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Citation patterns in chemistry dissertations at a mid-sized university: An internal citation analysis and external comparison

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Abstract

This study analyzes the references cited in 34 chemistry dissertations and compares the results with an earlier study of citations in American Chemical Society journals. The dissertations cite more references and older references and a greater diversity of sources. They have the same tendency to heavily cite journal articles from a small core of traditional journals. This study underscores the value of comparing internal citation analyses with external citation analyses, and of analyzing the number of citing authors as well as the number of citations. Interlibrary loan and internal usage statistics were also used to inform collection development and library instruction.

Introduction

The references cited by researchers in their publications (citations) reflect the subjects, sources and authors that they consider important and relevant. Garfield (1962) lists fifteen reasons for providing citations, led by "paying homage to pioneers" and "giving credit for related work" (30; see Cronin 1984; Bornmann and Daniel 2008 for further discussion). Smith (1981) describes the purposes and early development of citation studies, noting that by "studying the range of subjects, countries, languages, and document forms referred to by a group of known core sources, one can begin to establish the boundaries of a subject literature" (94).

Gross and Gross (1927) are credited as the first to use citation counts to evaluate the importance of scientific work. However, their goal in analyzing citations in articles published by the *Journal of the American Chemistry Society* was to identify the journals needed by the Pomona College library to "successfully to prepare the [chemistry] student for advanced work, taking into consideration also those materials necessary for the stimulation and intellectual development of the faculty" (386). Many subsequent researchers have used their strategy of examining citations in journal articles to evaluate library collections. Kelly (2015) refers to these as "external citation studies [that] represent the global pool of research", contrasting these with "internal citation studies" that examine "locally produced research" (p. 860). Internal studies based on citations in faculty publications and/or graduate student dissertations are popular with librarians because they reflect the specific needs of the institutions that academic libraries serve (e.g., Edwards 1999; Hoffman and Doucette 2012; Timms 2018). However, Kelly (2015) observed that libraries aiming for a "balanced collection that meets local need as well as external standards of excellence - cannot wholly rely on just one method of citation analysis" (878) and recommends both internal and external citation analyses. Studies that do so, however, are surprisingly rare.

In addition to informing collection development, comparing the citations in dissertations with those in leading journals in their discipline can inform the pedagogy and mentoring that contributes to students' expertise and professional development (Swart 2019). As part of their mandate to teach information literacy, academic librarians can provide guidance on good citation practices as well as effective searching, evaluation and selection of sources. Librarians thus have a dual interest in citation analyses, embracing both collection development and information literacy.

This study analyzes the references cited in 34 chemistry dissertations at a mid-sized academic university for the years 2008-2018 and compares the results with those from an earlier citation study based on articles sampled from ten journals published by the American Chemical Association ("ACS Study"; Rose-Wiles and Marzabadi, 2018). The major questions are how often different types of sources are cited (journal articles, books etc.); what is the age of citations; how diverse are the journals cited; what are the most frequently cited journals and books, and which are available in the library's collection. Further, do the results reveal differences between the citation patterns in graduate student dissertations (this study) and those found in published articles (ACS study), or internal journal usage statistics. The broad objectives are (1) to inform collection development by identifying the most frequently cited journals and books, and any not included in our library holdings; and (2) to understand the citation practices of our chemistry graduate students, particularly in comparison to published chemists.

Seton Hall University (SHU) is a private Catholic University located in South Orange, New Jersey. SHU is ranked as a "high research activity" institution among doctoral universities in the latest Carnegie Classification, and there is considerable emphasis on faculty and student research. SHU has an enrollment of close to 10,000 students, (FTE 8,232) comprised of 60 percent undergraduates and 40 percent graduate students. Chemistry originally fell under the Department of Physical Studies, which became a concentration during the 1936-37 academic year. With the building of a new science building in 1954, the facilities were upgraded to support advanced study in the natural sciences. The Department of Chemistry (now Chemistry and Biochemistry) has awarded doctoral degrees since 1965 and is the oldest graduate program at SHU. On average there are 16 masters and 46 doctoral students; enrolment has largely been stable over the past five years. The Department has 15 full-time faculty, most of whom advise graduate students and oversee research groups. Graduate students frequently co-author articles with their faculty advisors and present at national and local conferences.

Literature review

Many citation studies have examined references cited by faculty and/or graduate student dissertations or theses at academic institutions, variously termed "local citation studies", "user studies" or "internal citation analyses", to better understand user needs and inform collection development (Walcott 1994; Kelly 2015). This study uses the term "internal citation analysis" to contrast this with "external citation studies" of citations in published journal articles. Kushkowski, Parsons and Wiese (2003) list 26 internal citation studies published between 1981 and 2001. Hoffmann and Doucette (2012) cite 34 similar studies published between 2005 and 2010.

The number and diversity of internal citation studies has continued to increase becoming more international in scope and including a greater variety of subject areas (e.g. Das and Deka 2020 [library and information science]; Miller 2011; Barnett-Ellis and Tang 2016 [biology]; Smyth 2011; Fasae 2011 [agriculture]; Burrows et al. 2019 [social sciences and humanities]; Wirth and Mellinger 2011 [water resources]; Fransen 2012 [engineering and computer science]; Vallmitjana and Sabaté 2008; Kayongo and Helm 2012; Swart 2019; [multiple disciplines]; Zhang 2013; Gohain and Saikia 2014; Saikia and Saikia 2020; Flaxbart 2018 [chemistry]; Kaczor 2014 [atmospheric science]; Becker and Chiware 2015; [engineering]; Condic 2015 [reading and education leadership]; Kelly 2015 [engineering statistics and computer science]; Nagaraja and Prashanth 2015 [pharmaceutical sciences]; Rosenberg 2015 [anthropology and sociology]; Anyaegbu 2016 [law]; Ahmadieh, Nalbandian and Noubani 2016 [biology engineering and political science]; Griffin 2016 [educational leadership]; Graziano 2018 [LGBT studies]; Salami and Olatokun 2018 [science]; Timms 2018 [marine biology]; Xiang 2019 [East Asian studies]; Flynn 2020 [mathematics and statistics]).

Internal citation analyses typically include the number and source type of references cited, and many include the age of citations and/or a list of the most frequently cited journals. Most focus on trends over time and/or interdisciplinary differences within an institution. Kelly (2015) is one of the few authors to compare results from internal and external analysis. Differences in methodology and the statistics reported make it difficult to directly compare studies, but in general, authors in the humanities and social sciences cite more monographs and older publications, while those in the sciences cite more journal articles and recent publications. A common finding is that a small number of journals account for a large percentage of citations, often conforming to the 80/20 "Pareto Rule" that approximately 80 percent of the use of books and serials in libraries is accounted for by about 20 percent of the collection (Trueswell 1969; Nisonger 2008), although dissertations typically cite a wider diversity of journals than published articles. Vallmitjana and Sabaté (2008) observe that the number of references cited by dissertations has increased over time (see also Ortega 2008).

