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A Review of Research on the Quality and Use of Chemistry Textbooks

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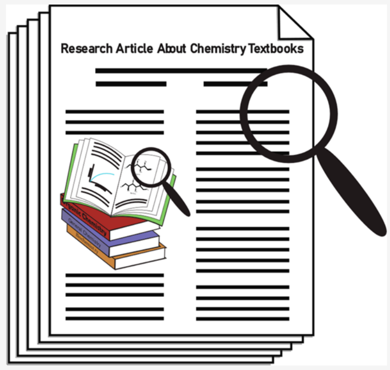
ABSTRACT: The number of studies analyzing chemistry textbooks has steadily increased over the years and has notably surged in the past decade. In this literature review, we examine the research literature on chemistry textbooks. The review spans 40 years of research (from 1981 to 2021) and includes 79 studies published in over 20 different journals, analyzing secondary and postsecondary chemistry textbooks used in more than 17 countries. We synthesize the samples and methods used as well as the findings of the studies around chemistry textbooks. Based on this synthesis, we provide multiple concrete implications to improve the rigor of future studies of chemistry textbooks because most of the articles in our review lack a discussion of the limitations of their studies, half do not use any theoretical or analytical framework(s) to guide the design of their studies and the interpretation of findings, and a quarter do not specify the country of use for the textbooks in their samples. Additionally, we provide concrete recommendations for textbook developers to improve the quality of chemistry textbooks. Importantly, textbook developers need to ensure that their products are grounded in research and theory about student learning.



KEYWORDS: *general public/high school/introductory chemistry, first-year undergraduate/general, second-year undergraduate/upper-division undergraduate, chemical education research, communication/writing, textbooks/reference books*

1. INTRODUCTION AND PURPOSE

This paper reviews the research literature on secondary and postsecondary chemistry textbooks.[1−79] Chemistry textbooks are valuable tools not only for students to learn and practice concepts and skills but also to shape students' perceptions of the field of chemistry, which can influence their motivation to learn and their career aspirations.[8,22] Chemistry textbooks are also valuable tools for instructors who use them as curricular guides and a source of visualizations to supplement their course artifacts (e.g., lecture slides and worksheets).[80] Research has shown that textbooks influence the way instructors plan their lessons, introduce chemistry topics, and design assessments to evaluate students' understanding.[6,8,21,26,27,80] Given the importance, as well as the cost, of textbooks, their development and selection must be grounded in research on their effectiveness. Therefore, this review summarizes the landscape of the existing studies of chemistry textbooks and identifies areas for future research. To accomplish this goal, we investigate the following questions:

1. What types of chemistry textbooks have been studied (e.g., country of use, grade level, chemistry subject, etc.)?
2. What frameworks and methods have been used in studies around chemistry textbooks?
3. What are the key findings of chemistry textbook studies?
4. What aspects of chemistry textbook effectiveness and use require further investigation?

2. METHODS

2.1. Search and Selection of Articles

This review article follows the guidelines published by the editors of *Chemistry Education Research and Practice*[81] and recommendations from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).[82] Our sampling criteria included (1) research papers published in peer-reviewed journals that (2) are written in English and (3) focus on chemistry textbooks as their sample that (4) are used in high school and university settings. We excluded commentaries, conference proceedings, book chapters, and dissertations. Studies were not excluded based on chemistry discipline (e.g., inorganic chemistry textbooks, physical chemistry textbooks, etc.), country of origin, or publication year. To our knowledge, this is the first literature review of the research on chemistry textbooks, which is why we did not exclude any studies based on their date of publication. Therefore, our review spans 40 years of

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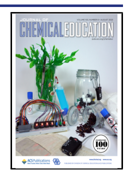

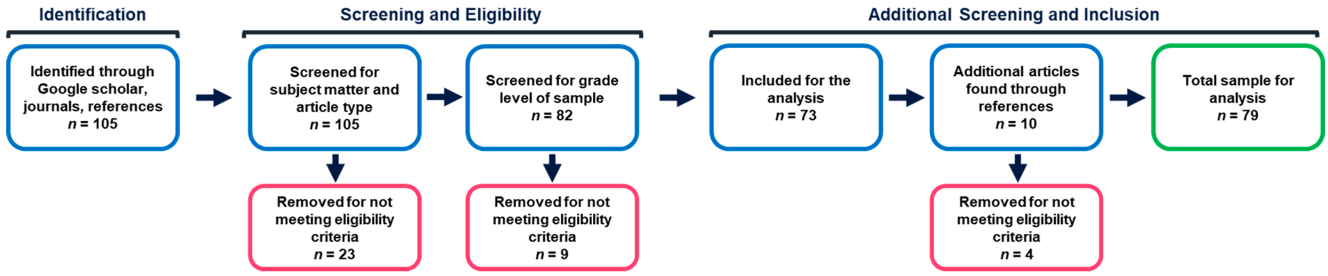

Figure 1. PRISMA flow diagram summarizing the process for identifying, screening, and including articles.

research and includes articles from 1981 (the oldest article we identified)[33] through 2021.

We used the keyword "chemistry textbook(s)" to search for studies in Google Scholar and journals such as the *Journal of Chemical Education* and *Chemistry Education Research and Practice*. The Google Scholar search alone resulted in a thousand raw records. Initially, we identified 105 articles that fit our sampling criteria based on their titles and abstracts (Figure 1). However, after an in-depth screening of each article's research questions, methods, and results, we excluded 32 studies that did not fit one or more of our sampling criteria. We examined the references of the included articles and found 10 additional studies to potentially include. Upon more in-depth screening of these articles, we excluded 4 that did not fit our inclusion criteria. The final sample included 79 studies.[1−79] While we intend this review to be comprehensive, we acknowledge the possibility of unintentional omissions. Of note is that none of the articles in this review are written by the authors of this manuscript.

