Charting open science Landscapes: A Systematized Review of US Academic Libraries' Engagement in Open Research Practices

Kristen L. Scotti,[1] *Chenyue Jiao*,[2] *Melanie A. Gainey*,[1] *Emily A. Bongiovanni*,[1*] and *Emma R. Slayton*[1]
[1]Carnegie Mellon University Libraries, Pittsburgh, Pennsylvania 15213
[2]University of Illinois Urbana Champaign, Champaign, Illinois 61820

ABSTRACT

Open Science aims to make research publicly accessible, transparent, and reusable, promoting collaboration across disciplines and fostering relationships among government, academia, industry, and society. International and regional reviews have explored the roles of academic libraries in promoting open science on both global and local scales. However, practices within U.S. academic libraries have not been examined comprehensively. This study addresses this gap. We employ a systematized literature review methodology to map U.S. academic library engagement in key areas of open science (*e.g.*, open access, open data, open educational resources) and overlap analysis is used to assess shifts from discrete initiatives (*e.g.*, open access, research data management) to holistic, integrated services that span the research lifecycle. Using a comprehensive search strategy, we identified 3,752 publications for inclusion in the study. We find that U.S. academic libraries are actively engaged in open science practices, with the most extensive involvement in open access and the provision of infrastructure to support open science. However, engagement in activities related to citizen science remains limited. Through thematic overlap analysis, we find that ~50% of publications report activities across two or more themes of open science, suggesting a possible shift toward more comprehensive practices. A key challenge reported by libraries is the need for continuous professional development to address technical skills gaps. As research needs and corresponding librarian responsibilities continue to evolve, maintaining librarian professional development opportunities will remain crucial for equipping librarians with the skills necessary to continue supporting and advancing open science initiatives.

KEYWORDS: open research, open knowledge, e-science, digital scholarship, scholarly communication

1. INTRODUCTION

The open science movement aims to make research publicly accessible, transparent, and reusable to scientific and broader communities [1–3]. These ideals have long been part of scientific discourse [4–6]; however, what we now refer to as open science evolved from the open access movement [7,8], which began with the rapid development of digital technologies in the 1990's [5,9]. Advocacy efforts to promote the sharing of research data and methodologies (especially with respect to the reproducibility crisis [10]), coupled with a growing emphasis on equitable access and participation in research [11], expanded the open access movement into open science [8]. Comparatively, open science is a more comprehensive approach to openness as it seeks to democratize knowledge across all disciplines and phases of research. Open science further promotes collaborative research, including cross- and inter-disciplinary and participatory (where

[*] Corresponding Author: ebongiov@andrew.cmu.edu (E.A. Bongiovanni)

citizens are directly engaged in the research process); it also promotes the strengthening of relationships among government, academia, industry, and society [9].

The United Nations Educational, Scientific, and Cultural Organization (UNESCO) Recommendations on Open Science [12] defines open science as a set of principles and practices designed to make scientific research accessible to all, benefiting both researchers and society. Other definitions align with UNESCO's; for example, the White House Office of Science and Technology Policy (OSTP) [13] describes open science as the process of making research products broadly available, while respecting diverse cultures, ensuring security and privacy, and fostering equity and reproducibility. Similarly, FOSTER (Facilitate Open Science Training for European Research) [14] describes open science as the practice of making research results and underlying data and methods openly available for reuse. Academic literature elaborates on these themes [15,16], emphasizing collaborative knowledge-sharing.

The FOSTER open science taxonomy [14,17] divides the open science umbrella into themes. The original taxonomy [14] identified six core themes, including: open access (OA, unrestricted access to scholarly publications), open data (OD, accessible and reusable research data), open reproducible research (ORR, transparent workflows and methodologies), open evaluation (transparent and equitable assessment practices, including open peer review and alternative research assessment metrics), open science policies (guidelines and regulations supporting open science principles), and open science infrastructure and tools (*e.g.*, platforms for collaboration and data preservation). The recently expanded taxonomy [17] contains ten themes, adding open educational resources (OER, openly licensed teaching materials), open innovation (OI, collaborative idea-sharing and co-creation), and citizen science (public participation in research). The expanded taxonomy also integrates UNESCO's Recommendations on open science [12], addressing inclusivity, cultural diversity, and ethical knowledge-sharing within open practices. A sunburst diagram depicting the expanded taxonomy is shown in **Error! Reference source not found.**.

Academic libraries play a critical role in advancing open science practices [18–20]. A systematic review by Shmagun et al. [21] investigating, in part, domain-dependent contributions to open science found that most research papers on open science practices were published within the field of library and information sciences. The global engagement of academic libraries in open science has been explored in previous reviews [18,19,22]. Liu and Liu [19] found that libraries are active in areas of OA, research data management (RDM, mapping to OD), OER, and citizen science. Giustini et al. [18] reported similar findings in their review of health science libraries. Both studies reported an upward trend in relevant publications over time, noting a shift from a dominant focus on OA toward an increased emphasis on RDM between 2014 and 2016. The evolving nature of research support services, more generally, is also discussed in the literature [23,24]; these reports emphasize the need for librarians to develop new competencies and collaborate effectively to meet researchers' evolving demands. These findings reveal a shift in librarian responsibilities as libraries aim to provide diverse services across the research lifecycle.

Fig. 1. Sunburst diagram showing the breakdown of themes within the recently expanded FOSTER taxonomy of open science [17]. Core themes include: Open Access (OA), Open Data (OD), Open Education (OE), Open Reproducible Research (ORR), Open Innovation (OI), open science infrastructure and tools (Infra), open evaluation (Eval), open science policies, declarations, and guidelines (Policy), and citizen science (Citizen). A category that integrates UNESCO's Recommendations on Open Science [12] is also included. Each core theme is further divided into subthemes, as shown in the diagram.

Open science is a global movement, and international reviews offer valuable insights into overarching trends and best practices on that scale. However, the unique contexts of individual geographic regions necessitate focused explorations, and regional reviews offer tailored insights into specific regional challenges and opportunities. Moreover, although open science aims to promote equitable access to research [25], recent studies raise concerns about our capacity to meet these equity goals [11,26]. For example, disparities in resources, infrastructure, and capacity across regions can exacerbate existing inequities within the open science paradigm [11]. Regional studies allow examination of these issues locally, providing essential information to guide policy development for equitable participation and inclusive practices. Such regional reviews have been conducted for varying geographic scales (*e.g.*, Africa [27–29], Australia [30], the Balkans [31], China [32], Italy [33], Japan [34], and Uruguay [35]). A similar in-depth review is needed for the United States.

This work aims to examine open science-related activities, strategies, and terminology employed by U.S. academic libraries in their engagement in open practices. The overarching goal is to inform best practices, identify areas of opportunity, and promote a collaborative environment that supports the adoption of open and participatory research practices across disciplines and institutions. This paper is the first part of a two-part study; here, we conduct a systematized literature review to provide a broad perspective on the ways in which U.S. academic libraries are engaging with open science. The second part of this work focuses on institutional-level engagement, analyzing trends across institution types to offer deeper insights into practices across institutions of varying research intensity.

1.1. U.S. Open Science Policies

As shown in the timeline in Fig. 2, U.S. policies have played an important role in advancing open science practices in the U.S. [36–40]. Initial efforts, such as the 2008 National Institutes of Health (NIH) Public Access Policy [41], which required publicly funded research publications to be made freely available, focused on promoting open access. As the OA movement gained momentum, the focus expanded to include open data. Policies such as the National Science Foundation's requirement for data management plans (DMPs) in 2011 [42] prompted libraries to expand their research support services to include data management activities [37,43–45].

The U.S. Office of Science and Technology Policy's (OSTP) Public Access Memos, issued in 2013 (Holdren Memo, [46]) and 2022 (Nelson Memo [47]), reflect the evolving nature of the federal commitment to open practices. The 2013 Holdren Memo required larger federal agencies to develop public access policies with 12-month embargo periods on publications, whereas the 2022 Nelson Memo directed all federal agencies to do so. By December 31, 2025, all federal agencies must provide immediate and unrestricted access to both research results *and* data [47]. This directive reflects a shift toward a more integrated approach in promoting open science and demonstrates a growing recognition of the interconnectedness of various aspects of the research process.

Academic institutions have also instituted policies governing open practices, both to align with federal mandates and to promote broader participation in open practices [48,49]. Academic libraries are often charged with managing and implementing these policies [49,50].

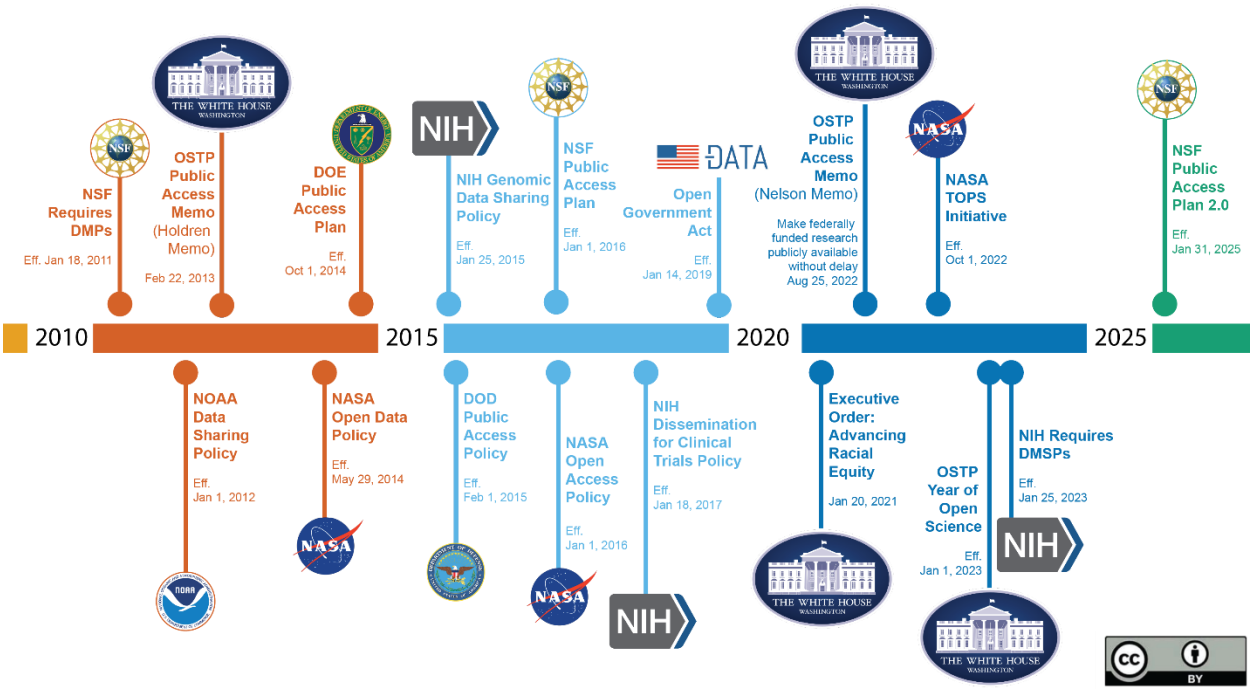

Fig. 2. Timeline of U.S. federal data sharing policies and milestones, showing key developments in public access, open data, and open science initiatives from 2010 to 2025. The timeline highlights major policies and mandates across several federal agencies, including: Department of Defense (DOD) [51], Department of Energy (DOE) [52], National Aeronautics and Space Administration (NASA) [53–55], National Institutes of Health (NIH) [56–58], National Institutes of Justice (NIJ) [59], and National Oceanic and Atmospheric Administration (NOAA) [60]. The timeline also includes significant federal directives, such as those from the U.S. Office of Science and Technology Policy (OSTP) [13,46,47], the Executive Order on Advancing Racial Equity and Support for Underserved Communities Through the Federal Government (January 20, 2021) [61], and the Open, Public, Electronic, and Necessary (OPEN) Government Data Act (H.R.1770, 115th Congress) [62].