Wu, Wang and Chen (2012) observe that the proliferation of online journals and search tools help researchers to expand the scope of their searches and access lesser-known publications. However, inexperienced researchers (among whom one might include graduate students) may lack the expertise to critically evaluate sources and therefore cite "more references written by lower status authors, more references published in less prestigious journals, and older references" than do their more experienced counterparts (2191). Condic (2015) reports that graduate students in English and education leadership cite a greater diversity of sources and source types than faculty, cite journals with lower impact factors, and include more references with older publication dates. However, Condic attributes this to "the comprehensive nature of literature reviews found in dissertations" and the need for "more theoretical and background information" (555), rather than a lack of expertise, noting that deep indexing and easy linking from Google Scholar and library discovery tools makes it easy for researchers to locate and access older and more obscure publications.

Doctoral dissertations represent "the pinnacle of graduate students' research activity" (Timms 2018, 178), although Flaxbart (2018) suggest that "chemists in particular often regard the dissertation as a mere degree compliance requirement rather than a valuable scholarly work" (2).

Various studies report deficiencies in the citation practices of graduate students, including literature searches that prioritize convenience over rigor, questionable choice of sources, and practical errors such incorrect and/or incomplete citations (Beile, Boote and Killingsworth 2004; Clarke and Oppenheim, 2006; Azadeh and Vaez 2013, Ahmadieh, Nalbandian and Noubani 2016; Swart 2019). Sjøberg (2010) observes that graduate students in computer science are often reluctant to read older literature, and Zhang (2013) notes that chemistry student dissertations predominantly cite articles published within the last ten years. Johnson (2014) reports complaints from faculty that engineering students do not conduct robust literature reviews or select literature that would place their research in broader perspective.

Several authors call attention to issues with the search proficiency and references cited by chemistry graduate students (George and Munshi 2016; Gordon et al. 2018; Swart 2019). Failure to cite relevant publications is particularly troubling in chemistry, where current research frequently builds on earlier findings. In this regard, graduate students may be perpetuating patterns in the published literature. For example, the editors of the *Journal of Physical Chemistry Letters* observe that important and relevant references are sometimes absent from published papers and discuss the importance of selecting and citing scientific references correctly (Kamat and Schatz 2014). Augustine (2016) asserts that researchers in catalysis rely too much on the "readily available current literature" and need to recognize the importance of earlier work in understanding current results (2394).

The American Chemical Society (ACS) guidelines for bachelors' degree programs mention "managing citations and related information" (2015, 17-18) but do not specifically address literature reviews or citation practices, and there are no guidelines for dissertations other than those related to copyright and reuse of material. Hoffmann et al. (2016) point to a lack of attention to good citation practices in chemistry, noting that over time they have seen "less and less guidance for the budding scientific writer" (10967). Departmental guidelines, "writing up research" handbooks and journal instructions to authors may provide helpful information, but these typically focus on organization and format. Scientific writing courses, when offered, tend to be generic rather than discipline specific. The scientific literature in this regard seems sparse and limited to specific cases. For example, Dong (1996) addresses citation practices and advisor mentoring of non-native English speakers' science dissertations. In a broader context, Trevorrow and Martin's (2020) guidelines for writing a research article for *Magnetic Resonance in Chemistry* include a section on referencing that can be applied to science journal writing in general.

Ortega's (2008) review of citation studies conducted prior to 2007 includes nine that include chemistry and/or biochemistry. Despite variations in methodology and results, there is a clear tendency for chemists to predominantly cite journal articles and relatively recent publications (see also Flaxbart 2001, 2018). Two additional studies not included in Ortega's review (Edwards 1999 and Gooden 2001) provide details of source types cited (again journal articles dominate) and the most frequently cited journals, but not the age of citations. Ortega's own study of articles published by chemistry faculty and graduate students at the University of Oklahoma between 1975 and 2005 found that 77-90 percent of citations were journal articles, with a median age of references ranging from 5.0 to 7.5 years.

Among subsequent studies of chemistry citations, Vallmitjana and Sabaté (2008) analyzed citations from 46 chemistry and chemical engineering dissertations submitted to the Universitat Ramon Llull, Barcelona between 1995-2003, reporting a median reference age of nine years. The authors also examined the journals cited by subject area and publisher and the relationship between citations and journal impact factor. Zhang (2013) analyzed citations from 43 chemistry and engineering dissertations submitted between 2002 and 2011 at Mississippi State University, also focusing on the most-cited journals cited but not the age of cited references. Gohain and Saikia (2014) analyzed citations from 30 dissertations in the chemical sciences submitted to Tezpur University, Assam, India, between 2008 and 2012, and Saikia and Saikia (2020) analyzed citations from 34 chemistry dissertations from Dibrugarh University in Assam submitted between 2015 and 2019. The explicit objective of these studies was to inform collection development.

Collection development

Librarians have used citation analysis to inform collection development since the seminal paper by Gross and Gross (1927). As Timms (2018) notes, the "ideal core collection is unique to a specific local context" (179), reflecting the curricular and research foci of an institution's faculty and students (although see Kelly 2015, for a broader view). Internal citation analyses have primarily been used to evaluate journal subscriptions, especially in this age of diminishing library budgets and escalating subscription prices. However, a few have been used to evaluate book collections and use (e.g., Flaxbart 2018), especially regarding the dominance of commercial book publishers (Franks and Dotson 2017; Phillips 2018).

There has been much discussion of what Edwards (1999) terms "the merits and pitfalls of citation analysis as a collection development tool" (12), including flawed methodology and sources of bias (see Smith 1981 and Stankus and Rice 1982 for earlier discussions). Williams and Fletcher (2006) note that multiple citations to the same journal by a single author can skew journal rankings, especially in a small sample, and suggest counting both overall citations to a journal and the number of authors citing it to determine more accurate rankings. Miller (2011) and Zhang (2013) are among the few authors to follow this procedure. A further question for librarians is whether citation counts accurately reflect demand for a resource. The citations in dissertations reflect only what students cite in their research and not what additional resources they may have consulted (Miller 2011; Kelly 2015). Prior to the wide availability of online databases and discovery tools, Edwards (1999) noted that citation rates were not consistently correlated with print journal use as measured by shelving counts, emphasizing the need for both citation and usage statistics (including in-house use) to inform collection development. In addition, citation studies cannot capture what students may have decided not to use simply because the item was not available in their library (Miller 2011).

Beile, Boote and Killingsworth (2004) caution that references cited in dissertations may not be a reliable basis for collection development because students frequently cite "low quality" sources and tend to rely on items that are held by their library ("locally owned"; 352). Ahmadieh, Nalbandian and Noubani (2016) suggest that students "tend to choose and use easily available information sources over higher-quality sources" and "because convenience, speed and ease of access are a preference for students, citation analysis studies may not be the best tool to use for collection development decisions" (104). Clarke and Oppenheim (2006) report that over 75 percent of students surveyed claimed that a barrier to using interlibrary loan was that it was "more convenient to use articles that are readily available" (15), a finding echoed by Connaway, Dickey and Radford's (2011) aptly titled article "If it is too inconvenient I'm not going after it".

Despite the caveats regarding basing collection development decisions on citations by graduate students, such studies can be useful indicators of which resources students use and whether they are using a library's resources (Barnett-Ellis and Tang 2016). They can identify heavily cited items that are lacking in library collections or important to retain, especially when used in conjunction with traditional circulation, in-house use and ILL data (Smith 1981; Edwards 1999). Additionally, they can complement journal usage statistics to help identify titles that are rarely cited for potential cancellation. In conjunction with external analyses, internal citation analyses can also identify foundational monographs or important journals that students should be citing so that these can be drawn to the attention of graduate advisers and promoted by librarians.