2.2. Analysis of Articles for Patterns

The first and the second authors read all the articles and independently cataloged each article in Excel by identifying and/or summarizing the following characteristics of each study: (1) year published, (2) journal, (3) textbook(s) in the sample including the country of textbook(s) use and the associated chemistry subject (e.g., general chemistry, physical chemistry, etc.), (4) research question(s) and/or purpose of each study, (5) theoretical framework(s), (6) data collection and analysis methods, (7) main findings and conclusions, (8) limitations, and (9) implications. Cataloging articles in this way allowed us to compare the articles across all study characteristics and sort the articles by focusing on a specific characteristic of interest. In addition, the first two authors used narrative coding to write a summary for each article with a focus on each study's textbook(s) sample, goals, and emergent findings.[83] All three authors met weekly to discuss each article and its corresponding summary to ensure that we consistently attended to the same characteristics and captured all critical aspects of each study. As an outcome of these discussions, we updated each summary with any missing information. Once all articles were summarized, we used constant-comparative analysis to identify patterns across the studies.[84,85] Constant-comparative analysis allowed us to systematically compare and contrast the findings across articles to identify recurring patterns and insights. These recurring patterns and insights are presented in section 3.2 as key findings that emerged across the various studies. We used strategies such as researcher triangulation, peer debriefing, and reflexive journaling to ensure the credibility and confirmability of the identified patterns.[86−88]

3. RESULTS AND DISCUSSION

The results of this review are organized into two main sections. The first section, "Characteristics of Studies around Chemistry Textbooks", includes aspects of the studies themselves, such as textbook(s) sample, theoretical framework(s), and methods used; this section (3.1) answers research questions 1 and 2. The second section, "Findings from Studies around Chemistry Textbooks", describes the identified patterns in findings and conclusions from these studies; this section (3.2) answers research question 3. Finally, research question 4 is addressed in the Conclusions and Implications (section 5). The percentages used to report findings are rounded to the nearest whole number.

3.1. Characteristics of Studies around Chemistry Textbooks

The 79 studies were published from 1981 to 2021 (Figure 2). The number of studies focusing on chemistry textbooks has

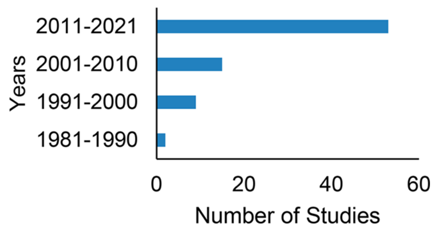

Figure 2. Publication years of the studies in this literature review.

been increasingly growing over the years (Figure 2) and we anticipate that this trend will continue. This highlights how timely this review is, as it is important to evaluate the current landscape of research on chemistry textbooks to inform the design and focus of future studies.

The studies were published in 22 journals, with the most common journals being *Chemistry Education Research and Practice* (n = 23, 29%), *Journal of Chemical Education* (n = 15, 19%), *International Journal of Science Education* (n = 8, 10%), *Journal of Research in Science Teaching* (n = 6, 8%), and *Research in Science Education* (n = 5, 6%). These studies analyzed textbooks used in a variety of countries (Figure 3). Notably, 25% of the studies (indicated by the red bar in Figure 3, n = 20) did not specify the country of use for the textbooks in their samples.

The majority of the analyzed studies (n = 41, 52%) exclusively focused on secondary chemistry textbooks, whereas fewer studies focused on postsecondary textbooks (n = 30, 38%). Some studies (n = 8, 10%) examined and compared secondary and postsecondary textbooks. A more in-depth analysis of the studies that included postsecondary textbooks in their samples showed that about half of these studies focused on general chemistry textbooks and about a quarter focused on organic chemistry textbooks. We found only two studies focusing on

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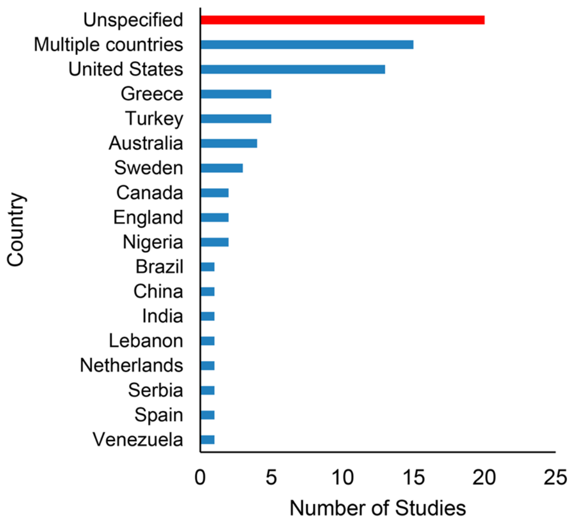

Figure 3. Countries of use for the textbooks in the study samples of articles in this literature review.

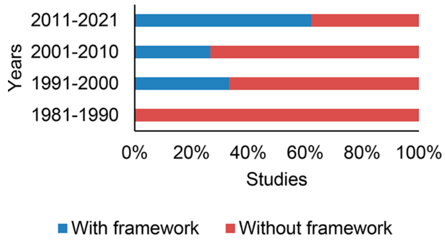

Figure 4. Percentage of studies with or without theoretical or analytical framework(s).

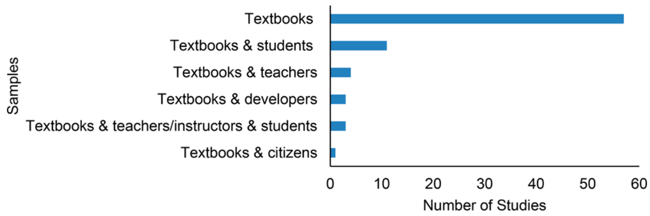

Figure 5. Samples in the studies in this literature review.

physical chemistry textbooks,[10,36] one study on biochemistry textbooks,[34] and no studies on analytical, inorganic, and other chemistry subjects textbooks.