2. METHODS

The methods described here were pre-registered in May 2024 (https://osf.io/pv7k2/) [63], and amended on October 21, 2024. The data and code used in this work is available on our OSF project page, except for data files containing extracted text from article PDFs (described in Section 2.6), which are not included due to copyright and licensing restrictions. (The code used to extract text from PDFs is available.)

2.1. Research Questions

The objective of this work was to explore how U.S. academic libraries are engaging in open science practices. Specifically, we aimed to answer the following research questions (RQ):

- RQ-1. How are U.S. academic libraries engaging in open science practices across individual themes such as open access (OA), open educational resources (OER), and research data management (RDM)?
- RQ-2. How have U.S. academic libraries supported a shift from open access (OA), open educational resources (OER), and research data management (RDM) toward comprehensive open science practices?
- RQ-3. What specific terminology are U.S. academic libraries using to describe their activities and initiatives related to open science?

2.2. Study Design and Approach

We employed a systematized review methodology [64] for this work, incorporating elements of systematic and scoping reviews without strictly adhering to either of their methodologies. A comprehensive search, characteristic of systematic reviews, was conducted, aiming for an exhaustive collection of scholarly literature on U.S. academic library activities related to open practices. Our screening process (Section 2.5) deviated from traditional systematic or scoping review methodology in that we did not utilize two independent reviewers throughout the screening process [64]. Given the substantial number of studies retrieved (n = 56,962), one reviewer conducted the initial screening, while a second reviewer screened a subset of articles excluded by the first reviewer to verify their exclusion. This method (a version of which is described in the literature [65]) was adopted to manage the workload within our time constraints while attempting to mitigate potential bias. We adhered to the reporting guidelines outlined in the PRISMA extension for scoping reviews [66].

2.3. Literature Search

2.3.1. Search strategy development

Given diverse terminology associated with open science initiatives [67], broad keyword search strategies can be used to maximize the capture of relevant literature. Consistent with previous work [18,19,67,68], we embraced an inclusive definition of open science, encompassing efforts aimed at enriching transparency, accountability, and accessibility throughout the research process. We initially conducted exploratory searches using keywords from the FOSTER open science taxonomy [14,17] and identified additional terms based on how authors referred to their work. The additional search terms identified during this phase were incorporated into our final search strategy. Our complete search queries are provided in supplemental materials, Table S 1.

2.3.2. Database and supplemental searches

Our search approach combined multiple methods to identify relevant articles: bibliographic databases, supplemental sources, manual examination of library-focused journals, and citation tracing. We searched seven bibliographic databases, including: Web of Science Core Collection (WOS, Clarivate Analytics), Scopus (Elsevier), LISTA (Library, Information Science, and Technology Abstracts), LISA (Library and Information Science Abstracts), IEEE Xplore Digital Library, LSD (Library Science Database, ProQuest), and the ProQuest Education Collection (Education Database and ERIC, Education Resources Information Center). The search strings used for each database are provided in the supplemental materials (Table S1). We utilized OpenAlex [69], Open Science Framework (OSF) [70], and Google Scholar as supplementary sources. Searches in OpenAlex were conducted using openalexR [71], an R wrapper for accessing the OpenAlex API, employing a subset of the keywords from our bibliographic database searches followed by automated searching to screen titles and abstracts of the results for the remainder of the keywords. Google Scholar and OSF searches were also conducted using a subset of our identified keywords; for OSF searches, we also reviewed institutional pages of U.S. colleges and universities. Forward and backward citation tracing was conducted using SpiderCite from SR-Accelerator [72] following the methods outlined by Hirt *et al*. [73]. References identified by SpiderCite were first checked for duplicates against our Zotero library using SR-Accelerator Deduplicator; only unique references were imported to Zotero. Lastly, we identified 58 highly relevant journals and conference proceedings during our searches and scanned their

tables of content to locate further articles. These sources and the dates of the searches are listed in the supplemental materials (Table S 2).

2.4. Eligibility Criteria

To be included in this review, studies had to meet the following criteria:

- *Timeframe*: The study was published on or after January 1, 2010.
- *Location*: The study described activities at institutions located within the United States.
- *Setting*: The study pertained to activities within libraries affiliated with a college or university.
- *Focus*: The study included a description of activities related to open practices, including any mention of current or planned services and/or needs assessments.
- *Institution-specific data*: The study described institution-specific activities.
- *Article availability*: The full text of the study was available.

Studies that did not meet all inclusion criteria were excluded from the review.

The concept of open science as a framework for open research practices was not widely discussed prior to 2010 [18]. Hence, we focused our search on the years 2010-2024. We excluded studies that focused on library activities that fell outside the scope of open science initiatives. Our approach aimed to capture intersections between core library services and open science activities, acknowledging that not all initiatives aligned with these principles may be explicitly labeled as "open science" (and the like). For example, we included the term, "literacy" in our search queries (Table S 1) to capture instructional services that overlap with, but may not be called, open science, and excluded studies that reported activities related to information and/or digital literacy alone. We also excluded studies reporting other traditional library services that do not directly overlap with open science, *e.g*., reference services, use of physical space, cataloging, marketing, and interlibrary loan. This approach aligns with methodologies used in previous research [19,23]. Our objective was to provide a comprehensive overview of open science related activities in U.S. academic libraries. Therefore, only studies containing institution-specific data were considered; studies were excluded if they reported aggregated data across multiple institutions or if the institution was unidentifiable. Similarly, review articles were excluded from analysis but were utilized for citation tracing purposes. Lastly, when the full text of a study was unavailable through open access, institutional subscriptions, or interlibrary loan, we attempted to secure the text by contacting the corresponding author. Studies were excluded due to unavailability only if these efforts were unsuccessful.

2.5. Article Screening

The open-source citation manager, Zotero [74] was used for reference management, screening, and article coding. Bibliographic data from searches were imported to Zotero. Deduplication of studies was first carried out in Zotero, then Deduplicator in SR-Accelerator [75], and finally, using exact title matching. Each unique reference was assigned an identification number, which was recorded in Zotero's "Extra" field.

Initially, one reviewer (KS) screened titles and abstracts of search results. Studies that met inclusion criteria or lacked enough information for a decision based solely on title and abstract screening were moved to full-text screening. Excluded studies were tagged in Zotero with their exclusion reason (exclusion codes correspond to the eligibility criteria (Section 2.4) and are

provided in supplementary materials, Table S 3). Article PDFs were retrieved during title/abstract screening for the purpose of checking author affiliations to exclude non-US articles.

Relying on a single reviewer can increase the likelihood of bias in screening, coding, and analysis [76], potentially leading to the exclusion of relevant studies [77–79]. To mitigate this issue, a subset of studies that were excluded by the primary screener based on setting, focus, or institutional-specific data underwent screening by a second reviewer (CJ). These exclusion categories were deemed most likely to have resulted in invalid exclusion (location, timeframe, and article availability are easier to verify). A total of 38,134 references were excluded for these reasons; of these, 1,682 references (~4%) were reviewed by the second screener. References were randomly selected for re-screening using a custom JavaScript program in Zotero. Exclusion disagreements between reviewers were resolved through discussion and consensus. Bibliographic files containing both excluded and included articles are available on our OSF project page (https://osf.io/pv7k2/).

Searches were carried out between May 6, 2024, and June 18, 2024 (supplementary materials, Table S 1 and Table S 2). A total of 56,888 unique references were retrieved (14,388 duplicates were removed from 71,350 retrieved references, Fig. 3). A total of 44,411 references were excluded during title and abstract screening; an additional 8,725 references were excluded during full-text screening. Finally, 3,752 studies met our inclusion criteria; the PRISMA flow diagram is shown in Fig. 3.

The second screener uncovered three references that were incorrectly excluded by the primary screener; thus, the primary screener incorrectly excluded ~0.2% of the 1,682 studies that were double screened. This rate is lower than reports in the literature, which range from 0.4%-13% [79–81]. Based on this error rate and the number of exclusions that were not re-screened (n = 33,922), we estimate that an additional 60 articles may have been incorrectly excluded based on exclusion codes of setting, focus, or institution-specific data. This value represents less than 2% of included articles (n = 3,752), thus unlikely to significantly impact the results. Given the large number of included publications, we have not included a table of included studies. Bibliographic details of both excluded and included articles are available for export from our OSF project page (https://osf.io/pv7k2/).

2.6. Study Coding, Data Extraction, and Data Analysis

Consistent with previous efforts to map open science activities within academic libraries [18,19,68], qualitative coding was used to map relevant activities to the FOSTER open science taxonomy [14,17]. The FOSTER taxonomy provides a structured and comprehensive framework for categorizing open science themes. Using this established taxonomy, we can better ensure that our classifications are consistent with recognized open science practices and comparable to other reviews.

We employed the recently expanded FOSTER taxonomy [17] (Fig. 1), which organizes open science into ten themes: Open Access (OA), Open Data (OD), Open Educational Resources (OER), Open Reproducible Research (ORR), Open Innovation (OI), policy frameworks, infrastructure and tools, responsible evaluation of open science, and citizen science, and a category based on the UNESCO Recommendations on Open Science [12]. Throughout our

analysis, we treated OA, OD, OER, ORR, OI, policy, infrastructure/tools, open evaluation, and citizen science as core themes. For the UNESCO category, we coded studies using the activity codes shown in supplementary materials, Table S 3 to highlight how academic libraries are integrating these activities within the core themes, emphasizing connections to Diversity, Equity, Inclusion, and Accessibility (DEIA) efforts and the United Nations Sustainable Development Goals (SDGs) [82].

Using the FOSTER descriptions of these themes [14,17], along with previous mappings of library activities [18,19], and a preliminary review of our search results as guides, we developed a list of open science-related library activity groups and mapped those to the relevant FOSTER themes (see Tables 4-12). Each identified activity group was assigned an activity code (activity codes are provided in supplementary materials, Table S 3), and relevant codes were applied to studies using Zotero's tagging functionality. After activity coding, studies were assigned open science theme tags (e.g., "_OA," "_OD," "_OER") to reflect the mappings shown in Tables 4-12. Neither activity nor theme codes were designed to be exhaustive; most articles received multiple codes. Metadata, including reference type (e.g., journal article, conference proceeding, report) and university affiliation, were also recorded using Zotero fields (see supplementary materials, Table S 4).

Data analysis was performed in Python and R; the corresponding code is available on our OSF project page (https://osf.io/pv7k2/). Zotero field codes (including code tags) of included studies were exported from Zotero to a CSV file. The CSV file was imported into Python, and activity and theme codes were parsed from the Zotero "Manual Tags" field. A dataset was created by assigning all unique tags to separate columns and populating the cells with zeros (false) or ones (true) based on whether a given activity or theme code was associated with that publication.

Text analysis was used to map the usage of open science terminology over time and to explore keyword co-occurrence. First, we created a keyword list and grouped synonymous terms (*e.g.*, where "e-science" includes "e-science," "electronic science," "electronic research," and "e-research"). A custom JavaScript program was used to extract the full text of articles from PDFs stored in Zotero. These texts were processed in Python to identify keyword occurrences by year, with the keyword list converted into a binary data frame to indicate the presence or absence of each keyword within a given article.