Libraries and information literacy instruction

It is important that as fledgling professionals, graduate students learn how to search the relevant literature rigorously and effectively and to critically evaluate the sources they choose to cite for accuracy, relevance and credibility. The need to embed these information literacy skills in chemistry curricula has been widely discussed in the literature, although most authors focus on undergraduates (e.g., Lee and Wiggins 1998; Lawal 2001; Forest and Rayne 2009; Gawalt and Adams 2011; Tomaszewski 2011; Locknar et al. 2012; Mandernach, Shorish and Reisner 2014; Ferrer-Vinent et al. 2015; Jacobs, Dalal and Dawson 2015; Lovitt, Shuyler and Li 2016; Yeagley et al. 2016). Kromer (2015) is one of the few to specifically include citation practices and outcomes, noting a significant increase in scores on a required bibliography among students who attended a library instruction session.

Among studies focused on chemistry graduate students, Currano (2005) describes a required ten-week course on chemical information team-taught by science librarians. While the course focused on effective searching, it included a final assignment to compile a guide to the literature on a chosen topic that accurately cited the pertinent literature. Garritano (2008) reports that voluntary biweekly seminars on various aspects of chemical information literacy, including effective searching, were well-attended, perhaps in part due to the offer of free ice cream. Fong and Hansen (2012) describe their experience with a “mini-course” designed for a biochemistry research group as an alternative to traditional information literacy classes. Fong (2014) surveyed chemistry librarians in the US to determine what they are doing to teach research skills to chemistry graduate students. The response rate was low (25/99), but it was clear that there were significant gaps in teaching the aspects of information literacy most closely related to citation practices. Only six of 17 respondents taught “different types of sources”, seven taught “evaluation of sources” and “citation styles”, and only two taught “how to write a literature review” (7). Six librarians reported (or assumed) that “someone else” taught these skills, leaving around 40 percent of students likely to have received no formal training.

Methods

The current study is modeled on a larger analysis of references cited by articles published in ten ACS journals between 2011 and 2015 (Rose-Wiles and Marzabadi, 2018). However, while citations in ACS journals are available on Scopus and easily downloaded in Excel, dissertations are not indexed in Scopus. After many requests, ProQuest provided the references cited by 34 dissertations submitted by graduate students in the Department of Chemistry and Biochemistry between 2008 (the earliest data for which data could be provided) and 2018. The files, which were in xml format, were converted to Excel and matched with the ProQuest dissertation number by which each file was identified to a master list compiled from local records. The columns retained for analysis were the major subjects of the dissertation (organic chemistry, biochemistry, analytical chemistry and physical chemistry; the sole dissertation designated as “inorganic chemistry” was included in “organic chemistry” as this was the secondary subject), cited reference year, reference details, source type (journal article, book, book chapter, website, patent, standards, dissertation or “other”) and source title. Standards and patents were subsequently combined with “other” as these comprised <1 percent of citations. Columns for dissertation publication year, author, and age of each cited reference were added to each file.

Most of the files received from ProQuest included the references cited at the end of each chapter and (where it was included) a master list at the end of the dissertation. The references were numbered at the start of the "reference detail" column in a variety of formats (enclosed by parentheses or square brackets, followed by one or the other, with one or more spaces etc.), so it was necessary to manually de-duplicate the reference lists. Two dissertations published during the study period were excluded because the references were in the form of footnotes and could not be downloaded. Citations for two additional dissertations were compiled manually for a total of 34 dissertation reference files. Missing references were added manually after checking the files against the references cited in the original dissertations. Obvious errors were corrected, including missing journal information and/or publication year, citation years outside the publication run of a journal, and citations incorrectly categorized as books.

Once the data files were "cleaned" and again checked against the original dissertation reference lists, Excel's Pivot Table function was used to summarize the citations for each dissertation by reference year (excluding those with no date), source type, book title and journal title. Subsequent calculations included the number of references cited by each dissertation by year and major subject, the number and percentage of citations by source type, the number of unique journals cited (first converting journal titles to standard abbreviations as students had used a variety of non-standard abbreviations), and journal diversity (journals cited / journal articles cited). The median reference age for each dissertation was calculated following the protocol of Ortega (2008) and Rose-Wiles and Marzabadi (2018). The 34 individual files were then combined into one master spreadsheet and the Excel pivot table function used to summarize results by dissertation year, major subject, and for the overall dataset. The variables examined included the average number of references cited, the distribution of source types, median reference year for citations, the Price

Index (percent of references ≤ five years old), the percent of references ≤ 10, 10-19 and > 20 years old, and the number of years that encompassed 90 percent of references.

A list of journals and books cited was compiled from the combined citation file. Journals with multiple components (A, B, C etc.) were treated as separate publications except for *Journal of Physical Chemistry*, where many citations preceded the time when the journal was split or did not identify the relevant section. Journals with ≥ 25 citations and cited by ≥ 10 authors were listed by number and percent of citations, and columns for publisher and journal impact factor were added. The citations/citing authors and impact factors were ranked from highest to lowest, and Spearman's rho was used to determine correlations between citation and impact factor rankings for each list. The journals on the combined list were checked against our library holdings and their coverage dates (online and in print) noted to identify those with citations that fell outside the coverage dates (i.e., they were not "locally owned"). ILL borrowing requests for the relevant titles dating back to 2013 were supplied by our access services librarian (earlier years were not available due to a change in the ILL system) and checked against the citations to determine which articles had been requested. Usage statistics for the top journals based on the number of full-text downloads for 2019 and 2020 were provided by our electronic resources librarian and compared with the number of citations in the dissertations.

A list of unique books cited and the number of citations for each one was generated from the master spreadsheet, and a "publisher" column added. Different editions, reprints or individual volumes of a book were treated as one title. Publishers that had been merged with or acquired by others were assigned to the parent company wherever possible. Very few books had multiple citations by a single author, so only the total number of citations was used for analysis. Each title was checked against the library catalog, noting if the book was held in the collection and if so whether it was available in print and/or as an eBook.

Results

The 34 dissertations cited a total of 4,637 references (Table 1). The average number of citations was 136 (range 87-211; SD 39.7). Based on 4,530 references (excluding 107 citations, mostly websites, with no publication year), the median reference age was 11.8 years (range 2.4 – 27.5 years). Books had a slightly older median citation age than journal articles (13.2 years). The Price index (citations $\leq$ 5 years old) was 22 percent, 43 percent of citations were $\leq$ 10 years old, 29 percent were 10-20 years old, and 28 percent were > 20 years old. Overall, 90 percent of all references cited were published within the previous 39 years. There is no clear temporal pattern in the percentage of journal citations or the diversity of journals. Examining citations by dissertation year shows no consistent change in the number of median age of references (Table 1).

Examining citations by sub-discipline reveals more differences, with the caveat that the distribution was skewed toward analytical chemistry (15/34) with only three dissertations in physical chemistry (Table 2). On average, organic chemistry and biochemistry cited more references than analytical or physical chemistry. The median reference ages ranged from 8.6 years for biochemistry to 13.4 years for organic chemistry. Biochemistry dissertations cited the highest percentage of journals (94 percent) while physical chemistry had the highest journal diversity (0.64).

Journal articles accounted for 87 percent of all citations. Only 7.9 percent of citations were books or book chapters (Table 3). Websites and "other" sources each comprised 2.2 percent of citations. Conference papers and dissertations together comprised <1 percent. Physical chemistry cited the most books and biochemistry the least, while analytical chemistry cited the most websites and "other" sources.

