JOURNAL OF CHEMICAL EDUCATION

Article

Cite This: *J. Chem. Educ.* 2020, 97, 383−389

pubs.acs.org/jchemeduc

Green Chemistry Coverage in Organic Chemistry Textbooks

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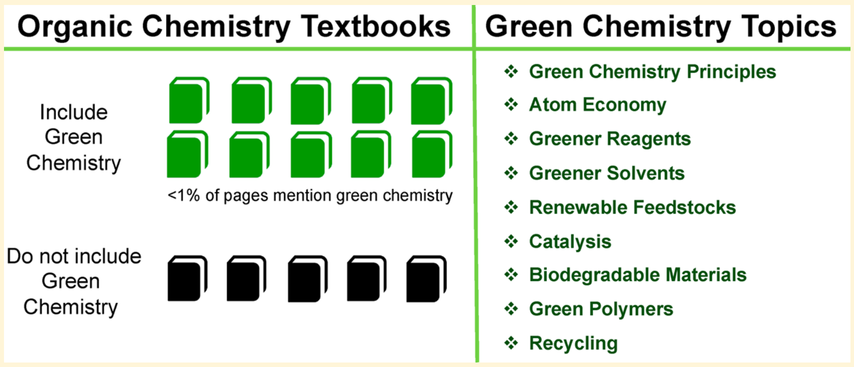

ABSTRACT: This paper examines the current state of the implementation of green chemistry into organic chemistry textbooks. Content analysis of the 15 most used organic chemistry textbooks revealed that only 10 of them had any mention of green chemistry. In textbooks that contained mentions of green chemistry, it was mentioned on less than 1% of pages. Green chemistry topics mentioned include the 12 green chemistry principles, atom economy, greener solvents and reagents, recycling, biodegradable materials, renewable feedstocks, and catalysis. Only three textbooks contained several end-of-chapter problems with green chemistry content, and all but two included the majority of green chemistry content in extraneous textboxes. The current presentation of green chemistry concepts and lack of assessment items is more suitable for a lecture-based approach as opposed to creating a student-centered learning environment.

KEYWORDS: *Green Chemistry, Textbooks/Reference Books, Organic Chemistry, General Public, Second-Year Undergraduate*

Since the publication of Anastas and Warner's classic textbook on Green Chemistry, the movement to incorporate green chemistry in the chemistry curriculum has been on the rise.[1] There are two ways to implement green chemistry in undergraduate education: in existing courses[2] or as a stand-alone course.[3,4] While connections to various areas of chemistry exist,[5,6] most literature examples report the implementation of green chemistry into organic chemistry.[7] When it comes to integration of green chemistry into the curriculum, organic chemistry instructors are the gate keepers of this process.

One of the most important decisions that organic chemistry instructors make every year is which textbook to use. This choice affects coverage of concepts and to what extent they are discussed, as well as the order in which topics are introduced in the classroom. Textbook selection will impact students as they spend a significant amount of time interacting with textbooks.[8] Factors including cost, readability, organization, the number and cognitive level of problems, and the quality of ancillary materials may influence the decision to adopt a textbook; however, one of the most important factors is content. Instructors generally want to select a textbook with the content that is representative of their instruction.

Content analyses of organic chemistry textbooks have been performed to determine common patterns and assess discrepancies for topics such as acid−base properties of pyridine and pyrrole,[9] cyclohexane conformations,[10] electrostatic potential maps,[11] Wohler's synthesis of urea,[12] molecular representations,[13] and industrial applications of organic chemistry.[14] Two papers examined the sequence of topics in organic chemistry textbooks,[15,16] paying special attention to the textbook treatment of compounds containing carbonyl groups.

In 2009, Cann[17] reviewed 141 undergraduate chemistry textbooks and examined their treatment of green chemistry. Only 33 included some coverage of green chemistry, but mostly in a cursory manner. At that time, seven organic chemistry textbooks and five organic laboratories manuals had mentioned green chemistry. In the textbooks surveyed, the topics that were discussed were ibuprofen synthesis, ionic liquids, supercritical solvents, atom economy, pesticides, polymers, renewable feedstocks, and the principles of green chemistry. In conclusion, Cann called for the inclusion of green chemistry into instructional materials and suggested publishing periodic reports to assess the state of green chemistry coverage.