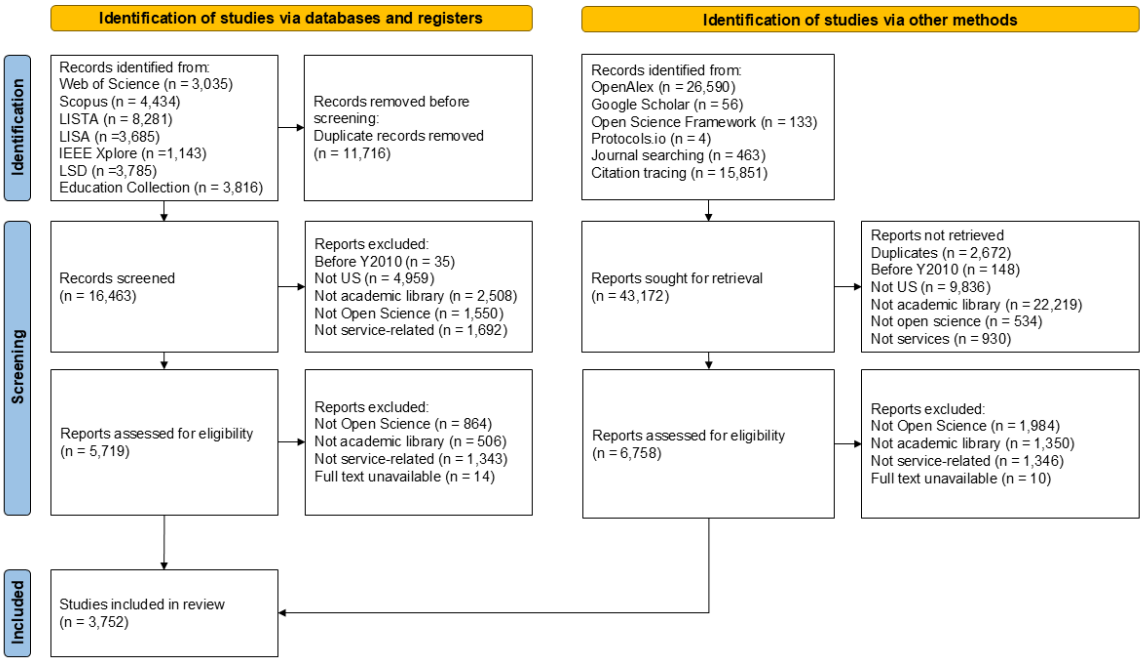

Fig. 3. PRISMA flow diagram.

3. RESULTS

3.1. Overview of Study Selection and Data Sources

Approximately one-third of the included studies appeared in multiple databases. To identify which databases yielded the highest proportion of included records, we tracked every database in which a given study appeared. Table 1 shows the total number of results retrieved from each database, the corresponding number of included studies, the number of unique studies (those found only in that database), and the inclusion rates (calculated as the number of included studies relative to the number of search results). The highest inclusion rates were obtained using Web of Science and Scopus, with ~17% of retrieved studies included. OpenAlex had the lowest inclusion rate (~5%) but provided 719 unique studies, representing ~19% of our included studies. The number of studies contributed from Google Scholar, Open Science Framework, Protocols.io, and journal searching is also provided in Table 1, but inclusion rates are not calculated since bibliographic data were only extracted for these searches if a study met our inclusion criteria. The inclusion rate for citation tracing is not provided because retrieved studies that had already appeared *via* other searches (whether included or excluded) were removed from citation tracing datasets prior to importing bibliographic data into Zotero (thus, the number of search results for citation tracing represents this filtered value).

Included studies (n = 3,752) were published by 486 different sources (not including studies published in OSF, Protocols.io, or *via* institutional repositories), including: 340 journals, 78 conference proceedings, and 68 books. The distribution of publication types for included works is provided in Table 2. Journal articles comprised ~70% of overall publications, news articles contributed ~9%, conference papers contributed ~8%, and book chapters and conference slides

each contributed ~4%. Remaining sources include reports, poster presentations, abstracts, and protocols.

Table 1. Sources of included publications, including the total number of search results, the number of included publications, the number of unique publications (publications appearing only in that database), and the inclusion rate (calculated as the number of included publications divided by the total results from that database/source).

Source	Search Results (*n*)	Included (*n*)	Unique (*n*)	Inclusion Rate (%)
WOS	3,035	502	37	~17
Scopus	4,434	750	78	~17
LISTA	8,281	882	269	~11
LISA	3,685	392	25	~11
IEEE Xplore	1,143	22	10	~2
LSD	3,785	347	18	~9
Education Collection	3,816	448	183	~12
OpenAlex	26,591	1,317	719	~5
Google Scholar	58	56	56	-
OSF	134	133	133	-
Protocols.io	4	4	4	-
Select Journals	535	463	463	-
Citation Tracing	15,851	693	693	-

Table 2. Distribution of publication types for included works, including the number and proportion of each type.

Source	Number of publications (%)
Journal articles	2,620 (~70)
News articles	350 (~9)
Conference papers	307 (~8)
Slide presentations	168 (~4)
Book chapters	139 (~4)
Reports	87 (~2)
Poster presentations	50 (~1)
Abstracts	24 (<1)
Protocols	7 (<1)

Fig. 4 shows a bar chart depicting the top 25 journal/magazine and conference sources contributing publications. Considering the major search databases used here, ~52% of the top 25 sources were covered by WOS and ~76% by Scopus. For library-centered databases, LISTA and LISA contributed studies from the greatest number of top sources, at ~88% and ~72% of sources, respectively, while LSD covered ~44%. *College and Research Libraries News*, *Journal of Librarianship and Scholarly Communication*, and *Journal of eScience Librarianship* contributed the greatest number of publications to this work (208, ~5% and 109, ~3%, and 81, ~2%, respectively). Web of Science did not contribute studies from any of those sources, and the *Journal of eScience Librarianship*—the third highest contributor—is not indexed by any of the seven search databases we used (the same is true for *International Journal of Digital Curation*).

OpenAlex, which aggregates data from multiple sources (*e.g.*, Crossref, arXiv, PubMed, and institutional repositories) [69], captured ~92% of the top 25 sources (including studies from *Journal of eScience Librarianship* and *International Journal of Digital Curation*). While OpenAlex provided the lowest inclusion rate (*i.e.*, the proportion of included studies relative to retrieved studies), it identified key sources that were not captured by the traditional databases. These findings indicate that relying exclusively on traditional bibliographic databases may be insufficient for evidence synthesis that relies heavily on library literature. While incorporating supplemental sources like OpenAlex and/or manually searching the tables of contents of highly relevant journals significantly increases the effort required for reviews, these steps may be necessary to address gaps in indexing coverage.

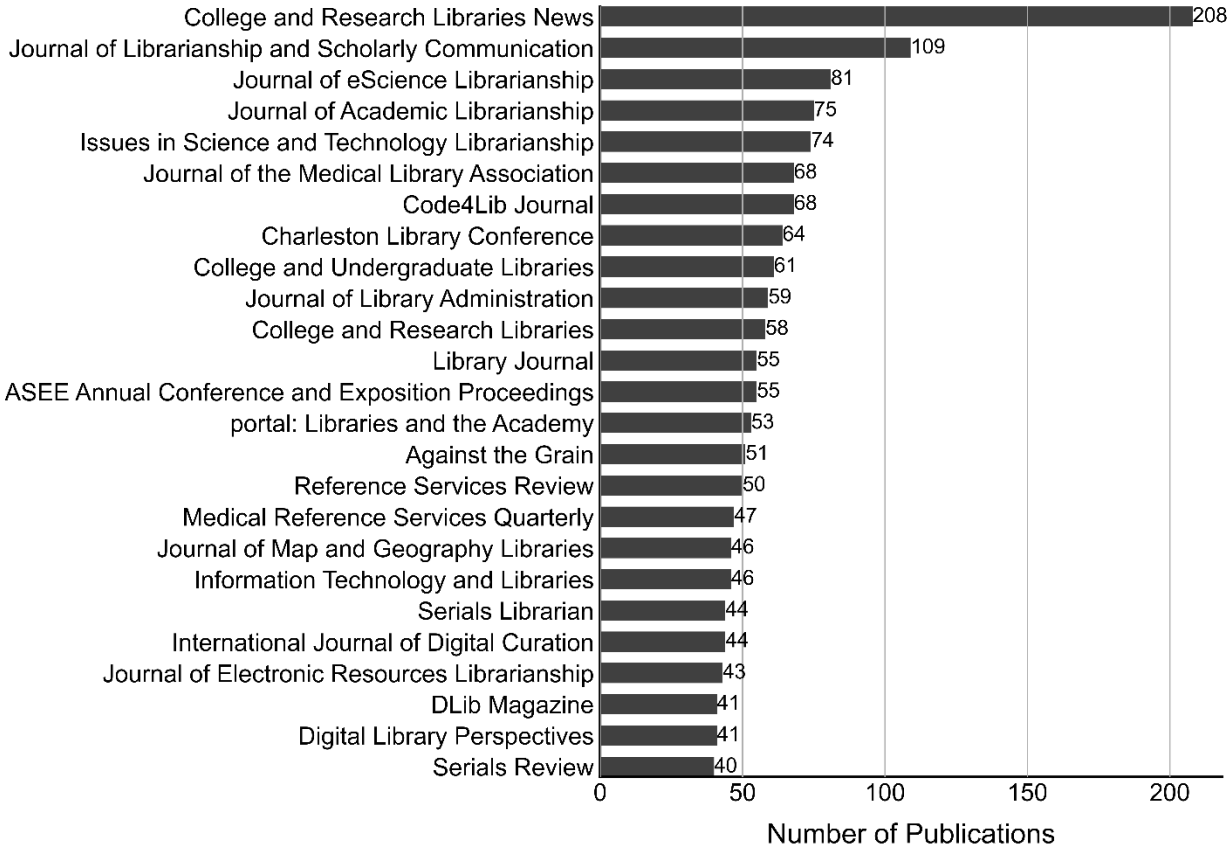

Fig. 4. Bar chart showing the top 25 journal/magazine and conference proceeding sources that contributed publications to this study.

3.2. Mapping Open Science Initiatives in U.S. Academic Libraries

Academic libraries often document their initiatives in publications, reports, and case studies, which serve as a source of data reflecting their evolving roles. By systematically reviewing these materials, we can capture both explicit and implicit shifts in library practices as they transition from supporting discrete open science themes, like open access or open data, to more integrated, comprehensive approaches to open practices. This method allows for a longitudinal analysis, showing how libraries' commitments to different open science themes have developed over time.

The bar chart in Fig. 5 shows the number of included publications by year. The number of publications peaks in 2017, with 366 publications; a downward trend is observed thereafter, with 190 publications in 2023. This decline is partially explained by methodological factors. Citation tracing contributed ~19% of the included publications. From 2017 to 2023, the number of publications dropped by ~48%; for the same period, the decrease in publications contributed by citation tracing decreased by ~66% compared to a ~45% decrease for publications identified *via* other methods. Thus, the decline in studies contributed by citation tracing is ~1.47 times (or ~50%) greater than the decrease from other sources. We used both forward and backward citation tracing to identify studies. Backward citation tracing, which identifies works cited within included studies, favors older publications because it takes time for publications to be cited. Forward citation tracing identifies newer works that cited included publications and requires time for new research to build upon and cite existing work. Our reliance on citation tracing introduced a bias toward earlier years.

The COVID-19 pandemic, impacting the U.S. beginning in January 2020, likely also contributed to a reduction in published studies. While COVID-19 related publications increased during the pandemic [83], generally, the publication rate of non-COVID related publications declined [84]. A general decline in the rate of initiating new projects has also been reported post-COVID [85]. This, coupled with pandemic-related declines in library budgets and staffing shortages [86,87], as well as a need to shift efforts toward supporting virtual services [88–91], has likely contributed to the decline in publications we observe here.

The subplots in Fig. 5 represent the proportion of publications (each year) that described activities within each of the open science themes. Table 3 provides the total number of publications (across all years) mapped to each of the FOSTER themes (where a single publication may be mapped to multiple themes). Of the 3,741 studies analyzed, 52% described activities that mapped to OA, 23% to OD, and 15% to OER. These findings align with previous reviews with some deviations.