***Journals cited*.**

Overall, 951 unique journals were cited at least once. Of these, 46 (5 percent) accounted for 50 percent of journal citations, the top eight titles accounted for 25 percent of citations, and 274 (29 percent) accounted for 80 percent. Journal diversity was 0.24. There were 24 journals with ≥25 citations (Table 4), accounting for 1,621 citations (40.3 percent of the 4,021 total journal citations). There were no significant correlations between journal citation rank and impact factor rank (Spearman's rho = 0.012, two tailed). There were 23 journals cited by ≥10 authors (Table 5), accounting for 1,464 citations (36 percent of journal citations). There was a significant correlation between journal rankings by the number of citing authors and journal impact fact ranks (rho = 0.491, p = 0.017, two-tailed). In both analyses the top journals were dominated by two publishers, ACS and Elsevier. The citations analysis showed that 11 of the top 24 journals, accounting for 18 percent of all journal citations, were published by ACS. Six journals, accounting for 13 percent of citations, were published by Elsevier. The analysis by number of citing authors showed seven of the 23 top journals were published by ACS, accounting for 14 percent of the citations, and four titles were published by Elsevier, accounting for 13 percent of the citations.

Books cited.

There were 366 citations to 270 books, for an average of 1.4 citations per book (range 1-10). Most (82 percent) were cited only once, and only ten books were cited more than three times. Over a third (35 percent) of the books cited were published ≤ 10 years prior to the dissertation, while 33 percent were published >20 years previously. Fifty of the books cited, accounting for 20 percent of the book citations, were clearly textbooks. Overall, the books cited spanned 69 publishers, some now defunct, but 58 percent of these accounted for only one book citation. Four publishers accounted for 53 percent of all books cited: Wiley (26 percent), Elsevier/Academic Press (11 percent), Taylor and Francis / CRC Press / Marcel Dekker (9 percent) and Springer (7 percent). Oxford University Press and Cambridge University Press followed with 3 percent each. The only other publishers receiving > two percent of citations were Prentice Hall (seven citations), Plenum (six), Freeman (five) and Cengage (four). There were four citations (1 percent) to books published by the American Chemical Society and one to a book published by the Royal Society of Chemistry. Overall, books published by major (mostly commercial) publishers accounted for 79 percent of citations and university presses accounted for seven percent.

Dissertation citations compared with citations in ACS journal articles.

On average, the dissertations cited more references than the articles in the ACS sample (136 versus 89) and a larger proportion of older sources (Table 6). The median reference age was 11.8 years compared with 6 years in the ACS sample, and the Price Index was 22 percent vs. 44 percent. Organic chemistry had the oldest median reference age in both samples. Journal articles comprised 87 percent of dissertation citations and 94 percent in the ACS sample. The dissertations cited more books than the ACS sample (7.9 percent vs. 2.4 percent). Conference papers comprised only 0.3 percent of dissertation citations, compared with 2.5 percent in the ACS sample. The dissertations cited almost twice as many websites and "other sources", including other dissertations (4.9 percent vs. 2.5 percent)

The dissertations cited a greater number and diversity of journals (0.24 compared with 0.05 in the ACS sample) and 46 journals accounted for 50 percent of references versus 24 in the ACS sample (Table 6). However, more than half (56 percent) of the journals cited by the dissertations were only cited once, and only 7 percent were cited > 10 times. Two thirds (16) of the 24 top journals ranked by number of citations were also among the top 24 titles in the ACS study (Table 4). There was a significant correlation between the ACS citation ranks and those in the dissertation sample (rho = 0.540, d.f. 23, p = 0.006). More than half (13) of the top 23 journals ranked by the number of citing authors were among the 23 top ranked journals in the ACS study (Table 5), and there was a significant correlation between the ACS author citation ranks and those of the dissertation sample (rho = 0.701, p < 0.001, two-tailed). The top cited journals in both the dissertations and ACS sample were dominated by a few publishers, ACS and Elsevier in the former and ACS and Wiley in the latter.

Citations to books were not analyzed in the original ACS study, but this study analyzed the books cited in the sample of 60 articles published in the *Journal of the American Chemical Society* (JACS) for comparison. The median reference age for books in the dissertation sample was older than the JACS sample (13.2 years versus 10.2 years). Only 25 percent of books cited in the JACS sample were ≥20 years old compared with 33 percent of those cited in dissertations. The JACS articles cited 22 book publishers, 55 percent of which had only one citation. The book citations were also dominated by a handful of commercial publishers, although Springer featured more prominently than Elsevier compared with the dissertations (Figure 1). Commercial publishers accounted for 81 percent of citations, close to the 79 percent in the dissertations. University presses accounted for 9 percent of citations, again like the 7 percent for the dissertations. There were three citations to books published by the Royal Society of Chemistry and no citations to books published by ACS.

Library Holdings: Journals

Combining the 24 journals with ≥25 citations from Table 4 and those with ≥10 authors from Table 5 resulted in a total of 30 "top" journals and 1,711 citations. The library has current online subscriptions to 25 (83 percent), and one (PNAS) is available open access through PubMed with a six-month embargo. Overall, 80.3 percent of journal articles cited corresponded with years that the journals were available online through library subscriptions or purchased back-files. An additional 14.6 percent corresponded with print holdings, for a total availability of 95 percent. By comparison, the library had online subscriptions to about two-thirds (68 percent) of the top 30 journals cited in the ACS study.

The analysis by number of citations identified two journals among the top 24 with no current subscriptions, although both have substantial holdings of earlier volumes in print. *Science* and *Chemical Society Reviews* rank #20 and 23 respectively, compared with #7 and #24 in the ACS study. The number of citing authors analysis identified two additional titles, *Bulletin of the Chemical Society of Japan* and *Organic* and *Biomolecular Chemistry* (shared rank #19*)* to which the library does not currently subscribe or, in the former case, have any access at all. These ranked #39 and #508 respectively in the ACS study. There were two journals, *Carbohydrate Research* and *Chromatographia*, with citations outside the date range of our library holdings. However, none of the citations were recent, the latest being 2004 and 2011, respectively.

Interlibrary loan borrowing requests between 2013 and 2018 were examined for the six journals that had more than five citations outside the range of the library's print holdings or online subscriptions. Five of the journals had multiple requests (range 7-25), but only one request (from *Chemical Society Reviews*) corresponded with a cited reference. Six of the ILL requests were for articles included in library subscriptions, three online and three in print. Only one journal, *Organic and Biomolecular Chemistry*, had more than two requests for current articles.

Institutional usage statistics for the years 2019 and 2020 were available for 20 of the top 25 journals based on the number of citations in the dissertations. *Nature* and *Proceedings of the National Academy of Sciences* were excluded as both are interdisciplinary and had extremely high use, leaving a sample size of 18. Comparing the number of citations in the dissertations with the number of full text downloads showed a positive correlation for 2019 ($r = 0.517$ d.f. = 16, $p \leq 0.05$) and 2020 ($r = 0.614$, $p \leq 0.01$). Calculating the ratio of citations to institutional usage across both years indicates that two journals, *Journal of Chromatography A* and *Carbohydrate Research*, were heavily cited in relation to their overall use (Table 7). *Chemical Society Reviews* also showed a relatively high ratio of citations to usage, but this is unsurprising as the library has no current online subscription and the print subscription ended in 2009.