We also captured the theoretical and/or analytical frameworks that were used to analyze chemistry textbooks or design studies around chemistry textbooks.[89] Several frameworks were used in multiple studies that employed theoretical frameworks: Johnstone's Triangle,[2,7,10,12,14,43,50,51,54,79] Cognitive Load Theory,[1,14,19] Bloom's Taxonomy,[27,48,63] Mayer's Multimedia Principles,[7,12] Ainsworth's Design, Functions, Tasks (DeFT) Framework,[15,19] Robert's Curriculum Emphases,[18,52] and the Framework on Scientific Literacy.[22,28] We identified multiple other frameworks that were each used in a single study on chemistry textbooks (e.g., the Information Processing Model,[3] Vygotsky's Zone of Proximal Development,[5] Kozma and Russel's Representational Competence,[7] Fink's Taxonomy of Significant Learning,[11] Han and Roth's Semiotic Model,[15] Vermunt and Verloop's Taxonomy of Learning Activities,[18] Wu and Shah's Five Principles of Textual Diagrams,[19] Constructivism,[30] the Analogy Classification Framework,[32] Bunge's Five Ontological Categories,[35] Ausubel and Novak's Meaningful Learning,[77] and others). Importantly, about half of the articles (*n* = 39, 49%) did not use any theoretical/analytical frameworks to guide the design of their studies and the interpretation of their findings. We hypothesized that older studies would have been more likely to lack frameworks and that newer studies would have incorporated them more frequently, in alignment with the increasing standards for conducting research. Upon examining the publication years of the studies lacking frameworks, we identified that most textbook studies published before 2010 did not use a framework (Figure 4). Surprisingly, 20 of the 53 studies published in the past decade (38%) did not incorporate a framework.

With respect to the samples and methods used in studies around chemistry textbooks, we found that 72% of studies (*n* = 57) featured exclusively textbook(s) samples. The rest of the studies incorporated not only textbooks in their samples but also secondary or postsecondary students (*n* = 15, 19%), teachers or university instructors (*n* = 5, 6%), textbook developers (*n* = 3, 4%), and citizens (*n* = 1, 1%). The percentages exceeded 100% because some studies incorporated mixed samples (Figure 5). Overall, this shows that less than 30% of studies focus on understanding how students and/or teachers/instructors use chemistry textbooks or how developers write and evaluate chemistry textbooks.

Most studies (*n* = 58, 73%) employ qualitative methods, while fewer employ quantitative (*n* = 9, 11%) or mixed-methods (*n* = 12, 15%) designs. Among the studies which used a qualitative approach, most used deductive coding, some used inductive coding, and several studies used a combination of inductive and deductive coding to analyze the textbooks. A representative example article that used a qualitative approach is a study by Nyachwaya and Gillaspie.[1] In this study, the authors characterized how five general chemistry textbooks incorporate representations. The authors deductively coded a random sample of pages in these textbooks using the modified Graphical Analysis Protocol to capture a variety of features such as the number of representations per page, the proximity of each representation to its corresponding text, the function of each representation, the conceptual integration of representations with text, and others. As shown, qualitative coding was predominantly used in the studies that analyzed various aspects of the textbooks in their samples. Qualitative coding was also used in the few studies which interviewed human subjects (e.g., students, instructors, textbook authors),[6,16,21,41,45,69]

Most of the studies that included both human subjects and textbooks relied on quantitative or mixed-method designs by collecting data using surveys, questionnaires, or assessments. A representative example article that used a quantitative approach is a study by Smith and Jacobs[29] who investigated how students and instructors from across 10 universities in the United States (U.S.) used general chemistry and organic chemistry textbooks. The students and instructors completed a survey about the time spent using various textbook resources and the quality and helpfulness of specific textbook features. The authors then conducted a variety of analyses, including a correlation analysis between the weekly hours of studying and students' anticipated letter grades. In general, qualitative methods were primarily used to analyze various aspects of textbooks, whereas quantitative or mixed methods designs were primarily used in studies that focused not only on textbooks but also on human subjects.

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3.2. Findings from Studies around Chemistry Textbooks

This section describes two main groups of studies: those that characterized various aspects of chemistry textbooks (n = 71, 90%) and those that also included human subjects in their samples (n = 21, 27%) to characterize how chemistry textbooks are written, perceived, or used. Each main group of studies is further subdivided into categories that reflect the focus of the corresponding studies (Table 1). The percentages in Table 1 exceed 100% because some studies fall into both groups (e.g., examination of a specific component of chemistry textbooks as well as how instructors or students perceive this component).

Table 1. Two Main Groups of Studies as Well as Subcategories of Studies

Focus of Studies	Number of Studies	Percent of Studies
Characterization of the various aspects of chemistry textbooks (n = 71, 90%)		
Presentation and sequencing of topics	n = 39	49%
Presentation of images and representations	n = 15	19%
Emphasis and focus of questions, worked examples, and practice problems	n = 10	13%
Use of analogies, metaphors, and teleological explanations	n = 5	6%
Gender and racial representation in chemistry textbooks	n = 5	6%
The cohesion of text and complexity of vocabulary	n = 3	4%
Characterization of how chemistry textbooks are written, perceived, or used (n = 21, 27%)		
Students' perceptions, use, and understanding of textbooks' content	n = 15	19%
Teachers' and instructors' perceptions and use of textbooks	n = 5	6%
Developers' approach to writing, reviewing, and publishing chemistry textbooks	n = 3	4%

3.2.1. Characterization of the Various Aspects of Chemistry Textbooks.

The studies in this section (n = 71, 90%) are grouped to summarize what is known about various aspects and components of chemistry textbooks: presentation and sequencing of topics (n = 39, 49%), emphasis and focus of questions, worked examples, and practice problems (n = 10, 13%), number, type, and presentation of images and representations (n = 15, 19%), the cohesion of text and complexity of vocabulary (n = 3, 4%), use of analogies, metaphors, and teleological explanations (n = 5, 6%), and gender and racial representation in chemistry textbooks (n = 5, 6%).