Received: April 23, 2019
Revised: December 5, 2019
Published: December 18, 2019

DOI: 10.1021/acs.jchemed.9b00397
J. Chem. Educ. 2020, 97, 383−389

We undertook this 10-year old challenge and examined the content coverage of green chemistry concepts in organic chemistry textbooks that are currently used for instruction in institutions in the United States. This information will be useful to organic chemistry instructors who would like to make an informed choice about the adoption of an organic chemistry textbook or who want to locate instructional materials pertaining to green chemistry content. The guiding questions for this review were as listed:

- What proportion of the text is currently devoted to green chemistry topics?
- Which green chemistry topics are currently included in modern organic chemistry textbooks?
- In what way do green chemistry topics relate to the narrative of the book?

■ ORGANIC CHEMISTRY TEXTBOOKS

We surveyed recent edition textbooks that are currently used in U.S.-based schools and regularly updated. Textbooks were obtained from the publishers. In this manuscript, textbooks are referred to using the first author, followed by the edition number. The 15 textbooks examined are referred to throughout this paper as follows: Klein, 3e;[18] Solomons, 12e;[19] Brown, 8e;[20] McMurry, 9e;[21] Wade, 9e;[22] Bruice, 8e;[23] Karty, 2e;[24] Jones, 5e;[25] Vollhardt, 8e;[26] Loudon, 6e;[27] J. Smith, 6e;[28] Carey, 11e;[29] Sorrell, 2e;[30] Ouellette, 2e;[31] M. Smith, 2e.[32] Edition numbers were kept as we have noticed some trends for selected textbooks compared to their previous editions.

■ GREEN CHEMISTRY CONTENT COVERAGE

The presented content coverage included the instances in textbooks where the content was explicitly linked to green chemistry. While individual organic chemistry instructors can make connections between green chemistry and organic chemistry topics during the instructional time using their expertise, these anecdotal curriculum implementations do not represent a nationwide trend in teaching organic chemistry. As the purpose of this manuscript is to evaluate organic chemistry textbooks with respect to the treatment of green chemistry concepts, we focused on examples where these connections were made by the textbook authors.

Number of Pages

In Table 1 we summarized the numbers of pages in textbooks where green chemistry is mentioned as well as the total number of pages that have chemistry content. As shown by the table, green chemistry received quite little to no coverage. Green Chemistry was mentioned in 10 of the 15 textbooks surveyed. In the textbooks that contained any green chemistry coverage, only 6 pages on average mentioned green chemistry. The textbook that had the most coverage was Karty, 2e,[24] which contained 17 pages of green chemistry content, which constitutes ~1.2% of the entire text.

Green Chemistry Topics

The number of pages provides only limited information on the coverage of green chemistry in textbooks. To look deeper into the problem, we have conducted content analysis to reveal which green chemistry topics are included in the textbooks. The results are summarized in Table 2. While some of these topics are general enough that one can find remote connections to them in the narrative, we specifically focused on instances where an explicit connection to green chemistry was made.

Table 1. Comparison of the Number of Pages of Green Chemistry Coverage in Widely Adopted Organic Chemistry Textbooks

		Number of Pages	
Publisher	First Author, Edition	Green Chemistry Coverage	Total in Textbook
Wiley	Klein, 3e	2	1252
	Solomons, 12e	1	1124
Cengage	Brown, 8e	1	1302
	McMurry, 9e	7	1054
Pearson	Wade, 9e	0	1307
	Bruice, 8e	1	1240
W.W. Norton	Karty, 2e	17	1369
	Jones, 5e	4	1247
Macmillan	Vollhardt, 8e	12	1335
	Loudon, 6e	0	1480
McGraw Hill	J. Smith, 6e	7	1291
	Carey, 11e	4	1170
University Science Books	Sorrell, 2e	0	988
Academic Press	Ouellette, 2e	0	1031
CRC Press	M. Smith, 2e	0	1128