Library holdings: books

Overall, 108 (40 percent) of the 270 books cited are currently held by the library and four are freely available online, together accounting for 50 percent of the total book citations. More than half (57 percent) of the books held by the library are currently available as eBooks, accounting for 56 percent of citations. The library's eBook collections have expanded significantly in the past few years, so some books may not have been available as eBooks at the time a dissertation was researched or written. Conversely some that were available as eBooks at the relevant time may have later been withdrawn, as publishers or vendors tend to remove frequently accessed books from subscribed eBook collections. A similar proportion (43 percent) of books cited in the JACS sample were held by the library, with 58 percent available in eBook format.

Comparison with earlier chemistry dissertation citation studies

None of the six studies of chemistry dissertation citations added to those included by Ortega (2008) provide all the data obtained for this study, but some comparisons are given in Table 8. The average number of citations (n=136) falls within the range of four previous studies but is far less than those for the two studies from universities in India (Gohain and Saikia 2014 and Saikia and Saikia 2020). However, these cited fewer journals and had considerably lower journal diversity. The predominance of citations to journal articles is consistent across studies. Book citations (7.9 percent) are within the range of previous studies, although on the low end. Conference papers are rarely cited in the four studies that report them, but the 0.03 percent found in this study is below their 2 percent average. Based on the rather disparate values provided, the number and diversity of journals cited in this study tends to be higher, and the age of reference cited somewhat older.

Discussion

The results of this study are consistent with previous finding that doctoral students in chemistry predominantly cite journal articles in their dissertations. This is a well-established pattern for both dissertations and published articles in chemistry and other sciences. Our doctoral students cite a greater diversity of sources and a larger proportion of older sources than chemists cite in their published articles, which is also consistent with earlier studies. They cite more books, fewer conference papers and more websites and other sources than published chemists. The comparison between chemistry dissertations and articles published in ACS journals during a similar period confirms these trends. It is unclear whether the sparse citations to conference proceedings, even compared with other internal dissertation analyses, reflects unawareness of or failure to search the relevant literature, lack of funding to attend conferences, or a preference for citing the peer-reviewed articles that frequently follow conference papers. An open question is whether students citing older and less prestigious sources reflects a lack of the expertise needed to critically evaluate sources or the tradition of deep literature reviews and historical relevance in dissertations. However, examining the websites and "other" sources cited by our chemistry graduate students may shed some light on this question.

Some of the sources that ProQuest classified as "websites" were articles published in institutional repositories, company websites or scholarly blogs, although it is unlikely these were peer-reviewed so they were not reclassified as journal articles. Most of the remaining websites were manufacturer or vendor pages that included product descriptions or guidelines. There was a scattering of research lab or university-based tutorials, government websites and other open data sources. There was only one citation to Wikipedia, and it was a comprehensive and well-referenced entry. The "other" citations were predominantly technical manuals or trade publications, patents or standards, and some sources that could not be traced. A perusal of the dissertations indicates that websites and "other" sources were most often used in the Methods sections. Dotson and Franks (2015) attribute the increasing popularity of web pages in engineering, computer science, mathematics and physics dissertations to improvements in technology and the ready availability of scholarly works on professional association websites, and this rather than poor research habits is likely the case for chemistry as well. However, a potentially troubling observation from this study is the number of textbooks (often older publications or editions) among the books that graduate students cited. It is unclear if students are citing their old undergraduate textbooks rather than locating original articles as a matter of convenience or laziness, or if these texts contain something original or significant.

Despite the considerable diversity of journals cited, many were only cited a few times, and more than half were cited only once. Overall, 29 percent of journals accounted for 80 percent of citations. This is higher (more diverse) than the "80/20" rule (Trueswell, 1969; Nisonger 2008), but still indicates a strong tendency to cite a relatively small core of journals. ACS journals figure prominently among the top-cited journals, which is unsurprising given their specialized focus on chemistry. A similar trend was noted in previous studies of chemistry dissertations and the ACS study, supporting the conclusion that chemists are rather conservative in the sources they cite. There was a strong correspondence between the journals most frequently cited by our doctoral students and the ACS study, although the *Journal of Chromatography B* was a clear outlier, ranked first among total citations versus 75th in the ACS sample, along with *Chromatographia* (20 versus 630). This likely reflects the prevalence of chromatographic methods in graduate work, as this is a major focus in the department. *Journal of Chromatography* was cited by all 15 of the analytical chemistry dissertations and the three listed as physical chemistry, but 63 percent of the citations were from five dissertations with the same advisor who specializes in high performance liquid chromatography. The inclusion of the *Bulletin of the Chemical Society of Japan* among the top journals cited in the dissertations is surprising as the library has no subscription or print holdings. Despite having a much lower impact factor, it was cited by ten dissertations compared with 16 for *Chemical Communications* and 14 for *Organic Letters*, the journals most likely to have similar subject coverage. The relative popularity of this journal warrants further investigation.

Although there was a high level of correspondence between the journals most often cited by our graduate students and the articles in the ACS study, 83 percent of the citations were to journals with current online library subscriptions compared with 68 percent in the ACS study. The latter did not examine library holdings in print (none of which are current), and neither study allowed for articles published as open access in hybrid journals, but this is still quite a significant difference. It is unclear whether this means that the library holdings are adequate for the needs of our graduate students, who do not study every sub-field of chemistry, or that the convenience of local holdings is at least partially determining the sources that they cite. Discussing a similarly high level of citations to locally owned books, Flaxbart (2018) calls this "a classic chicken-or-egg" question: do students use what the library owns, or does the library hold what the students need" (9). The relatively low ranking of *Science* among the journals cited by the dissertations (#20 versus #7 in the ACS study) hints at the former, but further investigation is clearly needed. Studies of interlibrary loan requests may help address this question.

Interlibrary loan requests for the six frequently cited journals with no corresponding library holdings for the relevant dates indicates that our doctoral students are not using interlibrary loan to obtain the full text of articles. Advances in ILL services, especially "unmediated" (automated) consortial systems, make it fast and easy to obtain articles that are not held locally (Lee and Weldon 2019), and article turnaround is typically less than 24 hours. However, users may still prefer articles that are immediately available, and/or may be obtaining articles through open web sources, social media networks or friends at other institutions. Wirth and Mellinger (2011) note that 20 percent of the citations in water resources dissertations had corresponding ILL requests, so this may be a recent development. Barton, Relyea and Knowlton (2018) report a very low correlation between ILL requests and journal usage statistics in engineering and technology and suggest that ILL requests are primarily driven by database search results rather than journal preference. However, their study did not specifically examine ILL requests by graduate students, whose search strategies are probably more focused and intentional than those of undergraduates. Flaxbart (2001) found that senior chemistry faculty tend to rely on scanning specific journal table of contents (likely a holdover from the time of print journals) rather than database searches, and the high citation rates for specific journals in both the dissertation and ACS studies suggests that journal preference is a significant factor for chemists.