Presentation and Sequencing of Topics. About half of the studies investigated how various topics are presented and sequenced in chemistry textbooks. The studies in this category investigated a wide variety of chemistry topics: bonding,[6,20,47,61,63,72,77] nature of science,[22,28,57,68,69] redox and electrochemistry,[26,30,50] gas laws,[17,59] models,[25,44] kinetics,[12,43] substance and matter,[54,76] energy,[49,76] delocalization and resonance,[3] ^{1}H NMR spectroscopy,[5] protein synthesis,[13] carbonyl chemistry,[16] thermodynamics,[35] acid−base chemistry,[45] physical and chemical change,[60] electrolysis,[64] heat,[71] gene function,[73] Millikan's oil drop experiment,[78] practical work and laboratory procedures,[65] air quality,[46] industrial organic chemistry,[33] and green chemistry.[11] Almost half of these studies analyzed exclusively secondary chemistry textbooks,[6,12,20,22,26,28,50,54,57,59,61,65,68,69,72,76,77] and a substantial number of studies analyzed general[30,43,44,46,47,49,63,78] or organic chemistry textbooks.[3,5,11,16,33] The remaining studies compared different chemistry textbooks: secondary and general chemistry textbooks,[17,45,64] secondary chemistry and biology textbooks,[13,25,73] secondary science, general chemistry, and physical chemistry textbooks,[35] and two studies compared textbooks for more than three subjects.[60,71] Most of the 39 studies analyzed *topic presentation*, and three examined *topic sequencing* in chemistry textbooks.

The studies that focused on *topic presentation* demonstrate that chemistry textbooks misrepresent their content, can be a source of misconceptions, and have many areas for improvement. For example, one study found that all but one of their 15 analyzed organic chemistry textbooks had errors, inappropriately showing the mechanism arrow depicting nucleophilic attack at the carbonyl lowest unoccupied molecular orbital.[16] A subsequent study found that the way secondary chemistry textbooks in their sample present kinetics may contribute to rote learning and misconceptions.[12] Another study found that all of the secondary chemistry textbooks in their sample explicitly or implicitly attributed the octet rule as the reason for bonding.[20] In addition, some studies showed that textbooks underrepresent important content. Some topics, such as the nature of science in secondary chemistry textbooks[28,57] or green chemistry in organic chemistry textbooks[11,23] were only addressed superficially, with little to no thorough explanation.

The studies that focused on *topic sequencing* found that organic chemistry and physical chemistry textbooks sequence many topics similarly. For example, all nine organic chemistry textbooks in the sample in one study introduced the reactivity of aromatic compounds before carbonyl compounds and aldehydes and ketones before carboxylic acids and their derivatives.[23] This was also true for many concepts and skills; for example, structure−property relationships and Lewis structures were consistently introduced in the first few pages. There was some variation, however, in the sequencing of Grignard and organolithium reagents in the examined textbooks. Additionally, some topics were not covered in many textbooks; a third of the examined textbooks did not cover green chemistry, and most did not cover combinatorial chemistry. Similarly, a study that examined the sequencing of thermodynamics in 20 physical chemistry textbooks found that most of the analyzed textbooks placed thermodynamics early in the textbook, yet there were differences in the topics that followed (e.g., kinetics and quantum chemistry). A few textbooks, however, sequenced topics differently by introducing quantum chemistry before thermodynamics.[36]

Emphasis and Focus of Questions, Worked Examples, and Practice Problems. Ten studies investigated end-of-chapter questions, worked examples, and practice problems in secondary,[18,48,55,77] organic chemistry,[3,5,19] general chemistry,[27,63] and one compared both secondary and general chemistry textbooks.[17] These studies focused on characterizing the *emphasis* of questions, worked examples, and practice problems within chemistry textbooks[17,18,27,48,55,63] and *how appropriately* questions, worked examples, and practice problems represented various chemistry concepts.[3,5,19,77]

Chemistry textbooks vary in the *emphasis* of their questions, examples, and practice problems. For example, one study found that questions in secondary chemistry textbooks assess memorization of chemistry content,[18] while another found that only approximately 5% of gas law questions in secondary chemistry textbooks were recall-based.[55] Additionally, other studies found that gas law chapters in general chemistry textbooks feature more short-answer qualitative practice problems than in secondary textbooks.[17,63] Finally, one study found that end-of-chapter questions in different general chemistry textbooks require very different strategies to complete them: recall of information, use of formulas to calculate an answer, and making predictions.[27] This study also noted a lack of problems in the higher cognitive categories that require students to apply what they have learned in new contexts and to use their knowledge to generate hypotheses, create models, and generalize ideas.

Concerning *how appropriately* questions, worked examples, and practice problems represented various chemistry concepts, results are similar to those described in the "presentation and sequencing of topics" section, in which chemistry textbooks have many areas for improvement. For example, one study found that end-of-chapter questions focusing on delocalization primarily asked students to draw resonance structures, but they hardly asked students to practice other related skills, such as identifying the hybridization of atoms, determining the relative stability and reactivity of ions, or determining the electrophilic and nucleophilic areas on a molecule.[3] Another study evaluated practice problems focusing on Newman and Fischer projections and found that most textbooks exposed students to illustrations of only symmetric, nonchiral molecules and that very few asked students to translate these representations to dash-wedge diagrams.[19] A different study found that the organic chemistry textbooks had worked examples and practice problems that covered all four of the expected ^{1}H NMR spectral features (i.e., the number of signals/proton equivalencies, chemical shift, integration, and splitting). However, there was variation in the extent to which the textbooks were interleaving versus blocking these spectral features.[5,90] Finally, another study found that a quarter of their analyzed secondary textbooks did not feature any practice problems associated with metallic bonding.[77] This study also reported problematic use of the words "cation" and "atom" in some textbooks when explaining metallic bonding.