Green Chemistry Principles. While green chemistry was mentioned in 10 of the 15 textbooks surveyed, only four textbooks had explanations or even examples of the green chemistry principles (GCPs). McMurry, 9e[21] was the only book that defined all 12 principles (ref 21, p 348). Texts by Klein, 3e (ref 18, pp 496−497) and Vollhardt, 8e (ref 26, p 114) contained selected subsets of the green chemistry principles most relevant to organic chemistry. The textbook by Karty, 2e[24] did not contain any of the 12 principles specifically but did include a link to an external Web site where readers can learn more about them (ref 24, p 674).

Atom Economy. Atom economy (GCP 2) was one of the most popularly discussed principle in the textbooks we analyzed. Six of the 15 textbooks analyzed contained information on atom economy. To illustrate atom economy, authors used comparisons of reactions with different atom economies: acid-catalyzed hydration of alkenes and oxymercuration-demercuration (Klein, 3e, ref 18, p 496), epoxidation and hydrohalogenation reactions for alkenes (Karty, 2e, ref 24, p 676), elimination vs the Wittig reaction for synthesis of alkenes (Klein, 3e, ref 18, p 877) oxidation of alcohols to aldehydes with different reagents (Carey, 11e, ref 29, pp 654−655), and various epoxidation methods (Sorrell 2e[30]). McMurry, 9e[21] covered the BHC company synthesis of ibuprofen (ref 21, p 348), but without proper comparison to the Boots Company method,[33] it is hard for a novice reader to understand what makes this method green. It is worth noting that in a few examples, such as in Sorrell, 2e,[30] atom economy was brought up as its own topic in the absence of any mention or ties to green chemistry (ref 30, pp 512−513).

Greener Reagents. Greener reagents (GCP 3) was mentioned in several textbooks and accompanied by examples. Vollhardt, 8e[26] used acetylation with acetic anhydride as opposed to the corrosive acetyl chloride to illustrate the principle (ref 26, p 763). Karty, 2e[24] described Baeyer−Villiger oxidation without solvent using hydrogen peroxide catalyzed by Fe_3O_4 nanoparticles (ref 24, p 1068). The same author also

DOI: 10.1021/acs.jchemed.9b00397
J. Chem. Educ. 2020, 97, 383−389

Table 2. Distribution of Green Chemistry Topic Coverage in Widely Adopted Organic Chemistry Textbooks

First Author, Edition Number	Coverage[a] of Specific Green Chemistry (GC) Topics, by Textbook									
	Definition of GC	GC Principles	Atom Economy[b]	Greener Reagent[c]	Greener Solvent[d]	Renewable Feedstock[e]	Green Catalysis[f]	Biodegradable Materials[g]	Green Polymers	Recycling
Klein, 3e	E	E	E	E	E	E	E	—	—	O
Solomons, 11e	E	—	—	E	—	O	E	—	—	—
Brown, 8e	E	—	M	—	—	—	M	—	—	—
McMurry, 9e	E	E	E	M	E	M	E	O	—	—
Wade, 9e	—	—	—	—	—	—	—	O	—	O
Bruice, 8e	E	—	—	—	—	—	—	O	—	—
Karty, 2e	E	M[h]	E	E	E	—	E	E	E	—
Jones, 5e	E	—	—	—	—	—	—	E	—	E
Vollhardt, 8e	E	E	E	E	E	E	E	E	E	—
Loudon, 6e	—	—	—	—	—	—	—	—	—	—
J. Smith, 6e	E	—	—	E	M	E	E	O	E	O
Carey, 11e	—	—	E	—	E	—	E	—	—	—
Sorrell, 2e	—	—	O	—	—	—	—	—	—	—
Ouellette, 2e	—	—	—	—	—	—	—	—	—	—
M. Smith, 2e	—	—	—	—	—	—	—	—	—	—