The number of citations was not significantly correlated with journal impact factor, but there was a significant correlation between journal impact factors and the number of citing authors. This supports Williams and Fletcher’s (2006) caution that multiple citations to the same journal by a single author can skew results, and that examining the number of authors who cite a journal gives a more accurate picture of its relative importance. However, Vallmitjana and Sabaté (2008) found a modest positive correlation between journal rank based on the number of citations and journal impact factor, noting that “this possible association must be studied more in-depth” (75). This study does not directly address the question, but it seems likely that graduate students follow the tendency of published chemists (including their advisors and mentors) to cite traditional, well-established journals that tend to have high impact factors, although *Bulletin of the Chemical Society of Japan* is an exception. In addition, libraries may keep subscriptions to high impact journals, while more obscure or specialized journals that have lower use are more likely to be cut due to declining budgets and increasing subscription prices. If local ownership is indeed a significant factor in journal use, this would tend to reinforce the association between impact factor and usage in an ongoing feedback loop.

Although books are cited far less often than journal articles, citation to books show some interesting patterns. The median age of citations is slightly greater than the median age for journal citations (13.2 vs. 11.8 years) and a third of the citations were to books > 20 years old. Zhang (2013) reported a similar pattern, where 28.5 percent of the books cited were > 20 years old. By comparison, the median age of book citations in the JACS sample was 10.2 years and 25 percent were > 20 years old, affording further evidence that chemistry graduate students cite a higher proportion of older references than published chemists. However, only two of the oldest 100 citations in the dissertation sample were books - three were technical bulletins and the remainder were journal articles. It therefore seems that graduate students are not selectively citing older books, but rather are citing more recent or current journal articles and (to a lesser extent) citing older, foundational or classic journal articles. This in turn suggests a quite robust search and citation strategy, although again the number of textbooks cited is potentially troubling.

In a study of book citations in chemistry dissertations at the University of Texas at Austin, Flaxbart (2018) reported that only 5.4 percent of the total citations were to books, compared with almost eight percent in this study (Table 3). The median reference age was 11 years compared with 13.2 years in this study. He reported that books < 10 years old predominated, which was not the case in this study, and that the number of citations to books decreased over time. There was no evidence of this in the current study, but Flaxbart's study covered a longer period (1988 to 2015) and referenced earlier studies that supported his conclusion. However, a notable contrast in this study is that our chemistry graduate students have clearly embraced eBooks, which account for more than half of all book citations. This likely reflects their convenient and instant availability online. Citations to books and book chapters were combined for the analyses in this study (partly because ProQuest did not differentiate these consistently), but internal statistics suggest that the most frequent use of eBooks is in the form of chapter downloads. The growing trend for major publishers to index books at the chapter level likely contributes to the discovery and citation of eBook chapters. This raises the question of whether libraries are disadvantaging discovery and use of books that are not available in eBook format, especially those from small non-profit publishers.

The results of this study and the books cited in JACS articles clearly show the dominance of a few commercial book publishers, which accounted for 79 percent and 81 percent of citations, respectively. A similar pattern is reported for books cited in other science dissertations, (Franks and Dotson 2017; Phillips 2018). Franks and Dotson noted that five publishers accounted for "nearly half or more of all books cited" (69) and that about 70 percent of books cited were from commercial publishers. Phillips' (2018) study of book citations in seven science-based dissertations at CUNY excluded book chapters but found a similar pattern, with 60 percent of the citations attributed to commercial publishers. Chemistry dissertations had the highest proportion at almost 84 percent, with the top five publishers accounting for almost 63 percent of citations. Their ranking and citation percentages parallel those for our dissertations (Figure 1), except that the rankings of Springer and Taylor and Francis are reversed.

The dominance of commercial publishers is concerning for academic libraries for several reasons. First, university presses arose in response to the lack of a commercial market for scholarly, highly specialized research (Phillips 2018), and if they cannot survive competition with profit-driven publishers this will have a negative effect on the dissemination of such scholarship. Second, if libraries focus their book purchasing budget on large commercial publishers, as Franks and Dotson (2017) suggest, they may be "overlooking small or specialty publishers that may viewed as more valuable by individual disciplines" (75). This may a particular concern for chemistry, given the high percentage of book citations to commercial publishers noted in this study, the JACS articles and by Phillips (2018). Third, Phillips asserts that commercial publishers are "price markers" in the scholarly book market, and "can and do charge more per book than university presses" (289). A comprehensive analysis of STM book prices confirmed that books published by commercial publishers are on average 61 percent more expensive than those from non-commercial publishers, including society and university presses (Liu, Gee and Terng, 2018). Chemistry books were among the most expensive, and eBooks were almost double the price of print books. The authors also note that commercial publishers account for 91% of all STM publishers, and that the same four publishers that accounted for more than half of the citations in this study produced 66.7 percent of STM books published by commercial publishers in 2016. Subsequent mergers and acquisitions have intensified their consolidation, reducing market competition and driving up overall prices. Although books represent a small percentage of many academic library acquisitions budgets, the high market share of commercial publishers combined with the erosion of purchasing power through budget cuts and price increases, especially regarding eBooks, pose barriers to maintaining diverse and well-balanced library collections.

Study outcomes and recommendations for collection development

This study supports the use of multiple measures to inform collection development, including internal analyses and comparison with external analyses (Kelly 2015), the number of citations and citing authors (Williams and Fletcher 2006), and internal usage and interlibrary loan statistics (Smith 1981; Edwards 1999). The internal citation analysis, the focus of this study, identified four frequently cited journals that are not available in the library, two of which were identified only when the number of citing authors rather than simply the number of citations were examined. Comparing the citations in the dissertations with journal usage statistics identified two subscribed journals with disproportionately high citation rates (*Carbohydrate Research* and *Journal of Chromatography A),* suggesting that these are particularly important for our doctoral students and should be kept even if overall usage appears low. Conversely, both the internal and external citation analyses confirmed that several low use journals that are marked for cancellation are rarely cited by either our graduate students or published chemists.

The quite robust citation rates for older articles and books in the ACS study and especially the dissertation analysis show a need for care in deaccessioning older materials, including print journals that are not available electronically. It also suggests there may be value in obtaining access to journal back-files or purchasing archival eBook collections where budgets permit. The ACS heritage archive has been heavily used since the library obtained it in 2015, but again this raises the question of whether convenience drives usage and citation. The finding that 15 percent of all journal citations are to print only holdings is quite significant, although without in-house use statistics (print journals do not circulate in our library) it is unknown how often students actually consult print journals. Our interlibrary loan department quite frequently receives and fulfills requests for articles that are available in the print collection, but < 3 percent (3/85) of the ILL requests examined in this study were for articles available in print. This raises the question of how students are obtaining articles and books that are not locally available, especially eBooks, which generally cannot be obtained through ILL. Anecdotally, many use social media or email networks, an issue if ILL requests are used to inform collection development and probably a copyright issue as well. However, if students are simply reusing existing citations or citing abstracts, SciFinder summaries or book reviews, this becomes a pedagogical and information literacy issue.

Implications for library instruction

The rate of citation errors noted in this study was low, but only the obvious issues were captured. These were primarily the use of non-standard abbreviations and inconsistent, incomplete or inaccurate citations, including the use of defunct URLs for websites. There is clearly a need more emphasis and instruction on correct citation practices, standard departmental guidelines on citation format, and greater awareness that librarians can offer help with literature reviews and citation practice. Some simple suggestions in this regard include better publicizing the library's chemistry research guide for graduate students, especially the journal abbreviations list, the library's literature review and citations guides, and the availability of individual or small-group research appointments with their subject librarian. We have also sponsored several presentations by a leading journal editor to give students (and faculty) insights into the best practices and pitfalls involved in submitting articles and responding to reviewers.