Giustini *et al*. [18] conducted a scoping review of health science libraries in 2021 and reported that 54% of 54 included studies mapped to OA, 43% to OD, and 6% to OER. Liu and Liu [19] published a systematic review in 2023, analyzing 65 studies; they mapped 45%, 34%, and 14% of those studies to OA, OD, and OER, respectively. Our percentages for studies mapped to OA are similar to both previous reviews, and our proportion mapped to OER is consistent with Liu and Liu. However, we mapped fewer relative studies to open data than either previous review. Given that Giustini *et al*. focused on health science libraries, our results are most comparable to Liu and Liu. While they also classified articles using the FOSTER taxonomy, their mapping differed slightly from ours. Specifically, data analysis and visualization services were mapped to OD, while we mapped these services to open reproducible research (ORR). Only ~5% of their studies described these activities, and these studies described other activities that would be mapped to OD in our classification system; thus, remapping data analysis and visualization would not significantly change the proportion of studies that they mapped to open data. We coded 206 studies with data analysis and visualization, mapping these to ORR; however, 166 of these studies described activities that we also mapped to open data. If we re-mapped the remaining 40 studies to OD, our proportion of OD studies increases only from ~23 to ~24%.

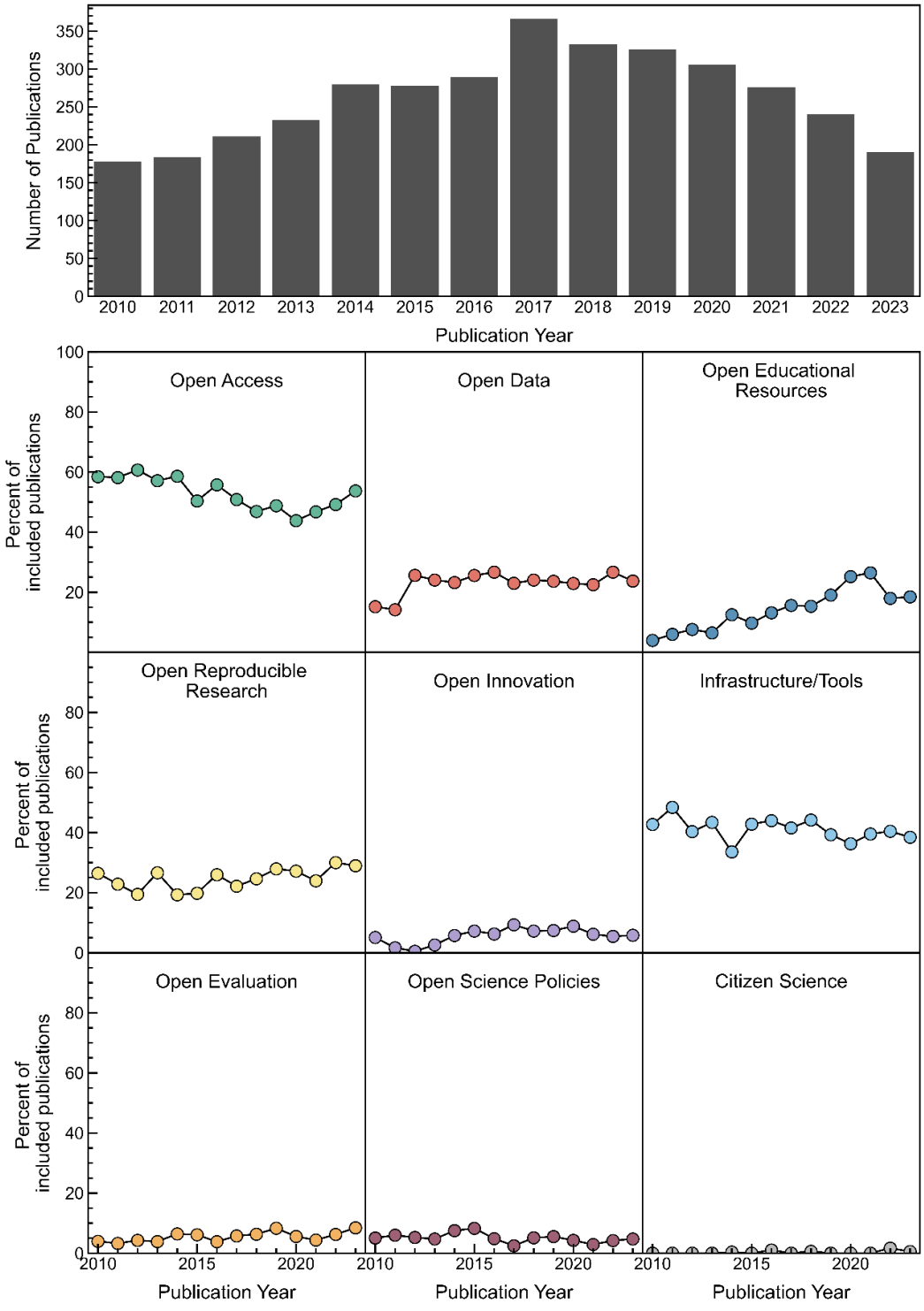

Fig. 5. Bar chart showing the number of included publications by publication year (top row) and subplots showing the proportion of papers per year describing activities within a given open science theme, including: open access, open data, open educational resources, open reproducible research, open innovation, infrastructure/tools, open evaluation, open science policies, and citizen science.

Table 3. Summary of publications mapped to each of the FOSTER open science themes. A single publication may be mapped to multiple domains. The "publications" columns provide the number and percentage of papers mapped to a given domain (relative to all publications, n = 3,752). The single theme publications columns provide the number of publications mapped exclusively to that domain (relative to all publications in that domain).

	Total Publications		**Single Theme Publications**	
FOSTER open science theme	Number	% of total	Number	% within theme
Open Access (OA)	1,957	~52	570	~29
Open Data (OD)	869	~23	164	~19
Open Educational Resources (OER)	562	~15	319	~57
Open Reproducible Research (ORR)	929	~25	158	~17
Open Innovation (OI)	228	~6	143	~63
Open science infrastructure and tools	1,530	~41	445	~29
Open and responsible evaluation of open science	208	~6	52	~25
Open science policies, declarations, and guidelines	188	~5	11	~6
Citizen science	11	<1	0	0
OVERALL	3,752	-	1,862	~50

Our dataset is over 5,000 times larger than either of the previous reviews. Since we used the recently expanded FOSTER taxonomy, we also mapped studies to more open science themes. Thus, these discrepancies likely result from broader coverage rather than significant shifts in the field or regional differences in U.S. academic libraries (especially since U.S. activities were overrepresented in the datasets of both previous international reviews).

As shown in Table 3, the FOSTER taxonomy themes of open innovation, open and responsible evaluation, open science policy, declarations, and guidelines, and citizen science are the least represented themes in our dataset, with <1% to ~6% of studies mapping to these themes. Potential opportunities to expand efforts in these areas are discussed in the following sections, where each theme is addressed individually.

Table 4. Mapping of the expanded FOSTER taxonomy's Open Access (OA) theme to library activity groups identified from the literature. Publication counts represent the total coded for each activity, with proportions based on the 1,957 publications mapped to the OA theme.

Open Access Subthemes	Activities	Number (proportion) of publications
Open access publication: Publication services	Providing publishing services for books and/or monographs, journals and/or conference proceedings	218 (11%)
Open access publication: Publication in open access journals (diamond and APC route)	Establishing and/or monitoring journal quality indicators/metrics	62 (3%)
	Managing and monitoring costs associated with APCs	61 (3%)
	Creating, maintaining, and assessing APC funding programs	64 (3%)
	Promoting/providing researcher identification services (*e.g.*, ORCID)	74 (4%)
Open access publication: Deposit in repositories (Green Route)	Building and/or managing an institutional repository for university-generated scholarly works	1,119 (57%)
	Building and/or managing a shared repository (accepts contributions from external users)	77 (4%)
	Promoting the use of repositories among researchers *via* outreach/promotional activities and/or offering mediated deposit services; providing recommendations for appropriate external repositories	169 (9%)
	Managing persistent identifiers for scholarly documents	34 (2%)
Use and reuse of open publications; copyright and open licenses	Supporting the management of authors' rights: providing guidance and promoting use of open licensing awareness and understanding, promoting copyright literacy, and providing guidance on embargo periods	191 (10%)
	Providing instruction on literature review methodologies	90 (5%)
	Providing instruction in citation management tools	105 (5%)
Open access initiatives	Providing instruction in activities related to scholarly communication, including funding options, publishing options, preparation of posters, oral presentation skills, and grant writing	241 (12%)
	Conducting needs assessments for scholarly communication activities related to open access	167 (9%)
	Promoting OA practices among researchers and organizing events aimed at promoting OA	428 (22%)

Table 5. Mapping of the expanded FOSTER taxonomy's Open Data (OD) theme to library activity groups identified from the literature. Publication counts represent the total coded for each activity, with proportions based on the 869 publications mapped to the OD theme.

Open data subtheme	Activity group	Number (proportion) of papers
Open research data: research data management, FAIR data principles, protection, and preservation of research data	Building and/or managing institutional data repositories; assisting researchers in identifying appropriate external data repositories.	328 (38%)
	Providing RDM training and guidance, including advising best practices, promoting FAIR principles, and providing corresponding instructional services	402 (46%)
	Establishing/maintaining persistent identifiers for datasets	22 (3%)
	Providing guidance in developing data management plans	172 (20%)
	Participating in data curation activities, advising on data privacy and governance, providing data quality checks, implementing error-checking systems, and providing metadata assistance	205 (24%)
	Promoting the sharing and reuse of data, including, through events, workshops, and other outreach; locating datasets for reuse, providing guidance on data citation, and utilizing open data in instruction and library operations	194 (22%)
	Creating and sharing open data	15 (2%)
Open data initiatives	Providing GIS services	217 (25%)
	Performing and addressing RDM-related needs assessments	245 (28%)

Table 6. Mapping of the expanded FOSTER taxonomy's Open Educational Resources (OER) theme to library activity groups identified from the literature. Publication counts represent the total coded for each activity, with proportions based on the 562 publications mapped to the OER theme.

OER Subdomain	Activities	Number (proportion) of papers
Open educational resources and e-learning platforms	Creating, maintaining, and/or managing an institutional repository that accepts OER	75 (13%)
	Promoting the sharing and reuse of OER: Providing guidance in creating/using OER content, licensing options, curating and evaluating OER content, and utilizing OER in instructional and outreach roles	370 (66%)
	Creating OER content	152 (27%)
Open education initiatives	Creating, managing, and assessing OER funding programs	138 (25%)
	Conducting needs assessments related to textbook affordability and OER	70 (12%)
	Creating/managing textbook affordability, alt-text, textbook reserve programs	143 (25%)

Table 7. Mapping of the expanded FOSTER taxonomy's Open Reproducible Research (ORR) theme to library activity groups identified from the literature. Publication counts represent the total coded for each activity, with proportions based on the 929 publications mapped to the ORR theme.