[a]Notation: E, topic is explained, and example(s) provided; O, topic is included but without explicit connection to green chemistry; M, topic is mentioned but no example provided; —, topic not covered. [b]GC principle 2. [c]GC principle 3. [d]GC principle 5. [e]GC principle 7. [f]GC principle 9. [g]GC principle 10. [h]Online link to green chemistry principles was provided.

compared H_2CrO_4 vs $KMnO_4$ in terms of toxicity and environmental impact and $NaBH_4$ vs $LiAlH_4$ in terms of risks of explosion. The later example can be viewed as an intersection of several green chemistry principles: greener reagent (GCP 3), greener solvent (GCP 5), and accident prevention (GCP 12). Oxidation with Oxone (J. Smith, 6e; ref 28, p 467) and the Swern oxidation (Jones, 5e, ref 25, pp 810−811) were mentioned as greener alternatives to various Cr^{6+} oxidation reagents. J. Smith, 6e[28] described use of diphenylcarbonate as a greener alternative to phosgene (ref 28, p 497). Solomons, 12e[19] provided examples of alkene oxidations with hydrogen peroxide in the presence of various iron catalysts to illustrate green chemistry (ref 19, p 521).

Greener Solvents. Several textbooks proposed a link between green chemistry and solvents (GCP 5). These links fall under three different themes: water as a solvent; solventless reaction; or replacement of solvents with ionic liquids. Examples of aqueous reactions include allylation (Carey, 11e, ref 29, p 636), the addition of acetylenic nucleophile to benzaldehyde (Karty, 2e, ref 24, p 847), and Diels−Alder reaction (Vollhardt, 8e, ref 26, p 663). Karty, 2e[24] used the Baeyer−Villiger oxidation (ref 24, p 1068) and crossed aldol reaction (ref 24, p 914) as examples of solventless reactions. Ionic liquids were mentioned in Vollhardt, 8e (ref 26, problem 52 on p 263), McMurry, 9e (ref 21, textbox on pages 826−827), and Karty, 2e (ref 24, textbox on p 1176) as an alternative reaction media with unique properties. In most cases, the textbooks introduced the reader to greener solvents as a way of avoiding toxic solvents. We did not find any discussion of alternative green solvents such as 2-MeTHF or ethyl lactate.

Renewable Feedstocks. Generally, all chemistry textbooks include examples of organic compounds that can be found in nature. However, the examples of transformation of renewable feedstock to chemicals (GCP 7) are less common. Concrete examples include bioethanol (Vollhardt, 8e, ref 26, p 303) and biodiesel synthesis via transesterification (Vollhardt, 8e, ref 26, p 988) or via alkene metathesis (Klein, 3e, ref 18, pp 1092−1093).

Green Catalysis. Unsurprisingly, catalysis as a chemical phenomenon is mentioned in all surveyed textbooks. However, connections between green chemistry and catalysis (GCP 9) are less common. Several texts mention specific examples of catalysts (e.g., Ta on SiO_2 for metathesis of butane, Vollhardt, 8e, ref 26, p 114 or metal catalysts for ibuprofen synthesis, McMurry, 9e, ref 21, p 348). On the other hand, only few texts compare stochiometric vs catalytic processes, for example, oxymercuration−demercuration vs acid-catalyzed hydration (Klein, 3e, ref 18, p 496), syn-dihydroxylation with OsO_4 vs $K_2OsO_2(OH)_4$/NMO system (Solomons 12e, ref 19, p 370) or zeolite-Os/H_2O_2 (Karty 2e, ref 24, p 1219). Several texts mention use of biocatalysts, for example, for synthesis of adipic acid (J. Smith 6e, ref 28, pp 1279−1280) or enzymatic resolutions of racemic mixtures (Carey, 11e, ref 29, p 161).