Number, Type, and Presentation of Images and Representations. Fifteen studies focused on analyzing representations within chemistry textbooks. Specifically, 12 (15%) examined the *number* and/or *type*/*level* of representations included in chemistry textbooks[1,2,7,9,10,15,19,20,50,51,53,79] and 6 (8%) characterized how *captions, labels*, and/or *indexing* can support the interpretation and comprehension of representations and the associated text.[1,2,7,10,51,79] Most of these studies analyzed secondary textbooks,[7,15,20,50,51,53,79] some analyzed postsecondary textbooks (general chemistry,[1] organic chemistry,[19] and physical chemistry[2,10]), and others compared textbooks associated with various chemistry disciplines or educational levels.[2,9] The findings in this subsection vary across chemistry textbooks used in different countries and educational settings.

Several studies explored the *number* of representations in textbooks. For example, it was found that most pages in physical chemistry textbooks contain at least one representation,[10] whereas most pages in general chemistry textbooks contain about four representations.[1] A study focused specifically on electrostatic potential maps (EPMs) found that EPMs are used more frequently in organic chemistry textbooks as compared to general chemistry textbooks.[9] Furthermore, a study that compared Turkish, U.S., and Indian secondary chemistry textbooks found that Turkish and U.S. textbooks rely more heavily on representations than Indian textbooks.[15]

Studies categorized *types* of representations based on their function. For example, some studies categorized representations as decorative (does not contribute meaning to text), representational (aids or adds concreteness to text), organizational (summarizes or adds coherence to text), or interpretive (adds new information not presented in the text).[1,79] It was found that U.S. general chemistry textbooks contain mostly representations that serve a representational function (79−90% of representations), with only some that serve a decorative purpose (5−14%),[1] whereas more than 55% of the images in secondary chemistry textbooks used in Brazil serve a decorative purpose.[79] Some studies investigated the *level* of representations via the lens of Johnstone's triangle[91] by characterizing representations as symbolic, macroscopic, submicroscopic, multiple (show a chemical phenomenon simultaneously at 2−3 levels), hybrid (show how the levels of chemistry coexist to form one representation), and mixed (combine chemistry level and characteristics of another type of representation). Macroscopic representations are most prevalent in Lebanese, Chinese, and Brazilian secondary chemistry textbooks,[7,15,50,51,79] whereas symbolic representations are most common in Turkish, Indian, and American secondary textbooks.[15,51] One study found that macroscopic representations increase in frequency as the grade level increases in Greek secondary textbooks.[14] Additionally, Lebanese and Greek secondary chemistry textbooks and U.S. physical chemistry textbooks use very few multiple, hybrid, and mixed representations.[2,7,10] However, when incorporated, the multiple, hybrid, and mixed representations generally lack sufficient connections between the various levels of chemistry. Similarly, another study evaluated how well textbooks from various countries support students in making connections between the three levels of Johnstone's triangle and found that Turkish and Indian secondary chemistry textbooks lack sufficient connections between the three levels, but textbooks used in the U.S. provide adequate connections.[15] Finally, one study found that symbolic representations are most prevalent in physical chemistry textbooks.[10]

Several studies found that U.S. and Greek secondary and postsecondary chemistry textbooks generally include adequate *captions* accompanying representations.[1,2,51] Additionally, in the case of representations that had captions in the U.S. physical chemistry textbooks, all captions were brief and explicit and provided a complete description of their corresponding representations.[10] Representations that did not have captions were mainly mathematical equations that did not require captions. Furthermore, most representations in U.S. postsecondary textbooks had *labels*.[1,10] However, some studies have also reported problematic or missing *captions* and *labels* in some textbooks. For example, one study found that about half of the Lebanese secondary textbooks in their sample have unclear *captions*.[7] Additionally, two studies reported a lack of systematic *labeling* in Greek and Lebanese secondary and postsecondary chemistry textbooks.[2,7] Regarding *indexing*, one study found that most representations within U.S. general chemistry textbooks are *indexed*,[1] while other studies found that many representations in secondary and postsecondary textbooks used in Greece,[2] Lebanon,[7] and Brazil[79] are not *indexed* at all, not *indexed* within the same page, or feature inconsistent *indexing*.

The Cohesion of Text and Complexity of Vocabulary. Even though text occupies a very significant proportion of space on the pages of chemistry textbooks, only one study (1%) directly investigated aspects of the text in general chemistry textbooks.[4] Additionally, two studies (3%) analyzed vocabulary/terms used in secondary chemistry textbooks.[13,56]

The study on the text used a computer program called Coh-Metrix to evaluate cohesion (the degree to which a reader must

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use domain knowledge to accommodate for conceptual gaps in the text) in general chemistry textbooks compared to cohesion in adult fiction books.[4] Ideally, cohesion should change very little throughout a chapter and decrease as the chapters progress. It was found that the analyzed chemistry textbooks tended to be more cohesive than novels, because novels contain content with which readers are more familiar. Additionally, cohesion levels differed significantly among the five examined general chemistry textbooks. Finally, the two studies that analyzed vocabulary reported that students are exposed to a lot of new terms in chemistry textbooks and might need support distinguishing between various terms.[13,56]

Use of Analogies, Metaphors, and Teleological Explanations. Five studies (6%) focused on other pedagogical tools such as analogies and/or metaphors in secondary textbooks[31,32,58,77] and biochemistry textbooks,[34] and one study examined the teleological explanations in general and organic chemistry textbooks.[62] These pedagogical tools were generally used to justify why submicroscopic particles adopt certain configurations or why certain substances react in a particular way.[62] The metaphorical "purpose" assigned to chemical systems that warrant the use of teleological explanations is frequently that of attaining stability or equilibrium (i.e., systems "strive" to become more stable or reach equilibrium).[62]

Analogies tended to be used more frequently in the earlier stages of the textbooks.[32] Pictorial analogies compromised over or around half of all analogies and were frequently positioned in the margins, whereas verbal analogies were incorporated into the text.[31,32,58] Many of the analogies were related to atomic structure, bonding, and energy.[31,32] Notably, despite the high prevalence of anthropomorphic language, textbooks rarely explain the limitations of the employed analogies, metaphors, or teleological explanations[31,62] or provide instructions on the role of metaphors[77] or how to use analogies.[34]