ORR Subdomain	Activities	Number (proportion) of papers
Ethics and integrity in research	Providing instruction in research ethics	15 (2%)
Open and reproducible research: Open laboratory books	Providing access/infrastructure/instruction for the use of electronic lab notebooks	13 (1%)
	Providing support/infrastructure for research resources and instrumentation identification (e.g., Research Resource Identifiers, RRIDs)	2 (<1%)
Open and reproducible research: Open science workflows	Providing infrastructure and/or instruction in reproducible workflows, open workflow platforms (*e.g.*, R-Squared, OSF, protocols.io), and advising best practices for reproducibility; promoting reproducible practices through events, workshops, *etc*., and recommending tools that enable ORR	116 (12%)
	Providing code support and instruction/training in data analysis and/or visualization	206 (22%)
	Hosting hackathons, Wikipedia edit-a-thons, map-a-thons, and the like	36 (4%)
Open and reproducible research: Open-source code and software	Utilizing OSS in instructional/training spaces to promote use and/or utilizing and/or evaluating OSS in own scholarly work/library operations	617 (66%)
	Creating/modifying and/or customizing OSS for library operations and/or scholarly purposes	93 (10%)
	Offering guidance regarding creation of OSS and corresponding licensing	5 (1%)
Open and reproducible research: Reproducibility tests	Carrying out reproducibility studies	9 (1%)
Open and responsible research initiatives	Providing evidence synthesis services, including advising search strategies, providing advice re: best practices, and conducting reviews (collaboratively or independently)	77 (8%)
	Conducting needs assessments related to ORR	5 (1%)

Table 8. Mapping of the expanded FOSTER taxonomy's Open Innovation (OI) theme to library activity groups identified from the literature. Publication counts represent the total coded for each activity, with proportions based on the 228 publications mapped to the OI theme.

Open Innovation Subdomain	Activities	Number (proportion) of papers
Forms of open innovation	Building/maintaining spaces used as innovation hubs/commons, including makerspaces	172 (75%)
Open innovation initiatives	Providing support for entrepreneurship and innovation, *e.g.*, patent searches/licensing, economic development/commercialization support, market/industry research, use of business databases	74 (32%)

Table 9. Mapping of the expanded FOSTER taxonomy theme of infrastructure and tools to library activity groups identified from the literature. Publication counts represent the total coded for each activity, with proportions based on the 1,530 publications mapped to the infrastructure/tools theme.

Infrastructure/Tools Subdomain	Activities	Number (proportion) of papers
Open code repositories	Building/maintaining an institutional repository that accepts software	4 (<1%)
	Providing instruction for the use of open code repositories (for code reuse and sharing)	28 (2%)
Open collaborative platforms	Providing cyberinfrastructure for cloud and/or high-performance computing, including conducting needs assessments and trade studies/market analyses related to cyberinfrastructure	52 (3%)
	Facilitating data collaboration opportunities among researchers	9 (1%)
Open Science service providers	Participating in professional development related to open science activities	147 (10%)
	Incorporating open science metrics in strategic plans, policies, and initiatives; creating task forces and committees related to open science initiatives	76 (5%)
	Promoting open science practices	17 (1%)
Digital preservation in open science: Digital preservation systems and tools, interoperability protocols and guideline	Creating OA content by digitizing historical collections and hosting collections on IR or other publicly accessible spaces	1001 (65%)
	Conducting needs assessments related to digital preservation	8 (1%)
	Facilitating discovery of Open Access materials (e.g., via metadata, search engine optimization, linked open data, integration of IR with discovery system, indicating access in metadata, Open Access Button integration within discovery system, Open Athens)	355 (23%)
	Providing support for digital projects, including training/instruction in sharing, locating, and reusing resources, digital preservation and	309 (20%)

Table 10. Mapping of the expanded FOSTER taxonomy's open evaluation of science theme to library activity groups identified from the literature. Publication counts represent the total coded for each activity, with proportions based on the 208 publications mapped to the open evaluation theme.

Open Evaluation Subdomain	Activities	Number (proportion) of papers
Open peer review	Promoting the use of open peer-review journals/services	2 (1%)
Open and responsible metrics	Providing altmetric and bibliometric services and training; publishing research metrics, and profiling scholars to increase research reach	143 (69%)
	Promoting use of holistic measures to assess scholarly output	30 (15%)
Open and responsible evaluation initiatives	Open assessment of library operations and services	53 (25%)

Table 11. Mapping of the expanded FOSTER taxonomy's policy, declarations, and guidelines of open science theme to library activity groups identified from the literature. Publication counts represent the total coded for each activity, with proportions based on the 188 publications mapped to this theme.

Policy Subdomain	Activities	Number (proportion) of papers
open science policies: Regional, national, agency, and institutional	Helping researchers to understand open science guidelines/requirements of funding agencies	53 (28%)
	Tracking compliance with data management plans	8 (4%)
	Participating in the development and/or promotion of institutional policies related to open practices	131 (70%)

Table 12. Mapping of the expanded FOSTER taxonomy's citizen theme to library activity groups identified from the literature. Publication counts represent the total coded for each activity, with proportions based on the 11 publications mapped to the citizen theme.

Citizen Science Subdomain	Activities	Number (proportion) of papers
Citizen laboratory, distributed computing, collaboration networks, scientific dissemination, practices/policies/initiatives	Offering or facilitating sharing of infrastructure/resources, offering RDM support and/or curation services for participatory activities	11 (100%)

3.2.1. Open Access

Open Access (OA) refers to free access to scientific publications and materials [92,93]. The expanded FOSTER taxonomy [17] organizes OA into three categories: (1) OA publications, (2) the use and reuse of open publications (including copyright and open licensing considerations), and (3) OA initiatives. The (1) OA publications category is further divided into three subcategories: (a) publication services, (b) OA journal publications, and (c) self-archiving in repositories. As shown in Table 4, we identified 15 library activity groups across categories (1) through (3), mapping a total of 1,957 publications to the OA theme.

Library publishing services were mapped to the (1) OA publishing category, representing ~11% of the studies that described activities within the OA theme. Efforts within this subcategory include publishing OA journals (*e.g.*, [94,95], including student journals, *e.g.*, [96,97]), conference proceedings (*e.g.*, [98,99]), and books (*e.g.*, [100,101]). Advances in digital platform technologies have enabled more institutions to transition to library-based publishing, with many institutions using their institutional repositories as publishing platforms (*e.g.*, [94,102]). The motivation for initiating library publishing services often centers on promoting community-based publishing over commercial alternatives [103,104]. In some cases, these initiatives also align with social justice goals by providing platforms that amplify underrepresented voices and perspectives, promoting equity in scholarly communication (*e.g.*, [105]). However, these services face challenges related to sustainability and scaling due to limited funding, staffing constraints, and the need for collaborative partnerships [106]; many of these challenges were exacerbated by the COVID-19 pandemic [107,108].

We identified four library activity groups that mapped to the second OA publication subcategory (b, OA journal publications): (i) establishing and/or monitoring journal quality indicators (*e.g.*, [109,110]), (ii) managing costs related to APCs, (iii) offering APC funding programs, and (iv) promoting persistent identification numbers for researchers (*e.g.*, ORCID [111]). This subcategory accounted for the lowest number of publications mapped to the OA theme, representing only 3-4% of publications across all four activity groups. While many libraries manage APC funding programs [112,113], the sustainability of this model presents significant challenges [114], and in some cases, these funding programs are being replaced by transformative agreements [115]. Some institutions with APC funding programs are now adopting equity-based funding criteria, prioritizing early-career researchers to promote equitable access to publishing opportunities [114,116]. However with hybrid journals, APCs often result in institutions paying both subscription fees (for access) and APCs (for OA publishing) to the same publishers [117,118]. In response, institutions are turning to transformative agreements to shift from subscription-based access with APCs to fully OA publishing models [119–121]. Further, although many researchers support OA in principle, surveys have shown that they believe APCs are too expensive and that the financial burden should not fall on individual authors [117]. Platforms like Google Scholar have mitigated these issues by enhancing discoverability of open versions of articles, listing repository-hosted PDFs alongside publisher versions [122].

The third OA publication subcategory, (c) self-archiving in repositories, was most represented in the dataset. The library activity groups we identified within this subcategory include: (i) building and managing institutional and (ii) multi-institutional repositories, (iii) promoting repository use, and (iv) managing persistent identifiers for scholarly documents. Approximately 57% of studies

described activities related to (i) building and managing Institutional Repositories (IRs). Institutional repositories evolved as an offshoot of digital library services and play a critical role in supporting open access [123–125]. In addition to preserving digital content [126–129], IRs increase the visibility and accessibility of scholarly work [130,131], making research more discoverable to a broader audience [128,132]. Institutional repositories are so prevalent at this point [133] that librarians have advocated for consolidation of IRs into a national repository [134]. Activity group (ii) is closely related to (i) and involves creating/managing shared repositories (*i.e.*, repositories that accept deposits from more than one institution; *e.g.*, disciplinary repositories [135] and public-use repositories like arXiv, which is managed by Cornell University [136]). About 4% of publications mapped to the OA theme described activities within this group. Activities related to (iii) promoting the use of IRs among researchers constituted ~9% of OA mappings; these efforts mainly arise when deposit rates are low [137–142], which limits the comprehensiveness and impact of these platforms. For (iv) persistent identifiers, libraries are likely engaging in this work more extensively than reported. For example, digital object identifiers were introduced in the year 2000 [143]; if we included studies from that timeframe, we would likely see greater engagement with this activity group.

Three library activity groups were identified for the second OA theme category, (2) the use and reuse of OA publications category of the OA theme: (i) supporting the management of authors' rights, including providing guidance on open licensing and copyright (*e.g.*, [144,145]), (ii) providing instructional services in literature review methodology (*e.g.*, [146,147]), and (iii) offering instructional services related to the use of citation management tools (*e.g.*, [148,149]). Aiding authors navigating copyright issues and advocating for open licenses (i) directly facilitates the use and reuse of OA content, enabling others to legally share, build upon, and adapt the work. The instructional activities (ii, iii) mapped to this category promote the use and reuse of OA publications by equipping researchers with the skills to find, critically assess, and synthesize OA resources in their work.

Finally, we identified three library activity groups that mapped to the (3) OA initiatives category of the OA theme, all of which focus on instructional activities, OA-related needs assessments, and OA advocacy. Publications mapping to the OA theme through this category often describe OA advocacy *via* broader scholarly communication efforts, such as establishing faculty learning communities [150,151] and offering instructional programs in scholarly communication [152,153], while also covering open access. Hosting OA-related events is also commonly reported (*e.g.,* for Open Access Week [154] and Public Domain Day [155]).

3.2.2. Open Data

Open Data (OD) refer to data that are freely available for use, reuse, and redistribution [45], and align with the FAIR principles (Findable, Accessible, Interoperable, and Reusable). These principles promote transparency, reproducibility, and collaboration in research [156]. Libraries promote FAIR principles by providing infrastructure and support for data management, offering tools, platforms, and services that enable researchers to manage, store, and share data efficiently [157,158]. The expanded FOSTER taxonomy [17] divides OD into two categories: (1) open research data and (2) open data initiatives. We identified nine library activity groups within these subthemes, mapping a total of 869 publications to OD (

Table 5). The taxonomy describes the first category (open research data) as encompassing activities related to Research Data Management (RDM), FAIR data principles, and protection and preservation of research data. Seven of the nine library activity groups identified for the OD theme map through this category; these include activities related to: (i) data repositories, (ii) RDM instructional services, (iii) persistent identifiers for datasets, (iv) Data Management Plan (DMP) services, (v) data curation, (vi) promoting data sharing and reuse, and (vii) creating and sharing open data.

Approximately 38% of publications were mapped to the OD theme through the (i) data repository activity group. Unlike the OA activity group related to institutional repositories for preserving scholarly documents, we did not require institutions to house their own data repositories for this activity code to be applied. Many institutions that have IRs for scholarly documents cannot accommodate data (*e.g.* [159–161]); based on institutional characteristics and needs, it may not be advantageous or sustainable for these institutions to house these infrastructures. Thus, publications were coded with this activity code if they described activities related to managing data repositories *or* assisting researchers in identifying appropriate external data repositories.

The most frequently reported activity group was (ii) RDM instructional services, with ~46% of publications mapping to the OD theme describing these activities. Activities related to (iii) persistent identifiers were reported less, at ~3% of papers, likely for similar reasons as discussed previously. Approximately 20% of publications mapped to the OD theme described activities related to (iv) providing guidance in the development of DMPs, ~24% described (v) data curation activities (supporting the long-term reuse and accessibility of research data [162,163]), and ~22% described activities related to (vi) promoting the sharing and reuse of data.