Biodegradable Materials and Green Polymers. Design for degradation (GCP 10) was mostly mentioned in conjunction with polymers. Polylactic acid (PLA) was the most commonly discussed in the textbooks (Karty, 2e, ref 24, p 1354; Vollhardt, 8e, ref 26, p 949; McMurry, 9e, ref 21, pp 1052−1053; Bruice, 8e, ref 23, p 1207), followed by discussion of polyhydroxyalkanoates such as polyhydroxybutyrate (PHB) (McMurry, 9e, ref 21, pp 1052−1053; Klein, 3e, ref 18, p 1246; J. Smith, 6e, ref 28, p 1283) or poly-β-hydroxybutyrate-*co*-β-hydroxyvalerate (PHBV) (Vollhardt, 8e, ref 26, p 949; Bruice, 8e ref 23, p 1207; J. Smith, 6e, ref 28, p 1283). Jones, 5e[25] took an alternative approach and explained the concept of biodegradability using soaps and synthetic detergents (ref 25, pp 868−869). J. Smith, 6e[28] also provided examples of polyamides, such as thermal polyaspartate to illustrate the concept of biodegradability (ref 28, p 1283).

Recycling. Recycling was often mentioned as a stand-alone topic without explicit connection to green chemistry. While recycling is not one of the 12 principles of green chemistry, it is related to GCP 5 (safer solvents), GCP 7 (renewable feedstocks), and GCP 9 (catalysis). Recycling was also commonly mentioned in conjunction with polymers. The most often mentioned topics were polyethylene terephthalate (PET) recycling (Jones, 5e;[25] Klein, 3e;[18] Karty, 2e;[24] J. Smith,

DOI: 10.1021/acs.jchemed.9b00397
J. Chem. Educ. 2020, 97, 383−389

6e[28]) and recycling codes for plastics (Vollhardt,[26] 8e; Klein, 3e;[18] Wade, 9e;[22] J. Smith, 6e[28]). J. Smith, 6e[28] showed how caprolactam can be recovered from nylon (ref 28, p 1282) to illustrate recycling. Vollhardt, 8e[26] explained recycling within the context of converting cooking oils into biodiesel (ref 26, p 988).

Problems

Only three of the textbooks analyzed contained any problems pertaining to green chemistry. Karty, 2e[24] had the largest number of problems on green chemistry. The problems included percent yield and atom economy calculations, as well as two problems where the task was to identify a greener reaction from two alternatives presented (S_N2 reaction in ethanol vs DMF; mercury-catalyzed hydration of alkyne vs hydroboration−oxidation). Vollhardt, 8e[26] included two problems: one about the synthesis of ibuprofen and its atom economy (ref 26, p 773) and another problem on the properties and structures of ionic liquids (p. 263). Carey, 11e[29] included descriptive passage and interpretive problems (similar to the format used in the MCAT) on indium-mediated allylation reactions in water (ref 29, p 636).

Integration of GC Topics into the Narrative

While some authors integrated green chemistry concepts into the narrative of the textbook, the predominant way to introduce green chemistry material was in a textbox. Organic chemistry textbooks can be classified into three types with regard to treatment of green chemistry concepts. The first type treated green chemistry concepts as extraneous, optional material, the second type made an attempt to intertwine green chemistry concepts with the narrative but also had some green chemistry coverage in textboxes, and the third type integrated green chemistry in the narrative. The classification of textbooks that have more than four pages of green chemistry coverage is presented in Table 3.

Table 3. Characterization of Integration of Green Chemistry Concepts into the Textbook Narrative

	Textbooks[a]	
Integration Characterization	First Author	Edition
Primarily separate from narrative	McMurry	9
Mixed	Vollhardt	8
	Karty	2
	Carey	11
Primarily integrated in narrative	Jones	5
	J. Smith	6

[a]These are 6 of the 15 widely adopted textbooks that have greater than four pages of green chemistry coverage.

Karty, 2e[24] had the largest number of pages devoted to the topic of interest and provides many green chemistry applications in textboxes throughout the book. In a few cases, green chemistry information is integrated into the narrative and end-of-chapter questions. A notable difference in Karty, 2e[24] was inclusion of a section in the table of contents that deals with green chemistry. Another text with significant amount of green chemistry coverage, Vollhardt, 8e,[26] combined the textbox approach with interweaving concepts of green chemistry into the core narrative and linking them with central concepts (e.g., discussion of whether the S_N1 or S_N2 reaction is greener, ref 26, pp 280−281). J. Smith, 6e[28] and Jones, 5e[25] included explanations of green chemistry in the narrative and linked them to the core concepts by comparing greener reactions with less green alternatives.