Gender and Racial Representation in Chemistry Textbooks. Five studies (6%) examined gender representation[8,22,24,37] and representations of people of color in chemistry textbooks.[42] Three of these studies analyzed secondary textbooks[22,24,37] and two analyzed general chemistry textbooks.[8,42] Generally, these studies investigated images that contained depictions of people[8,24,37,42] or searched the index or text for names of people.[8,22,24]

Gender and racial representation in chemistry textbooks is unequal, as women and/or people of color are not portrayed to the same degree as men and/or white people. Specifically, one study reported that the appearance of males in images is significantly higher than females in the U.S. general chemistry textbooks.[8] Additionally, in images with many people containing only males, only females, or both, the frequency of images that contain only males is significantly higher than those with only females. Similarly, another study found that across the Turkish secondary textbooks analyzed, photographs and illustrations are male-dominated, with twice as many photographs and six times more illustrations depicting exclusively men.[24] This study also stated that only three of the 20 textbooks in their sample contain approximately the same number of photographs depicting men and women. Interestingly, there were a few cases of female-dominated textbooks, and they were most often authored by women.[24] Finally, a study that compared seven secondary chemistry textbooks from the 1880s to seven secondary chemistry textbooks from the 1970s found that only two textbooks improved their gender representation in images of adults and only one for representation of female youth.[37]

The studies that analyzed the index or text for names also found that these depictions are male-dominated. For example, one study found that names represented within Turkish secondary textbooks belong to males in almost all instances.[24] Similarly, another study showed that, of all the unique names of the STEM professionals listed in the index across the analyzed general chemistry textbooks, only 3% are women's names, and male names appear 60 times more frequently than female names.[8] Furthermore, most names are those of well-known male scientists, and there are very few cases in which well-known female scientists are mentioned.[8,24] The only female scientist that has been noted across the textbooks in these studies is Marie Curie.[24]

A single study looked at the representation of people of color. For this study, a person of color was defined as any person who, as perceived by the authors, could not pass for having a predominantly European ancestry. The study found that the extent of inclusion ranges from 3% to 28%, depending on the general chemistry textbook analyzed. Additionally, many of the photographs in the textbooks present people of color in nonscience contexts. Lastly, they found that all 11 textbooks analyzed possess some degree of invisibility (e.g., people of color not being represented in any important pictures), six had at least one incidence of fragmentation or isolation (e.g., pictures of people of color in which their ethnic group is the only ethnic group presented), and four contained stereotyping (e.g., depicting an African-American man in an athletic context or a young girl of Asian ethnicity studying).[42]

3.2.2. Characterization of How Chemistry Textbooks Are Written, Perceived, and Used. A fourth of studies (n = 21, 27%) characterized not only aspects of chemistry textbooks but also included human subjects in their samples. We grouped these studies to summarize what is known about how students perceive, use, and understand the content of chemistry textbooks (n = 15, 19%), how teachers and instructors perceive and use chemistry textbooks (n = 5, 6%), and how developers write, review, and publish chemistry textbooks (n = 3, 4%).

Students' Perceptions, Use, and Understanding of Textbooks' Content. Fifteen studies (19%) analyzed how students perceive, use, and understand the content of secondary,[12,21,56,61,67,70,72,74] general chemistry,[38−40,75] secondary and general chemistry,[64] organic chemistry,[16] and general and organic chemistry textbooks.[29] These studies used a variety of methods: surveys,[29,38,39,56,64,74,75] surveys and interviews,[16,21] and some tested student comprehension of the textbook content with assessments.[12,40,61,67,70,72] A subset of these studies examined student use of ebooks[38,39] or open educational resources (OERs).[40,70,75] Three of these studies asked students to complete surveys to compare ebooks/OERs and traditional textbooks[38,39,75] and two examined the difference in student assessment scores when using ebooks/OERs and traditional textbooks.[40,70]

When using textbook resources, general chemistry students spent most of their time using the textbook itself and only some of their time using the study guide/solution manual.[29] In contrast, organic chemistry students used the textbook less in comparison to the study guide/solution manual. The studies that evaluated student understanding of textbook content found some negative results. For example, studies that tested students' understanding of kinetics[12] and bonding[61,72] when learning from their secondary chemistry textbook found that many students had difficulties understanding these concepts. One study surveyed secondary students about the terms that might be hard for them and found that around half of the vocabulary terms in the survey were rated as difficult (e.g., terms such as amphiprotic, solvate, and syn-elimination).[56]

Several studies compared student use of print textbooks and ebooks/OERs. One study found that switching formats did not significantly affect the time that students spent using a textbook, but it affected the way students studied: those who used print textbooks were more likely to study with friends or in study groups, and students who used an ebook were more likely to study individually.[38,40] Another study reported that students who chose to use the OERs spent significantly less time using the textbook than students who used a print textbook.[75] Another study found that most students preferred to use print textbooks.[39] The few who preferred digital texts thought that they were more convenient and easier to use to find something specific. Finally, the studies that compared student understanding of content when using print textbooks and OERs found that students either performed the same[40,75] or had higher scores on assessments when using OERs.[70]

With respect to students' perceptions of chemistry textbooks, studies that surveyed students about the attributes of their secondary chemistry textbook found that students answered positively about the content, exercises, and questions within the textbook.[21] Another study found that students responded very positively about certain figures, such as summary sheets and decision trees, as concise and clear ways of presenting information.[16] Additionally, studies show that students think very highly of chemistry textbooks and regard them as very reliable and accurate sources of knowledge. Students do not question textbooks even when they interface with empirical data that contradicts textbooks' content. For example, in one study, high-school students performed electrolysis experiments and obtained data that contradicted the information in their textbook.[64] Despite this, when asked to evaluate their textbook, most students expressed an appreciation of their textbook and some doubted the experimental results that they obtained. Only 9% of students believed their experimental results should be trusted, and the textbooks may be wrong.