The expansion of RDM services has often been driven by policy changes from funding agencies (Section 1.1) that require more robust data management practices [43,164,23]. These shifts require researchers to develop new data competencies, and the responsibility for providing corresponding guidance and instructional services has largely fallen to libraries [165]. However, many libraries also face skill gaps in this area, necessitating professional development and enhanced technical training to meet the growing demands of RDM support effectively [159,166–168]. To meet these challenges, collaborative efforts like the Data Curation Network (DCN) have emerged, pooling resources across institutions to collectively offer data curation services to researchers across a wide range of disciplines [169].

We identified two library activity groups for the second category of the OD theme (OD initiatives); these include: (i) providing GIS services and (ii) conducting RDM-related needs assessments. About 25% of OD-related publications involved GIS services, which have been

valuable for engaging researchers outside STEM disciplines (*e.g.*, humanities researchers, a group that is often overlooked in RDM discussions [170–172]). Additionally, ~28% of the publications described RDM needs assessment activities, which libraries use both to evaluate the demand for RDM services and to assess whether existing services are meeting institutional needs. These assessments take a variety of forms, including traditional strategies such as conducting interviews [173,174], focus groups [175], survey studies [176], and RDM-specific strategies such as analyzing DMPs [177–179] or conducting bibliometric studies to assess researcher data generation and sharing practices [180,181].

A significant challenge in providing RDM services is the growing prevalence of big data [166,182,183]. Researchers across disciplines face varying needs, which are further complicated by departmental policies and increasing data storage demands [182–185]. There are also concerns that the efforts required to fully support big data may inadvertently marginalize researchers working with smaller datasets [186].

3.2.3. Open educational resources

Open Educational Resources (OER) are freely accessible, openly licensed educational materials, such as textbooks, curricula, and teaching tools [187,188]. Open educational resource initiatives often aim to reduce costs of educational materials for both students and educators [189] while improving the accessibility of high-quality learning materials. The rise of OER adoption can be traced back to UNESCO's 2002 Forum on Open Courseware, where the term OER was coined [190]. The expanded FOSTER taxonomy [17] divides OER into two categories, including: (1) OER and e-learning platforms and (2) OER initiatives. We identified eight library activity groups within these categories, mapping a total of 562 publications to the OER theme (Table 6).

Three library activity groups were identified within the first category of the OER theme (OER and e-learning platforms): (i) OER repositories, (ii) promoting the sharing and reuse of OER, and (iii) creating OER content.

Approximately 13% of publications mapped to OER *via* OER repositories (i). While larger institutions tend to utilize Institutional Repositories (IRs) primarily to preserve scholarly work of faculty and graduate students, smaller institutions often use IRs to promote undergraduate student work and to house teaching materials [127,140,142]. Thus, it is possible that many IRs accept OER materials, but smaller institutions report use of IRs for OER more frequently in the literature, reflecting the emphasis on this function within their contexts.

The most frequently reported activity group within the OER theme was (ii) promoting the sharing and reuse of OER. This group includes providing guidance in creating and using OER content, licensing options, curating, and evaluating OER content, and utilizing OER in instructional and outreach roles. Approximately 66% of OER-related publications reported activities within this group. There are multiple reports of initiating or expanding OER programs in response to the COVID-19 pandemic [191–193], and we see evidence of that in Fig. 5, with an increase in OER-related activities between 2020 and 2021, despite an overall decrease in publications. In many cases, libraries played a key role in supporting institutional transitions to online learning during this period, with multiple reports of OER programs expanding through increased collaborations with instructors to move courses online [193,194]. The pandemic also

exacerbated inequities within U.S. educational systems [195,196], prompting some libraries to expand OER efforts to address these disparities [192]. Additional OER promotional activities within this group include collaboratively redesigning courses with instructors to incorporate OER content [197–199] and using OER in library instructional roles; for example, using Wikipedia [200,201], open government materials [202,203], or institutional digital collections [204,205] in literacy instruction. A noted challenge with OER initiatives is achieving instructor buy-in due to concerns about resource quality and the corresponding librarian time investment to curate and evaluate OER materials [206,207]; accessibility concerns of OER materials have also been raised [206]. Lastly, approximately 27% of OER publications reported activities related to library-created OER [208–211].

We mapped four activity groups to the second OER category (OER initiatives); these include: (i) OER funding programs (~25% of publications describing OER activities), (ii) conducting OER-related needs assessments (~12%), and (iii) creating/managing textbook affordability programs (~25%). Funding programs for OER often offer stipends to faculty as an incentive to create educational materials that are then shared *via* open licenses. These programs increasingly emphasize that funded materials must foster DEIA objectives (*e.g.*, [212]), aligning with broader goals of promoting social justice through open education [213–216]. However, these programs are more difficult for institutions to adopt if they do not have established publishing platforms [206]. Additionally, requests for OER funding often exceed available funds [116] and funding programs have been discontinued due to budgetary constraints [217], prompting libraries to explore alternative promotional strategies. With limited OER funding, Cleveland State University used a "gratitude campaign" for OER promotion, which involved recognizing faculty who adopted OER in their courses [218].

Textbook affordability initiatives (iii, ~25% of publications mapped to the OER theme) differ from OER efforts in that they do not necessarily involve the use of openly licensed content. These initiatives often involve library-purchased textbooks to reduce students' financial burdens [219,220]. Many library programs use a blended approach [221,222], combining textbook affordability initiatives with OER efforts, creating a transition area between traditional educational materials and open content.

3.2.4. Open reproducible research

Open Reproducible Research (ORR) involves making research processes, methods, and tools openly available to improve research integrity, reliability, and reproducibility [223,224]. Among other practices, this includes sharing open laboratory notebooks, workflow tools, and research data and code. The expanded FOSTER taxonomy [17] divides ORR into three categories, including: (1) ethics and integrity in research, (2) open and reproducible research, and (3) open and responsible research initiatives. The second category (open and reproducible research) is further divided into four subcategories: (a) open laboratory books, (b) open science workflows, (c) open-source code and software, and (d) reproducibility tests. Twelve library activity groups were identified across the ORR theme categories, resulting in a total of 929 publications mapped to the ORR theme (

Table 7).

For the ethics and integrity in research (1) category, the relevant library activity group focuses on instructional services related to research ethics [225–228]. However, only ~2% of ORR publications were mapped through this group, likely because research ethics instruction is often handled by other institutional departments. Libraries often offer these services in the context of the NIH's Responsible Conduct of Research (RCR) training [229], which has enabled libraries to foster collaborative opportunities with other departments [225–227].

As stated above, the second category of the ORR theme(open and reproducible research) further divides into four subcategories. We identified two activity groups related to the first subcategory, (a) open laboratory books: (i) providing infrastructure and/or training in the use of electronic lab notebooks (ELNs) and (ii) providing support for Research Resource Identifiers (RRIDs). Only ~1% of ORR-related publications reported (i) ELN related activities [230,231]. Low engagement in this area may stem from concerns about data security and the challenge of meeting diverse research needs with a single solution [232]. Research Resource Identifiers (ii) are unique identifiers used to cite research materials and instrumentation and are used to increase reproducibility of studies across laboratories. Only two publications (<1%) reported activities related to RRIDs [233,234], suggesting that these efforts may be managed by other institutional departments or have not yet gained widespread engagement.

Three library activity groups were identified within the (b) open workflows subcategory for the second category of the ORR theme (open and reproducible research), including: (i) providing infrastructure or support in reproducible workflows (including platforms such as Open Science Framework, protocols.io, and *R*-Squared), (ii) providing instructional support in coding and data analysis and visualization, and (iii) hosting hackathons. About 12% of ORR-related publications reported activities related to (i) infrastructure or support, with activities often related to instructional activities or events to promote platforms that enhance reproducibility [235–239]. Offering (ii) instructional services for coding and data analysis and visualization often intersects with the expansion of RDM services [240,241]; about 22% of publications mapped to the ORR theme report activities in this area. Hackathons (iii) are time-bound events that traditionally involve a coding challenge [242,243], but the term is now often used as an umbrella [244]. Library involvement in hackathon-like events, includes traditional hackathons [245,246], edit-a-thons [247,248], data-a-thons [249], make-a-thons [242], and map-a-thons [250,251]; these activities were described in ~4% of publications mapping to the ORR theme. The extent of library involvement in these events often ranges from offering library space to host events [252], using these events as outreach [253], and using hackathons to integrate instructional services [250,254].

Three activity groups were also identified within the (c) open-source software subcategory of the second ORR theme category: (i) utilizing OSS in instructional spaces to promote use and/or using OSS in library operations, (ii) creating or modifying OSS for library operations or scholarly purposes, and (iii) offering guidance regarding OSS creation and corresponding licensing. The first activity group was the most frequently reported, representing ~66% of publications mapped to the ORR theme. Integrating OSS in instructional roles often involves coding instruction in open-source software (*e.g.*, Python, R), frequently following The Carpentries curriculum [255,256]. In library operations, OSS is commonly employed for

discovery layers and repository platforms as cost-effective alternatives to commercial software [257,258]. However, utilizing OSS in library operations often requires technical expertise, and many studies cite this as a barrier for integration (*e.g.*, [258–260]). Approximately 10% of ORR studies described (ii) creating and/or modifying OSS [126,261], often through collaborative cross-disciplinary development teams [262,263]. In contrast, only ~1% of studies described (iii) offering guidance on OSS development. One notable example is an instructional program at Oregon State University, which promotes student engagement in community-developed software [264].

We mapped activities related to carrying out reproducibility studies to the ORR theme through the (d) reproducibility tests subcategory of the second ORR theme category (open and reproducible research). Only nine studies (~1%) reported engaging in these activities. Examples include repeating OA citation advantage studies [265] and studies to identify core disciplinary journals [266]. The motivation for these reproducibility efforts included gaining a deeper understanding of trends over time [265,266].

Two activity groups were identified for the third category of the ORR theme, ORR initiatives. These include (i) providing evidence synthesis services and (ii) conducting needs assessments related to ORR. Evidence synthesis, sometimes referred to as "open synthesis" to reflect its interconnectedness with open science and to promote further transparency in the process [267], involves systematically collecting, analyzing, and integrating findings from multiple studies to generate comprehensive, reliable, and unbiased answers to specific research questions [268]. Approximately 8% of ORR studies reported (i) evidence synthesis services. While these services have traditionally been offered mostly in health science libraries [269], they are expanding to other disciplines [270]. However, evidence synthesis is resource-intensive [271,272], often requiring collaboration among experts across disciplines. Despite the challenges, policymakers, researchers, and practitioners recognize its value in providing reliable, high-quality summaries of research [23]. Many studies have also demonstrated that librarian collaboration in this work significantly enhances the quality of resulting reviews (*e.g.* [273–276]). Only five studies reported (ii) ORR-related needs assessments (~1%) and these tended to focus on discrete elements of ORR (*e.g.*, needs assessments related to electronic lab notebooks [232]).

3.2.5. Open innovation

Open Innovation (OI) often involves sharing knowledge and resources, crowdsourcing ideas, and involving various stakeholders in the innovation process to drive scientific and technological advances. This theme emphasizes cross-organizational and interdisciplinary collaboration [17]. As shown in Table 8, 228 publications were mapped to the OI theme through two library activity groups. The expanded FOSTER taxonomy divides the OI theme into two categories: (1) forms of innovation and (2) open innovation initiatives. We mapped activities related to (i) maintaining spaces for use as innovation hubs to the first category and activities related to (ii) providing support for entrepreneurship and innovation to the second. Approximately 75% of OI-related studies reported activities within the first activity group. Examples of these spaces include makerspaces with resources such as 3D printers [277,278] and Arduino/Raspberry Pi kits [279,280]. However, some libraries have discontinued makerspaces because those needs were being met by other institutional departments [281]. This may explain the relatively lower representation of this theme compared to others. The second activity group—supporting

entrepreneurship and innovation—was represented in ~32% of OI-related studies. These activities often involved instruction in patent searching [282] and market research analysis [283], with many of the efforts led by business librarians (*e.g.*, [284,285]).