■ DISCUSSION

While the majority of the textbooks had either mentions of green chemistry or included material that can be related to green chemistry, most of the textbooks still remain cursory when discussing green chemistry. Only 10 of the 15 textbooks analyzed contained any mention of green chemistry or its principles and only six textbooks contained four or more pages containing green chemistry. Furthermore, green chemistry content is often disjointed from the main narrative of textbooks. The utility of textboxes for instructional purposes is limited as both students and faculty reported ignoring boxed texts.[34] While some texts attempted to bridge green chemistry with the main narrative by comparison of two approaches, often the green chemistry content was presented as addressing a distinct principle of green chemistry without the integration of multiple principles and system thinking. In several cases, green chemistry concepts were mentioned, but no relevant examples were provided to illustrate the concepts. This is despite the availability of an account describing 12 green chemistry principles and relevant organic chemistry examples,[35] as well as 20 real-world cases, 16 of which are suitable for organic chemistry course.[36,37]

Most textbooks deliver the green chemistry content in a didactic manner that resembles a lecture-based approach, where all relevant information on a given topics is delivered to students by an instructor. However, meta-analytic evidence showed that active learning methods where class time is used to engage students in constructing understanding are more beneficial for students' learning than traditional lecture.[38] Implementation of active learning approaches often requires specialized instructional resources. Examination of three such texts for POGIL (Process-Oriented Guided-Inquiry Learning) by Ruder[39] and Straumanis[40] and PLTL (Peer-Led Team Learning) by Kampmeier and colleagues[41] reveals only cursory coverage of green chemistry concepts. The workbook for PLTL[41] includes a question on how two different industrial methods of phenol synthesis measure up to the standards of green chemistry (ref 41, p 200). The workbook by Ruder[39] includes two questions for which students could potentially produce answers linking green chemistry ideas with organic chemistry concepts. One question asks to compare different reactions for hydration of alkenes (ref 39, p 138), and the second asks students why S_N1 reactions are not suitable for the pharmaceutical industry (ref 39, p 108). Recent organic chemistry exams by the ACS Examination Institute, which are widely used for summative assessment at the end of organic chemistry courses, contain one item in which green chemistry is mentioned, but in almost all instances this item can be correctly solved without specific knowledge of green chemistry principles.

The absence of exercises and activities with green chemistry content in organic chemistry textbooks is a didactical shortcoming, as green chemistry can be a tool to provide the opportunities for students and instructors to engage in the active construction of knowledge.[42−44] The value of green chemistry is that it offers an extension of learning experiences from what is viewed as cognitive tasks in organic chemistry. Dee Fink[45] introduced the Taxonomy of Significant Learning with six categories of learning: foundational knowledge, application, integration, human dimension, caring, and learning

DOI: 10.1021/acs.jchemed.9b00397
J. Chem. Educ. 2020, 97, 383−389

how to learn. Learning becomes significant at the intersection of two or more categories. Traditionally, organic chemistry courses offer extensive opportunities for students to immerse in content (foundational knowledge, application, integration) and develop meta-cognitive skills (learning how to learn). Incorporating green chemistry in organic chemistry introduces additional aspects to learning in the form of human dimension (personal and social implications of what they learned) and caring dimension (develop new feelings and values). Thus, the infusion of green chemistry content could increase opportunities for significant learning and facilitates interconnections between concepts. Figure 1 represents Fink's Taxonomy of Significant Learning and alignment of its categories with organic chemistry and green chemistry. Connections to societal issues such as safer drinking water and more efficient synthesis of pharmaceuticals is also an opportunity to introduce students to the decision-making process in the context of sustainability which is essential for the development of leadership skills.