Teachers' and Instructors' Perceptions and Use of Textbooks. Five studies (6%) analyzed how teachers and instructors perceive or use secondary,[6,21] secondary and general chemistry,[45] general and organic chemistry,[29] and secondary chemistry, biology, and physics textbooks.[41] These studies used a variety of methods: analysis of course artifacts (e.g., instructors' lesson plans or curricula),[6,61] interviews,[6,41,45] surveys,[29] and both surveys and interviews.[21]

One study interviewed teachers regarding the attributes of their secondary chemistry textbooks.[21] The teachers felt that many activities within the textbooks they used encouraged memorization and that the textbooks were too detailed or challenging for their students. Two studies examined how instructors select models within secondary textbooks to use in instruction.[6,41] One study found that secondary chemistry instructors referenced their textbooks as sources to design their lesson plans.[6] Specifically, the way instructors presented models of chemical bonding in their course artifacts was very similar to how the textbooks they used presented these models. Additionally, similar to the textbooks that they used, the instructors also referenced the octet rule as the reason for bonding and anthropomorphized chemical species when explaining bonding. Notably, these studies show that textbooks serve as curricular guides that help instructors decide what and how to teach.[6,41] Specifically, textbooks strongly influence the order, selection, examples, and applications of science topics in instructors' materials.[41]

Developers' Approach to Writing, Reviewing, and Publishing Chemistry Textbooks. Three studies (4%) analyzed source documents (e.g., textbook development notes, raw textbook manuscripts), conducted focus groups, surveyed, and/or interviewed textbook authors,[66,69] publishers,[69] reviewers,[66] and editors[69] about aspects of secondary chemistry textbooks[31,69] or textbooks that span a variety of subjects including chemistry.[66]

One study that interviewed textbook authors found that most textbook authors expect teachers to explain the analogies from their textbooks, though the explanations in their textbooks should be sufficient for students to understand the analogies.[31] The authors could define the term analogy but struggled to distinguish between analogies and models. The authors also expressed having to navigate the requests of publishers to keep the costs of textbooks to a minimum. Another study investigated textbook authors, reviewers, publishers, and editors about the presentation of nature of science (NOS) ideas in their textbooks.[69] Even though the developers spent much time deliberating the accuracy, consistency, age, grade, and reading-level appropriateness when presenting NOS ideas, ultimately marketability and sales were the overarching factors influencing the presentation of these ideas in the textbook. To manage market risks, textbook developers agreed to make NOS ideas less obvious. Another study found that reviewers rated textbooks highly for grammar and consistency, but lower on interface and comprehensiveness.[66] Notably, physics and chemistry books tended to be rated significantly lower in comprehensiveness, accuracy, modularity, organization, interface, and overall quality than textbooks in other disciplines.

4. LIMITATIONS

This review analyzed and summarized 79 studies that examined secondary and postsecondary chemistry textbooks used in various countries.[1−79] While we intend for this review to be comprehensive, we acknowledge the possibility of unintentional omissions. Additionally, this review may be limited by the exclusion criteria used to select articles. For example, this review includes only peer-reviewed journal articles and excludes textbook chapters, dissertations, commentaries, and conference proceedings. Additionally, even though we included studies that analyzed textbooks used in a variety of countries, this review includes articles written in English only. These choices could have resulted in the omission of some research on chemistry textbooks and a skewed representation of research published in English. Finally, this review may be limited by the authors' bias or personal opinions, which could influence the selection of articles and the interpretation of the findings. We used strategies such as researcher triangulation, peer debriefing, and reflexive journaling to minimize this limitation and ensure the credibility and confirmability of the identified patterns.[86−88]

5. CONCLUSIONS AND IMPLICATIONS

This review provides a comprehensive overview of 40 years of research around chemistry textbooks. The number of studies dedicated to the analysis of chemistry textbooks has steadily increased over the years and has notably surged in the past decade. We expect this trend to continue in the future. This underscores the significance of this review as it is important to assess the present state of research on chemistry textbooks to

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guide the design of future textbooks and the direction of future studies on chemistry textbooks.

Conclusions and Implications for Research

Of the analyzed studies, the majority (52%) focused solely on secondary chemistry textbooks, while a smaller percentage (38%) focused on postsecondary textbooks. Some studies (10%) examined and compared secondary and postsecondary textbooks. A closer examination of the postsecondary textbook studies revealed that about half of these studies focused on general chemistry textbooks and about a quarter focused on organic chemistry textbooks. As shown, very few studies have analyzed postsecondary textbooks associated with upper-chemistry subjects (e.g., biochemistry, analytical chemistry, and inorganic chemistry). Research is needed to evaluate the effectiveness and use of higher-level postsecondary chemistry textbooks. Related to this, little is known about the effectiveness of postsecondary textbooks that employ different curricula (e.g., "traditional approach" vs "atoms-first approach" general chemistry textbooks, "functional groups approach" vs "mechanistic approach" organic chemistry textbooks, etc.).

About half of the articles (49%) did not use any theoretical or analytical framework(s) to guide the design of their studies and the interpretation of findings. Theoretical frameworks are critical, as they provide the conceptual foundation and help justify a research study by placing it within the broader context of existing theory-building research. Future research studies should use frameworks to ensure and improve the rigor of investigations around chemistry textbooks. The use of frameworks would help clarify the philosophical, epistemological, theoretical, and/or methodological presuppositions driving the researchers conducting research around textbooks.[89]

A fourth of the studies (25%) did not specify the country of use for the textbooks in their samples. Among the studies that did not provide this information, most were published by researchers affiliated with institutions in the U.S. When writing publications, researchers should explicitly state the country of use for the textbooks to help readers across the globe better understand the context of the study and the transferability of the findings.