3.2.6. Infrastructure and tools

In the expanded FOSTER taxonomy [17], the open infrastructures and tools theme encompasses shared infrastructures (virtual or physical) that support open research practices; thus, most of our identified activity groups could be mapped to this theme. However, such a broad mapping would not clarify the specific contributions libraries are making across open science. In general, the interconnected nature of activities across open science themes complicates classification efforts, as described by Silveira *et al.* [17].

The expanded taxonomy divides this theme into four categories: (1) open code repositories, (2) open collaborative platforms, (3) open science service providers, and (4) digital preservation. To minimize overlap across library activity groups, we attempted to adhere closely to the descriptions provided in the taxonomy's subthemes. This alignment necessitated some deviations from prior reviews. For example, Liu and Liu [19] mapped digital preservation to the OA theme, which is justified given that digital preservation activities often involve digitizing collections and making them publicly available. However, given the explicit definition of digital preservation in this newer taxonomy, we mapped these activities to this theme through the fourth category. Overall, eleven library activity groups were identified over the four taxonomy subthemes, and a total of 1,530 publications were mapped to this theme (Table 9).

Two library activity groups were identified for the (1) open code repositories category. These include (i) utilizing Institutional Repositories (IRs) to house open-source software (OSS) and (ii) providing instructional services on the use of open code repositories (*e.g.*, GitHub). Only four publications described hosting OSS in their IRs (~1% of publications mapping to infrastructure/tools) [286,287]. Approximately 2% of publications mapping to the infrastructure/tools theme described instructional services related to open code repositories. These activities often involve integrating this type of instruction within coding instruction [288,289].

We included two activity groups in the (2) open collaborative platforms category. Again, many library activity groups that were identified could be mapped here; only activity groups that were not addressed elsewhere were included. These include: (i) providing cyberinfrastructure for cloud and/or high-performance computing (including conducting corresponding needs assessments) and (ii) facilitating data collaborations among researchers. Activities related to (i) cyberinfrastructure and high-performance computing services [290–294] are not well represented in the dataset (~3% of publications mapping to the infrastructure/tools theme), likely because these services are often provided by other institutional departments. Libraries sometimes offer these services in collaboration with research computing groups [295] and other institutional departments [293], though in some cases these services are offered by the library independently [294]. The (ii) data collaborations activity group includes formal programs and infrastructures that aim to facilitate the reuse of data and to connect researchers who produce data to other researchers who can assist in data analysis [296–298]. Only nine publications were mapped to

infrastructure/tools through this activity group (~1%), and nearly half of these activities were described by one university (Carnegie Mellon University).

For the third category, (3) open science service providers, we identified three strategic activity groups that reflect the integration of open science practices within library organizational structures. These include (i) professional development, (ii) incorporation of open science into strategic plans, and (iii) outreach efforts explicitly promoting comprehensive open science practices. Offering (i) professional development programs in areas related to open science indicates that libraries are embedding these practices internally through capacity building. Approximately 10% of publications mapping to the infrastructure/tools theme reported such activities, with a variety of emphases (*e.g.*, skill development in digital humanities [299], research data management [164,300–302], and evidence synthesis [303–305]). Libraries also lead many of these efforts, providing instructional services to external institutions [306–309]. For example, the Research Data Management Librarian Academy [309]—a multi-institutional initiative led by Harvard Medical School with funding from Elsevier—developed an online program to enhance librarians' research data management skills. Similarly, Carnegie Mellon University's Open Science Primer [306] is an IMLS-funded project that aims to equip library practitioners to better meet evolving demands of open science. Incorporating open science into strategic frameworks reflects a long-term, organizational commitment to aligning library operations with open science principles. About 5% of publications relating to tools/infrastructure described such efforts [281,292]. Lastly, (iii) promoting comprehensive open practices through outreach shows an organizational commitment to external engagement with open science. Although only ~1% of publications in this theme mentioned these efforts; they focus on events, programs, and outreach task forces dedicated to advancing open science [281,310].

Four activity groups were identified within the (4) digital preservation category: (i) digital preservation efforts, (ii) needs assessments for digital preservation, (iii) facilitating discovery of OA materials, and (iv) supporting digital projects (focusing especially on digital humanities). Digitization efforts (i) were described by ~65% of publications mapped to this theme (*e.g.*, [311,312]), making it the most highly represented activity group within infrastructure/tools. The primary challenges in these efforts centered on metadata creation and maintenance [313–315]. Needs assessments for digital preservation efforts (ii) [316,317] were far less common (~1% of this theme's publications), likely because digitization is a core library service, only recently framed within the context of open science. Approximately 23% of publications mapped to infrastructure/tools described activities aimed at (iii) facilitating the discovery of open access materials. These efforts include improving metadata to enhance discoverability [318–321], incorporating OA tools within discovery layers (e.g., Open Access Button and Unpaywall [322,323]), and creative approaches such as linking digital collections to Wikipedia pages [324,325] or sharing videos stored in repositories on YouTube [326] to increase visibility and discoverability. Support for digital humanities projects (iv) was described in ~20% of the publications mapped to this theme. These activities ranged from providing guidance to researchers to librarians fully collaborating with external researchers on projects [171,327–329].

3.2.7. Open evaluation

In open science, open evaluation refers to transparent and inclusive methods for evaluating scholarly work, such as open peer review and alternative metrics that capture research impact

beyond traditional citation counts. Altmetrics measure the reach of scholarly work through online engagement, news coverage, policy documents, and other digital platforms [330]. The expanded FOSTER taxonomy [17] divides this theme into three categories: (1) open peer review, (2) open and responsible metrics, and (3) open evaluation initiatives. A total of four library activity groups were identified across these categories, and a total of 208 publications were mapped to this theme (Table 10).

For (1) open peer review, we included studies that described librarian advocacy [327,328]; only two publications described these activities. Two activity groups were included within the second category (open and responsible metrics); these included (i) providing bibliometric and altmetric services to researchers and (ii) promoting the use of holistic measures for assessing scholarly output. About 69% of publications within this theme described bibliometric services, including both altmetric [331,332] and traditional bibliometric [333,334] services. About 15% of the publications focused on promoting holistic measures of scholarly output. A notable example comes from Indiana University–Purdue University Indianapolis (IUPUI), where, with the help of librarian advocacy, the institution's promotion and tenure process was changed to reward open scholarship [335]. Other initiatives included faculty surveys on scholarly metrics [336] and the integration of altmetrics into institutional repositories and scholar profiles managed by libraries [337,338]. Lastly, we mapped activities related to open assessment of library-provided services to (3) open evaluation initiatives (~25% of publications within this theme). Reported activities within this group included integrating dashboards with library statistics into websites and repository platforms [339–341] and publishing data analysis workflows used for library assessments [342].

3.2.8. Open science policies and mandates

The expanded FOSTER taxonomy [17] includes policies and frameworks developed by institutions, governments, and organizations to support open science practices under the open science policies theme. Three library activity groups were identified within this theme: (i) helping researchers understand open science requirements of funding agencies, (ii) tracking compliance with data management plans (DMPs), and (iii) participating in the development of institutional open science policies. A total of 188 publications were mapped to this theme (Table 11). Approximately 28% of these publications described efforts to (i) help researchers understand funding agency requirements (*e.g.*, [43,343]), while ~4% described activities related to (ii) tracking compliance with data management plans (*e.g.*, [344]).

In 2008, Harvard University became the first U.S. academic institution to adopt a self-archiving policy [48]. One year later, University of Kansas became the first public university to do so [345]. Institutional open access policies are often used to address low rates of deposits in IRs [50,129], and libraries are often involved in the (iii) policy creation process and also charged with implementation [49,50,345–347]. Some OA policies are mandatory [120], while others encourage compliance while allowing opt-outs [48]. A significant challenge in policy adoption is faculty buy-in [348]. In some cases, institutions first adopt open access resolutions, which may later evolve into formal policies [49,345].

In addition to OA policies, libraries also engage with policies related to digital preservation [139,264], data management and sharing [349–353], open education policies (often driven by

textbook affordability initiatives [354,355]), and open-source software development policies [356]. Recently, there was also a call for librarian involvement with AI-related policy development [357]. While libraries contribute to many of these policy areas, the literature focuses overwhelmingly on OA policies, which account for ~78% of publications in this activity group.

3.2.9. Citizen science

Citizen science, or 'participatory research,' involves public participation in research through activities such as contributing data, analyzing results, or collaborating on research design. Participatory research fosters community engagement in the research process and democratizes knowledge production by including non-professional researchers [358]. This theme was not well-represented in the literature, with only 11 publications describing citizen science activities. As a result, all corresponding activities were mapped through a single activity group (Table 12). The University of Oklahoma contributed two studies to this theme: a soil collection project, where the library hosted the research datasets on their IR [359], and a crowdsourced transcription project focused on Civil War manuscripts [360]. Additionally, Indiana University Bloomington held a community-oriented map-a-thon [251].

3.3. Comprehensive Practices in Open Science

Identifying the prevalence of thematic overlaps within publications can highlight transitions from supporting isolated aspects of open science to providing comprehensive services that span the entire research lifecycle. Several case studies illustrate these integrated, wrap-around services. Florida State University [281], City University of New York [361], and Carnegie Mellon University [296] offer excellent examples, where open science initiatives are explicitly aligned with institutional support models. To examine the prevalence of such comprehensive services, we examined the existence of open science terminology within publications and identified overlapping themes across them. These results are presented in the following.

3.3.1. Open science terminology

Tracking the frequency of key terms over time helps identify trends, shifts in research focus, and evolving concepts within a field [362,363]. We used text analysis to map the usage of open science terminology across study years and to explore keyword co-occurrence. The heatmap in Fig. 6 shows the frequency of selected keywords over time (as identified from full-text searches across articles in the dataset). The *y*-axis lists the keywords we searched for. Except for Overarching, "umbrella" terms that describe open practices ('open science,' 'open research,' 'open knowledge,' and 'open scholarship') are shown individually and collectively (by grouping all open terms into the "Open Umbrella Terms" category). For terms that focus on specific themes, similar keywords are grouped to prevent over- or under-identification. Specifically, the 'e-science' category contains the keywords 'electronic science,' 'electronic research,' and 'e-research,' the 'open data' category includes 'open data,' 'data sharing,' and 'data reuse,' and the 'research data management' category includes 'research data' and 'data management.' Each cell in Fig. 6 represents the number of papers containing the keyword each year, normalized by publications in that year to account for annual fluctuations in publication counts.

The term, 'open science' was found in only one publication from the first year of this study (2010) but grew to ~13% of publications by 2022. The terms, 'open knowledge,' 'open research,' and

‘open scholarship’ are often used interchangeably with ‘open science,’ but are distinguished here to analyze the frequency of the individual terms. There is a growing argument for shifting towards these alternative terms to promote inclusivity across various academic disciplines[11,364]. Over the study period, the term, ‘open science’ is recorded in ~6% of publications (218 total), ‘open research’ in ~3% (124 total), ‘open scholarship’ in ~2% (72 total), and ‘open knowledge’ in less than 1% of publications (23 total), with ‘open science’ remaining the most frequently used descriptor of open practices, followed by ‘open research.’ When considered collectively, umbrella terms appeared in ~1% of publications in 2010. By 2023, this proportion increases to ~20%, suggesting wider adoption of these terms to describe open practices and potentially reflecting growing acceptance of the concepts they represent within academic discourse.