Low rates of citations to books and conference papers suggest that these may not receive sufficient attention in library instruction sessions or outreach. Flaxbart's (2018) discussion of barriers to citing books and ways to overcome them is useful since it covers discovery, access and utility as well as a disciplinary convention to rely mostly on journal articles. A key takeaway is his suggestion for librarians to "build awareness of the usefulness and purpose of books in information literacy curricula and outreach efforts aimed at graduate students (p. 9). Librarians should also emphasize the availability and efficiency of interlibrary loan services, which are clearly being under-used by our chemistry students and likely others as well. This should include the practical and ethical issues of citing abstracts or secondary sources without obtaining the full text of materials as well as emphasizing that using ILL rather than personal networks can help inform and potentially improve library collections and avoid potential copyright violations.

As Flaxbart (2001) notes, chemists tend to be self-reliant and quite competent in their information seeking behavior and this pattern likely extends to their mentored graduate students. Many of our graduate students do not directly contact a librarian until they submit their dissertation online and encounter problems. The most common issue is the absence of permission to re-use published figures, which is referred to the copyright librarian, who is also the liaison librarian for chemistry. She has found that presenting a library session during the mandatory weekly chemistry seminar, attending chemistry events and generally being visible and approachable for discussion helps to avoid later copyright issues, and citation practices and promotion of interlibrary loan services might usefully be added as talking points.

A survey conducted at the University of Bradford (UK) found that library and information skills (which included citing sources) consistently come last when students were asked to rank them against other skills such as employability, laboratory skills or subject knowledge, and that graduate students who need instruction the most tended to engage the least in attending lectures from chemistry subject librarians (George and Munshi 2016). The same issue is apparent at our institution. Librarians offer workshops for graduate students, but most have been poorly attended. Perhaps the library liaison can work more closely with chemistry faculty to help promote workshops on literature reviews and citation practices and consider offering food or ice cream (an "ice cream social" offered with a SciFinder session was very popular). We should emphasize that this is not merely a library issue but one of professionalism, and that poor literature reviews and sloppy citation practices can lead to article rejection and poor reputation.

Conclusions

The broad objectives of this study were to inform collection development and to understand the citation practices of our chemistry graduate students, particularly in comparison to published chemistry researchers. The results confirmed previous findings that both doctoral students and published chemists predominantly cite journal articles and rely heavily on a relatively small core of journals. Many of the most-cited journals are from a few major publishers and tend to have high impact factors. Books are cited far less often, but doctoral students cite books more often than published researchers. In both cases, a few commercial publishers dominate, which is a concern if this tendency is reflected in collection development and inflates prices. Although recent articles are most often cited, older articles and books are well-represented, suggesting that caution is needed in deaccessioning older material and that archival collections (especially journals and eBooks) may have considerable value for chemistry researchers. The analyses identified four well-cited journals that are lacking in the library collection, and two that were cited far more often than their overall usage statistics would predict. The analyses also confirmed that several rarely used journals under consideration for cancellation were rarely cited.

This study also confirms previous findings that doctoral students cite a greater diversity of sources than published chemists, including older sources, books, and websites. They do not appear to be relying on open web sources rather than subject databases, but rather using the internet to locate and cite technical information that is openly available. In contrast to earlier studies, our doctoral students appear to have embraced eBooks, which likely reflects their convenient and immediate availability. Convenience may also be a factor influencing students' choice of sources as most journals and many of the books cited are available in the library collection. Interlibrary loan requests for articles not held by the library were rare, leaving open the question of how (or if) students are obtaining the full text. The frequent citation of textbooks is another issue that warrants further exploration. Despite the latter concerns, the study suggests that our graduate students practice a quite robust search and citation strategy. However, more instruction and guidelines regarding correct and consistent citations is clearly needed, as well as promotion of interlibrary loan and library-based research assistance.

This study underscores the value of using both internal citation analyses and comparisons with external analyses to inform collection development and compare the citation practices of graduate students with published chemists. It also demonstrates the value of examining the number of citing authors as well as the overall number of citations, as well as interlibrary loan and internal usage statistics. However, the tantalizing question posed by Flaxbart (2018) remains: does the library generally hold what students need, or do students tend to use what the library owns?

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Table 1: References cited by 34 dissertations by age, source type and journal diversity (n = 4,637)						
Publication Year	No. of Dissertations	Average References cited	Median age of references	% citations to journals	% citations to books	journal diversity
2008	1	151	11.9	93%	5%	0.56
2009	2	87	14.8	76%	18%	0.43
2010	3	144	9.5	91%	9%	0.46
2011	3	95	9.0	89%	9%	0.62
2012	3	98	9.5	74%	20%	0.47
2015	4	212	14.0	87%	8%	0.38
2016	3	184	10.0	94%	3%	0.58
2017	8	117	11.1	83%	10%	0.61
2018	7	139	13.4	88%	8%	0.56
Total	34	4,637			410	
Average		136	11.8	87%	9%	0.53
journal diversity = #unique journals cited/#journal articles cited						

Table 2: Citation data by chemistry sub-discipline							
Major subject	dissertations	% of total	Average citations	Median age	Average # journals cited	Average % journals	Average journal diversity
Analytical chemistry	15	44%	115	13.3	36.7	79%	0.46
Biochemistry	8	24%	153	8.6	82.0	94%	0.58
Organic chemistry	8	24%	170	13.4	84.1	90%	0.58
Physical chemistry	3	9%	111	10.6	53.3	85%	0.64
Total/average	34	1	136	11.8	60.0	87%	0.53

Table 3: Average percentage of references cited by source type and sub-discipline.					
Source type	all subjects (n = 4637)	Analytical (n=1722)	Biochemistry (n=1226)	Organic (n=1357)	Physical (n=332)
Journal articles	86.8%	79.1%	94.4%	90.1%	84.9%
Books/book chapters	7.9%	10.9%	3.9%	7.2%	13.9%
Conference papers	0.3%	0.6%	0.0%	0.1%	0.0%
Dissertation/thesis	0.5%	0.6%	0.4%	0.5%	0.6%
Websites	2.2%	4.6%	0.5%	1.0%	0.0%
Other	2.2%	4.1%	0.7%	1.2%	0.6%

Table 4: Journals with >25 citations in the dissertation sample ranked by number of citations, compared with ACS sample.