Most articles (70%) lacked a discussion of the limitations of their studies. Including a limitations section is an important way for researchers to demonstrate their transparency and commitment to improving the quality of research in the field. The omission of a limitation section is particularly problematic in studies examining gender and racial representation in chemistry textbooks. For example, most of those studies did not acknowledge that they were framed within the context of binary definitions of sex and gender. Due to the variations of biological sex at the chromosomal, hormonal, gonadal, and genital levels, the use of the terms male and female is overly simplistic.[8] Additionally, most of these studies did not acknowledge that they did not explicitly determine the proportion of male/female or white/nonwhite individuals in an image (i.e., instead, the researchers ascertained what a reader of the text would likely perceive as the sex/race of the person in an image based on gender/race presentation cues). Moreover, four of the five articles examining gender and racial representation in chemistry textbooks did not include a positionality statement from the researchers to explain the potential influence of the researchers' backgrounds, beliefs, and perspectives on the study's findings. Future research studies examining gender and racial representation in chemistry textbooks should include positions of the researchers and a discussion of the limitations of their study designs.

Even though text occupies a very significant proportion of the space on the pages of chemistry textbooks, only three studies (4%) investigated aspects of text or vocabulary in chemistry textbooks. More research is necessary to investigate the possibility of improving the quality, accessibility, and comprehension of text in chemistry textbooks to make them more effective tools for learning.

Most of the studies (72%) featured exclusively textbook samples. Only about a quarter of studies incorporated human subjects (e.g., students, teachers/instructors, textbook developers) in addition to textbooks in their samples. A similar finding was reported in the review of science education textbook studies by Vojíř and Rusek.[92] More studies need to be designed to explore how students and teachers/instructors use textbooks as well as the reasoning that textbook developers use in writing and evaluating their products. For example, more research with students is necessary to identify features in print textbooks/ebooks/OERs that may be hindering learning as well as features and design choices that are effective for learning. Additionally, more research is necessary to understand how seeing pictures and names of predominantly white male scientists might affect students' sense of belonging, development of science identity, and motivation to continue in their majors. Interestingly, although research studies reveal numerous areas for textbook improvement, studies show that students tend to hold textbooks in a very high regard.

Finally, we observed a variation in findings when comparing results from different studies examining the same aspects of chemistry textbooks. For example, there is a variation in the distribution of Johnstone's levels of representation across various chemistry textbooks used in different countries and educational settings. More research is necessary to replicate these studies to improve the generalizability of these findings and to identify moderators that explain differences across settings.

Conclusions and Implications for Chemistry Teachers and Instructors

Teachers and instructors should be aware that some chemistry textbooks may misrepresent some content, may not make sufficient connections between the three levels of Johnstone's triangle, may not explain the limitations of the employed analogies and metaphors, and may be a source of misconceptions. It is therefore important to critically evaluate the information presented in textbooks, provide additional explanations, and address any inaccuracies with students. Teachers and instructors should also be aware that some topics in chemistry textbooks are only superficially addressed. Depending on the desired learning outcomes, teachers and instructors should supplement the textbook materials with additional resources or explanations to ensure a comprehensive understanding of the subject matter. Similarly, it is critical to evaluate the practice problems in chemistry textbooks to ensure the alignment between learning objectives and the assigned practice problems. This may require teachers and instructors to supplement instruction with additional practice problems that require higher-order thinking and the transfer of knowledge. Finally, instructors should recognize that gender and racial representation in chemistry textbooks is unequal. To foster inclusion, instructors can actively seek out supplemental materials that

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feature diverse perspectives and showcase the contributions of women and people of color in the field of chemistry.

Conclusions and Implications for Textbook Developers

The studies that focused on the presentation of topics and questions/worked examples/practice problems demonstrate that some chemistry textbooks misrepresent their content, can be a source of misconceptions, and assess memorization. These results indicate a need for textbook authors to evaluate the accuracy of the content and topics they present to ensure that textbooks do not contain errors that could lead to misconceptions. Developers should also consider the sequencing of topics to ensure that topics are appropriately introduced and covered in a logical and coherent order. Developers should also include problems that require higher-order thinking and challenge students to apply what they have learned in new contexts. Additionally, studies suggest that analogies, metaphors, and teleological explanations may be powerful pedagogical tools but may also lead to misconceptions and unwarranted overgeneralizations. To prevent this, textbook authors should explain the limitations of these pedagogical tools.

Textbook developers should also reconsider how they incorporate representations in their textbooks. One issue identified was the significant proportion of decorative images in some textbooks, which may be distracting and may not serve a clear educational purpose. There is also a variation in how effectively chemistry textbooks support students in making connections between the three levels of Johnstone's triangle. Other studies reported problematic or missing captions and labels in some textbooks and that most representations in some textbooks are not indexed at all or not indexed within the same page. These findings are discouraging because they suggest that some textbook developers are not paying enough attention to something so simple as integrating representations with text. Without proper captions, labels, and indexing, students may misinterpret the information presented in representations or struggle to find the relevant representation when reviewing or studying. This can result in wasted time, frustration, and ultimately lower learning outcomes. Therefore, proper captions, labels, and indexing of representations should be the minimum standards for publishing any chemistry textbook.

Finally, the existing studies that explore racial and gender representation in chemistry textbooks highlight the underrepresentation of women and people of color in both text and images. These results emphasize the need to amend textbooks to acknowledge and represent diverse populations because, otherwise, the students may assume that there is no scholarship produced by women and people of color or, perhaps worse, that the scientific community does not value it.

Multiple considerations need to be made in the development of textbook and supplemental instructional materials, including cost, textbook design choices, scope, and the comprehensiveness of the intended content. Given how influential textbooks can be in student education as well as how expensive textbooks can be, it is not unreasonable to hold textbooks to the highest standard. Textbook designers need to ensure that their products are grounded in research and theory about student learning.[9,93] The Chemistry Education Research field has made momentous strides toward understanding how to improve the teaching and learning of chemistry.[94,95] Textbook developers should be intentional about leveraging this research to include numerous supports for developing student problem-solving skills, scientific practices, metacognitive thinking, and transfer of knowledge, among other things.[94,95] Doing so may necessitate more effective interactions between textbook developers, education researchers, curriculum and materials developers, students and instructors, and other formal or informal dissemination systems (conferences, journal articles, developer workshops, etc.).[9,93] These interactions are critical to ensure that research and theory are put into an effective textbook design practice.

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