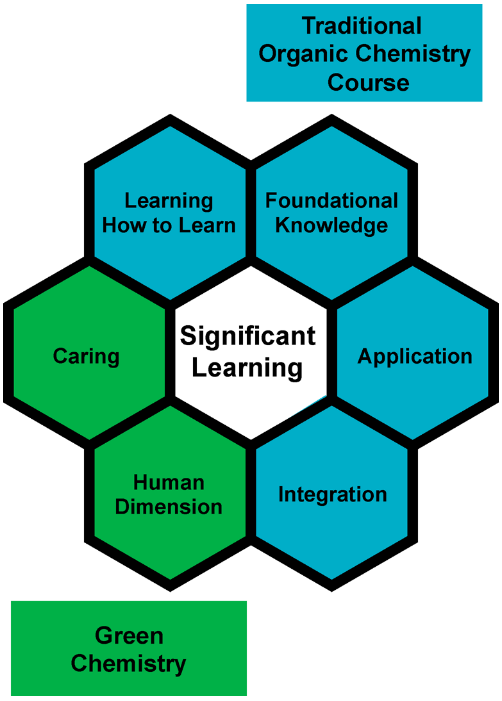

Figure 1. Fink's Taxonomy of Significant Learning aligned with learning in organic chemistry course.

There is an upward trend in coverage of green chemistry concepts from edition to edition. For example, the second edition[24] of Karty's textbook contains substantially more green chemistry content (17 pages) than the first edition[46] (1 page). Another example is a newly released 11th edition of a textbook by Carey[29] that includes coverage of various green chemistry principles (atom economy, greener solvents, and using catalysts), while the 10th edition[47] of this book did not include any mentions of green chemistry. While it is hard to rationalize the release of new editions every 3−4 years due to the lack of changing content, implementation of green chemistry could justify the need for an updated version. With the development of customizable texts and open educational resources, the process of including green chemistry into curriculum materials can be drastically simplified.

Professional societies and communities of practice can facilitate implementation of green chemistry into the curriculum. For example, the call for the implementation of green chemistry into the curriculum for ACS-certified programs was recently released by the ACS Committee on Professional Training in *Green Chemistry in the Curriculum*[48] supplement, intended to serve as a visionary guide for chemistry educators. The Green Chemistry Commitment[49] effort by Beyond Benign would be another testament to the trend for departments to add more green chemistry.

The coverage of green chemistry principles and topics was selective. While it can be understood why green chemistry principle 11 (real-time pollution prevention) is not thoroughly addressed in organic chemistry textbooks as it is more related to analytical than organic chemistry, there is no apparent reason why microwave conditions for running reactions (GCP 6) or reducing derivatization (GCP 8) were not discussed in any of the surveyed textbooks. Most of the green chemistry curriculum implementation happens in the organic chemistry laboratory (more than 100 laboratory experiments have been published in this *Journal* alone, and specialized organic green chemistry manuals[50,51] are available). However, it is important to cover green chemistry in organic chemistry textbooks that are used for lecture courses as laboratory and lecture are often taken together.

■ CONCLUSIONS

This paper provides a snapshot of organic textbooks in relation to their treatment of green chemistry concepts. We found that most textbooks have limited coverage of green chemistry ideas. Concepts that were mentioned the most were green chemistry principles, atom economy, catalysis, and safer reagents and solvents. Those texts that have green chemistry often present it as extraneous material with respect to the main narrative. There is, however, a slow movement toward integrating more green chemistry into newer editions of some textbooks. Additionally, the absence of assessment items and worked examples lends to a more lecture-based approach as opposed to a student-centered environment that involves active construction of knowledge facilitated by an instructor. As textbooks are a powerful medium for information transmission, coverage of green chemistry concepts in organic chemistry textbooks can be a controlling factor in the inclusion of green chemistry topics into the curriculum by instructors. While some instructors may bring green chemistry aspects and topics into their teaching or laboratory exercises as their own initiative, the state of this phenomenon is unknown and remains a topic for further exploration.

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Notes

The authors declare no competing financial interest.

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DOI: 10.1021/acs.jchemed.9b00397
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