Title	cited refs	% refs	authors citing	average citations per author	Cited rank	ACS study Rank	Impact Factor	Impact rank	Publisher
Journal of Chromatography A	335	8.3%	18	18.6	1.0	75	4.05	16	Elsevier
Journal of the American Chemical Society	235	5.8%	24	9.8	2.0	1	14.60	5	ACS
Angewandte Chemie	75	1.9%	15	5.0	3.5	2	13.00	6	Wiley
Journal of Organic Chemistry	75	1.9%	15	5.0	3.5	4	4.34	14	ACS
Analytical Chemistry	74	1.8%	17	4.4	5.5	10	6.79	10	ACS
Tetrahedron Letters	74	1.8%	15	4.9	5.5	15	2.28	21	Elsevier
Chemical Communications	70	1.7%	16	4.4	7.0	3	6.00	13	RSC
Journal of Physical Chemistry (A,B,C)	65	1.6%	15	4.3	8.0	11	2.88	19	ACS
Proceedings of the National Academy of Sci	52	1.3%	15	3.5	9.0	8	9.41	9	Nat. Acad.
Chemical Reviews	50	1.2%	16	3.1	10.5	6	52.76	1	ACS
Tetrahedron	50	1.2%	15	3.3	10.5	26	2.22	22	Elsevier
Nature	46	1.1%	18	2.6	12.0	14	43.07	2	Springer Nature
Carbohydrate Research	44	1.1%	7	6.3	13.0	28	1.84	23	Elsevier
Journal of Biological Chemistry	41	1.0%	12	3.4	14.5	16	4.24	15	Society
Nucleic Acids Research	41	1.0%	8	5.1	14.5	38	11.50	7	Oxford Univ. Press
Biochemistry	40	1.0%	8	5.0	16.5	40	2.87	20	ACS
Organic Letters	40	1.0%	14	2.9	16.5	12	6.09	12	ACS
Langmuir	39	1.0%	8	4.9	18.0	17	3.56	18	ACS
Journal of Medicinal Chemistry	36	0.9%	12	3.0	19.0	21	6.21	11	ACS
Science	31	0.8%	16	1.9	20.0	7	41.85	3	AAAS
Bioconjugate Chemistry	29	0.7%	6	4.8	21.0	51	4.03	17	ACS
Chromatographia	28	0.7%	4	7.0	22.0	630	1.60	24	Springer
Chemical Society Reviews	26	0.6%	12	2.2	23.0	24	40.44	4	RSC
Chemistry of Materials	25	0.6%	6	4.2	24.0	32	9.57	8	ACS
Total/average	1,621		13	5					

Table 5: Journals cited by > 10 authors ranked by number of citing authors in dissertation sample compared with ACS sample.

Title	citing authors	average citations per author	author rank	ACS study Rank	Impact Factor	impact factor rank	Publisher
Journal of the American Chemical Society	24	9.8	1	1	14.60	5	ACS
Journal of Chromatography / A	18	18.6	2.5	14	4.05	16	Elsevier
Nature	18	2.6	2.5	75	43.07	2	Springer Nature
Analytical Chemistry	17	4.4	4	10	6.79	8	ACS
Chemical Communications	16	4.4	5	6	6.00	11	RSC
Chemical Reviews	16	3.1	5	7	52.76	1	ACS
Science	16	1.9	5	3	41.85	3	AAAS
Angewandte Chemie	15	5.0	10.5	2	13.00	6	Wiley
Journal of Organic Chemistry	15	5.0	10.5	8	4.34	14	ACS
Journal of Physical Chemistry (A,B,C)	15	4.3	10.5	4	2.88	19	ACS
Proceedings of the National Academy of Scie	15	3.5	10.5	11	9.41	7	Nat. Acad.
Tetrahedron	15	3.3	10.5	15	2.22	23	Elsevier
Tetrahedron Letters	15	4.9	10.5	26	2.28	22	Elsevier
Organic Letters	14	2.9	14	12	6.09	10	ACS
Chemical Society Reviews	12	2.2	15	24	40.44	4	RSC
Journal of Biological Chemistry	12	3.4	15	21	4.24	15	Society
Journal of Medicinal Chemistry	12	3.0	15	16	6.21	9	ACS
Analytica Chimica Acta	11	1.7	18	84	5.98	12	Elsevier
Bioorganic & Medicinal Chemistry Letters	10	1.7	19	118	2.572	20	Elsevier
Bulletin of the Chemical Society of Japan	10	1.4	19	508	4.49	13	Chemical Soc. Japan
Journal of Chromatography B	10	1.5	19	34	3.00	18	Elsevier
Organic & Biomolecular Chemistry	10	1.2	19	39	3.41	17	RSC
Pure & Applied chemistry	10	1.2	19	124	2.36	21	de Gruyter
Total/average	326	4.0					

Table 6: Dissertation citations compared with citations in ACS journal articles.

Study	Total references analyzed	Average references cited	% articles	% conference papers	% book or book chapter	% other	
ACS journals	53,143	89	93.8%	2.3%	2.4%	2.5%	
Dissertations	4,636	136	86.8%	0.3%	7.9%	5.0%	
Study	Price Index (References < 5yrs old)	Refs. < 10 years	Refs. < 15 years	Refs. > 20 years	Median half-life	Median Reference Age	Age of 90% of references (years)
ACS journals	44%	68%	81%	11%	7.0	6.0	22.9
Dissertations	22%	43%	61%	28%	12.8	11.8	38.5
study	Refs from journals	Unique journals cited	diversity (journals/ journal refs)	journals accounting for 50% of references	% of references from top 30* journals cited	% Journals accounting for 80% refs	# journals in top 20%
ACS journals	49,317	2,560	0.05	24	58.6%	20.2%	7
Dissertations	4,025	951	0.24	46	44.0%	28.1%	6

Table 7: Citations to top journals in dissertations vs. usage based on full-text downloads.

Journal Title	citations	2019 usage	2020 usage	average use	ratio citations:usage
Journal of Chromatography A	335	265	369	317	1.06
Journal of the American Chemical Society	235	852	1094	973	0.24
Journal of Organic Chemistry	75	383	263	323	0.23
Angewandte Chemie (Int. Ed.)	75	289	294	292	0.26
Analytical Chemistry	74	255	235	245	0.3
Tetrahedron Letters	74	82	163	123	0.6
Chemical Communications	71	175	182	179	0.4
Journal of Physical Chemistry (A,B,C)	65	438	374	406	0.16
Chemical Reviews	50	191	221	206	0.24
Tetrahedron	50	80	104	92	0.54
Carbohydrate Research	44	13	35	24	1.83
Organic Letters	40	337	480	409	0.1
Biochemistry	40	305	212	259	0.15
Langmuir	39	223	146	185	0.21
Journal of Medicinal Chemistry	36	156	145	151	0.24
Bioconjugate Chemistry	29	154	180	167	0.17
Chemical Society Reviews	26	31	24	28	0.95
Chemistry of Materials	25	38	63	51	0.5

Table 8: Comparison with earlier citation analyses of chemistry dissertations.

Source	Edwards 1999	Gooden 2001	Vallmitjana 2008	Zhang 2013	Gohain & Saikia 2014	Saikia & Saikia 2020	this study
Sample size	32	30	46	43	30	34	34
Average references cited	114	123	91	162	366	383	136
% journals	77.4%	85.8%	79.0%	87.0%	78.8%	80.0%	86.8%
% books/book chapters	14.8%	8.4%	12.0%	7.1%	15.6%	11.8%	7.9%
% conference	1.8%	n/a	n/a	2.0%	1.7%	2.6%	0.3%
Unique journals cited	405	441	593	n/a	377	251	951
Journals accounting for 20%	4	n/a	n/a	n/a	10	n/a	8
Journals accounting for 50%	13	12	33	31	n/a	10	46
Journals accounting for 75%	40	n/a	n/a	n/a	50	n/a	192
Journals accounting for 80%	n/a	n/a	150	n/a	n/a	50	266
% refs covered by top 20	61%	n/a	40%	n/a	n/a	n/a	39%
diversity (journals/refs)	0.11	0.12	0.14	n/a	0.03	0.03	0.24

Figure 4: Most cited books by publisher in dissertations vs. JACS