aim to foster critical thinking, problem-solving, and metacognition. However, more empirical evidence is needed to determine how effectively these modern programmed approaches develop higher-order cognitive skills in chemistry education.

There is also a significant gap in understanding teacher experiences and implementation fidelity. Batamuliza, Habinshuti and Nkurunziza [1] examines teacher perceptions of integrating simulations into chemistry instruction, but broader research on how teachers adapt, implement, and perceive various programmed learning approaches would provide valuable insight into real-world implementation challenges and success factors.

Research on the integration of programmed learning with other pedagogical approaches remains relatively sparse. While studies like Utami et al. [37] examine hybrid approaches combining programmed elements with problem-based learning, a more systematic investigation of different integration models would help identify optimal combinations for various chemistry topics and educational contexts.

Finally, cost-effectiveness analyses of programmed learning implementations are notably lacking. While many studies examine educational outcomes, few rigorously analyze the resources required for implementation relative to the benefits achieved. Such analyses would be particularly valuable for educational institutions making decisions about technology investments and instructional approaches in resource-constrained environments.

8.3. Implications for practice and policy

The findings of this review have some implications for chemistry educators, curriculum developers, and educational policymakers seeking to implement or support programmed learning approaches.

For chemistry educators, this review suggests the importance of selecting appropriate programmed learning implementations based on specific learning objectives, student characteristics, and topic demands. Wu et al. [42] notes that different chemistry topics may benefit from different technological approaches, highlighting the need for thoughtful matching of instructional strategies to content. Educators should also consider integrating programmed elements with complementary pedagogical approaches, as exemplified by hybrid models such as POGIL [9] and SMART-PBL [37].

The review also emphasizes the importance of professional development for chemistry educators implementing programmed learning approaches. Batamuliza, Habinshuti and Nkurunziza [1] identifies insufficient professional training as a key challenge faced by teachers integrating technological tools, highlighting the need for targeted support. Professional development should address both technical skills and pedagogical approaches for effective implementation.

For curriculum developers, this review suggests several design principles for effective programmed learning materials in chemistry. These include breaking complex concepts into manageable steps, providing immediate feedback on student responses, incorporating visual representations of molecular phenomena, and embedding content within meaningful contexts. Broman, Bernholt and Christensson [4] emphasizes the importance of relevance and interest in context-based chemistry problems, suggesting that programmed materials should connect abstract concepts to real-world applications.

The review also highlights the potential of adaptive learning systems to address the diverse needs of chemistry students. Vincent-Ruz and Boase [39] demonstrates how adaptive learning technology can effectively engage students in discipline-specific thinking by personalizing learning pathways. Curriculum developers should consider incorporating adaptive elements that respond to individual student characteristics and performance patterns.

For educational policymakers, this review suggests the importance of supporting technology infrastructure for programmed learning implementations. Batamuliza, Habinshuti and Nkurunziza [1] identifies limited access to computers as a key challenge, highlighting the need for adequate technological resources. Policy initiatives should address both hardware requirements and support for software development and implementation.

The review also emphasizes the need for balanced assessment approaches that align with programmed learning goals. While programmed learning often excels at building procedural knowledge and conceptual understanding, assessment systems should also evaluate higher-order thinking skills and application abilities. Policy frameworks should support diverse assessment approaches that capture the full range of learning outcomes.

Finally, the review suggests the importance of research-practice partnerships for advancing programmed learning in chemistry education. Graulich et al. [8] describes a research network bringing together researchers and practitioners in organic chemistry education, highlighting the value of collaborative efforts. Policy initiatives supporting such partnerships could accelerate the development and implementation of evidence-based programmed learning approaches.

9. Conclusion

This scoping review has examined the theoretical foundations, applications, effectiveness, and future directions of programmed learning in chemistry education. Our analysis reveals a field that has evolved significantly from its behaviourist origins, incorporating technological advancements and theoretical insights to create increasingly sophisticated learning environments responsive to diverse student needs.

The historical trajectory of programmed learning reflects broader shifts in educational psychology. It transitions from behaviourist approaches emphasizing observable behaviour changes toward more complex models integrating cognitive, constructivist, and social learning perspectives. This theoretical evolution has been paralleled by technological advancements, from mechanical teaching machines and programmed textbooks to sophisticated adaptive learning systems leveraging artificial intelligence and immersive technologies.

Our mapping of programmed learning applications across chemistry domains reveals patterns in their perceived utility. Programmed approaches have been particularly prevalent in teaching structured, rule-based content such as nomenclature and stoichiometry, as well as conceptually challenging topics like stereochemistry and chemical bonding that benefit from visual representation and incremental development. Implementation approaches have diversified beyond traditional linear sequences to include computer-assisted instruction, adaptive learning systems, process-oriented guided inquiry learning, and blended learning models integrating programmed elements with face-to-face instruction.

The effectiveness of programmed learning in chemistry education shows considerable variation across contexts, implementations, and outcome measures. While many studies report significant advantages for programmed approaches in terms of academic achievement and student attitudes, evidence regarding long-term retention and higher-order thinking skills is more mixed. Effectiveness appears to be moderated by factors including topic complexity, implementation quality, student characteristics, educational level, cultural context, and integration with other methods.

Contemporary implementations of programmed learning increasingly leverage technology to enhance visualization, feedback, and personalization capabilities. Exemplars such as adaptive learning modules, virtual laboratories, and AI-driven tutoring systems demonstrate how programmed learning principles have been transformed through technological innovation. Modern approaches also increasingly integrate constructivist elements, creating hybrid models that maintain structured guidance while encouraging active knowledge construction, critical thinking, and real-world application.

Despite extensive research, several critical gaps remain that limit our understanding of programmed learning's optimal implementation and effectiveness. These include limited longitudinal studies examining knowledge retention, insufficient research on diverse student populations, questions about higher-order thinking skill development, limited understanding of teacher experiences and implementation fidelity, sparse research on integration models, and a lack of cost-effectiveness analyses.

Looking forward, the field of programmed learning in chemistry education continues to evolve, with emerging trends including AI integration, sophisticated adaptive models, immersive technologies, focus on higher-order thinking skills, cultural responsiveness, and attention to workplace preparation. These developments suggest the ongoing relevance of programmed learning principles in addressing persistent challenges in chemistry education, particularly when thoughtfully adapted to contemporary contexts and integrated with complementary pedagogical approaches.

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