Other terms, such as ‘scholarly communication’ and ‘e-science’ reflect concepts that overlap with open practices. Scholarly communication includes the creation, evaluation, dissemination, and preservation of academic research [365]. The term, ‘e-science’ describes data-intensive and networked research [366,367]. From 2010-2016, ‘e-science’ appeared more frequently than ‘open science,’ but this trend reversed starting in 2017.

For terms related to specific open science themes, ‘open access’ is the most used term (across all keywords investigated), with 30-48% of publications using that term over the study period. The research data management keyword category and ‘open source’ are recorded more frequently than the more comprehensive open practice terms. Notably, terms from the research data management keyword category were used more frequently than those within the open data category across all years. The usage of ‘open education’ shows an increase over the years 2019-2021, aligning with findings reported in Section 3.2.3 that OER-related studies increased in prevalence over the COVID-19 pandemic.

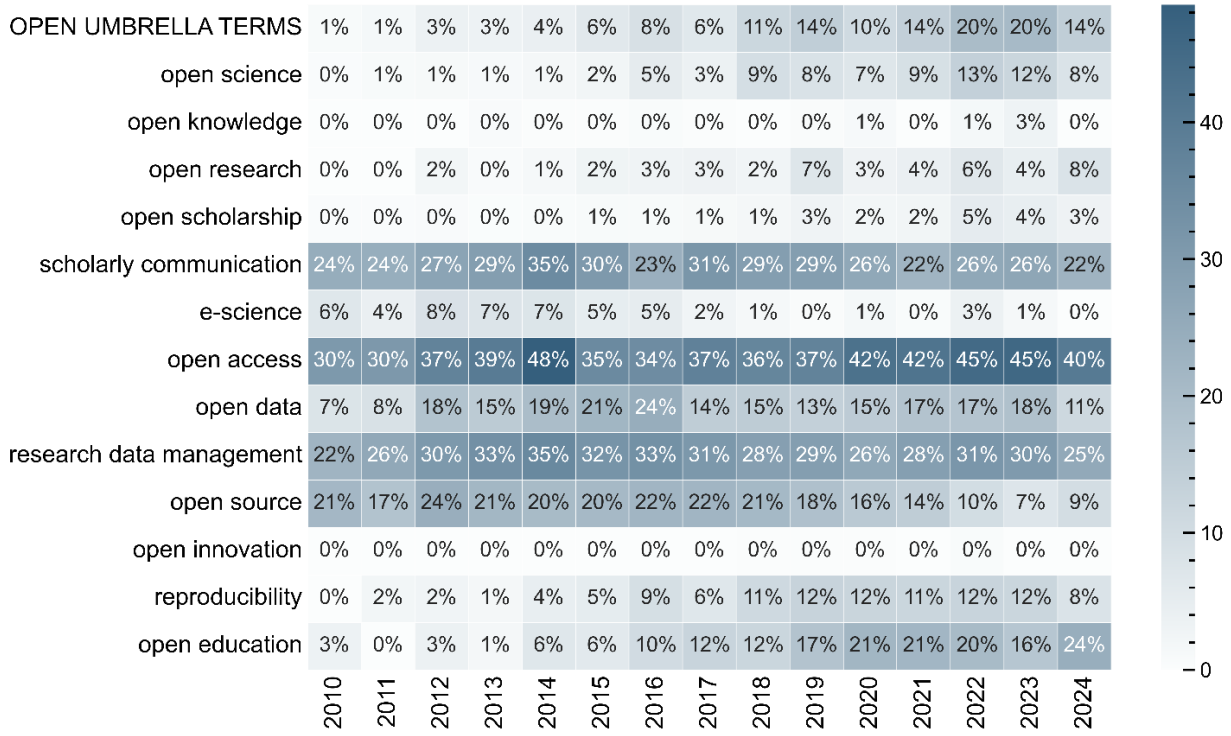

Fig. 6. Heat map showing the frequency of keywords over time as identified from a full-text keyword search across publications in the dataset. Each cell represents the number of publications containing a given keyword each year, with darker shades indicating higher relative frequencies. The *y*-axis lists keywords, and the *x*-axis represents the publication year of the articles. Umbrella terms for open practices (open science, open knowledge, open research, and open scholarship) are reported individually and collectively (within the "Open Umbrella Terms" category). The keyword category 'e-science' includes 'electronic science', 'electronic research', and 'e-research', 'open data' includes 'data sharing' and 'data reuse', and 'research data management' includes 'research data' and 'data management.

Fig. 7 shows a heatmap of keyword cooccurrence across publications (*i.e.*, the frequency for which keywords are used together within the same publications). Each cell represents the number of papers that mention both terms on the *x*- and *y*-axes; darker shades indicate higher frequency of co-occurrence. Keyword co-occurrence analyses can help identify relationships between different facets of open science and related concepts. For example, the relatively dense intersections around terms like 'open access,' 'research data management,' 'open data,' 'scholarly communication,' and the umbrella terms for open practices suggest that these themes often appear together in discussions, reflecting a more comprehensive approach to open practices than what might be suggested based on the keyword mapping of overarching open practice terms over time. Similarly, terms with fewer intersections—such as 'open innovation' and 'open education' highlight areas where the literature might be more specialized or less integrated with broader open science discussions.

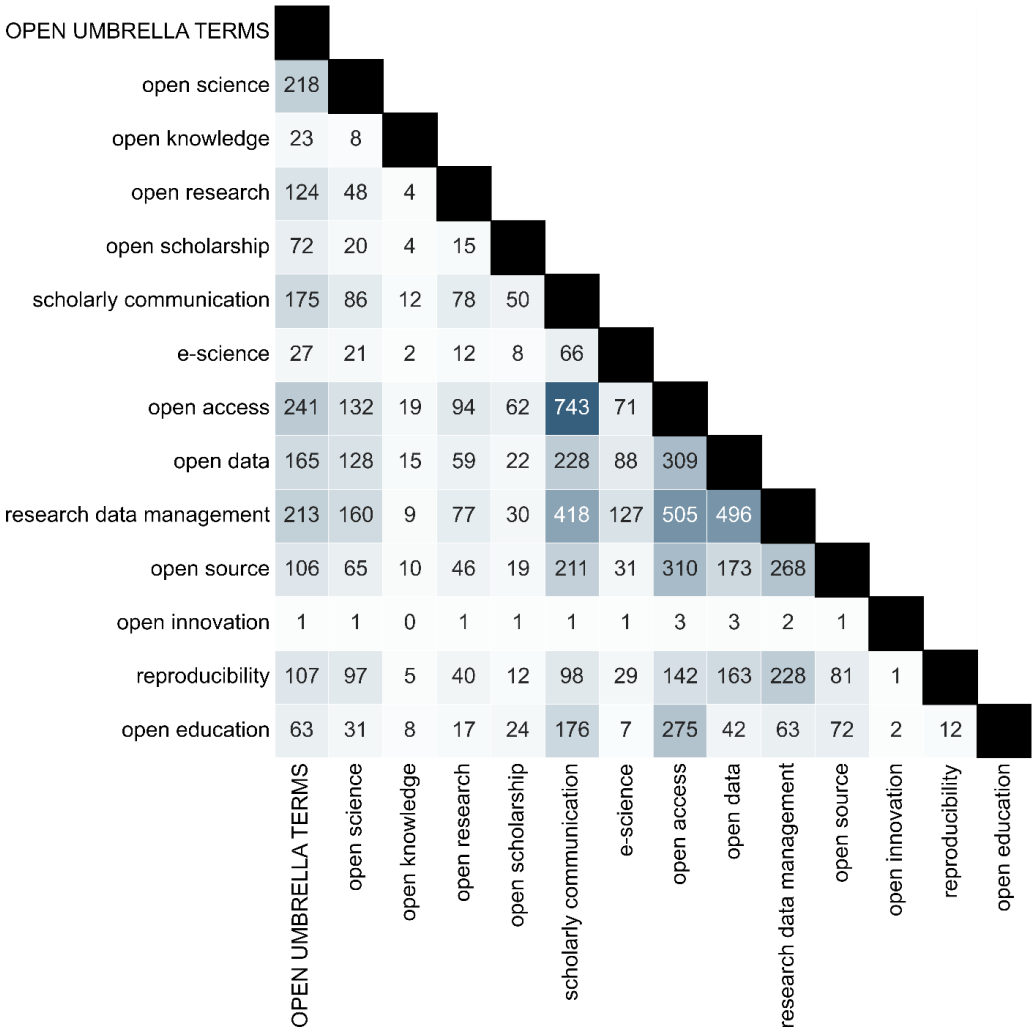

Fig. 7. Heat map showing the co-occurrence of keywords identified from a full-text keyword search across articles in the dataset. Each cell represents the number of papers a pair of keywords appeared together with, with darker shades indicating higher relative frequencies. The diagonal cells are colored black to denote self-pairing of keywords, excluded from the scaling. Only the lower triangle of the matrix is shown as the matrix is symmetrical. Umbrella terms for open practices (open science, open knowledge, open research, and open scholarship) are reported individually and collectively (within the "Open Umbrella Terms" category). The keyword category 'e-science' includes 'electronic science', 'electronic research', and 'e-research', 'open data' includes 'data sharing' and 'data reuse', and 'research data management' includes 'research data', 'data management'.

3.3.2. Thematic overlap and comprehensive open science practices

A high prevalence of publications that report activities across multiple open science themes may reflect broader engagement with open science within academic libraries. For example, a study that discusses activities in open access (OA), open data (OD), and open educational resources (OER) suggests a convergence of efforts. This may reflect ongoing efforts to remove departmental silos within libraries [368] and/or broader institutional commitments to open practices. Identifying the highest overlapping themes can also highlight emerging trends that reflect a more unified approach to open practices within libraries.

As introduced earlier, Table 3 provides the number of publications mapped to each of the themes identified in the expanded FOSTER taxonomy [17]. The single theme publication column provides the proportion of publications within that theme that mapped only to that theme. Giustini *et al*. [18] reported that most of the studies they mapped to the FOSTER taxonomy were assigned between one and four open science theme codes, with most receiving one. Here, about 50% of our studies mapped to a single theme, and ~50% mapped to at least two themes (Table 3). Nine themes were mapped here, whereas Giustini *et al*. mapped seven; thus, our mapping increases the likelihood that a single study is mapped to more than one theme. Of the 3,752 studies in this dataset, 1,862 were mapped to a single open science theme and 1,890 were mapped to at least two themes. Approximately ~17% of publications mapped to at least three themes, ~4% to four, ~1% to five, and nine (<1%) and one publication (<1%) mapped to six and seven themes, respectively. No publications mapped to more than seven themes.

The chord diagram in Fig. 8 offers a visualization of the thematic overlaps within publications. Excluding citizen science (where all eleven publications in the dataset map to more than one theme), publications mapped to the open policies theme show the greatest proportion of overlap with other themes (~94% of publications map to two or more themes). This is largely because publications that describe activities within this theme often do so in the context of describing research and instructional support services more generally (*e.g.*, [43,369,370]).

Open Reproducible Research (ORR) shows the second highest thematic overlap, with ~83% of publications mapping to at least two themes. The greatest thematic overlaps are observed for open access (OA, ~51% of ORR publications), infrastructure and tools (~40%), and open data (OD, ~34%). Approximately 66% of publications that map to ORR report the use of open-source software (OSS) in library operations or instructional services, and the majority of ORR publications map to OA, OD, and infrastructure/tools based on how they report their engagement with OSS. For example, use of open-source repository platforms can intersect with OA, OD, and/or infrastructure/tools (for infrastructure/tools, *via* digitization efforts, which are often made publicly available through IRs). Also, institutions reporting instructional services in data analysis, visualization and/or coding using OSS often report these activities alongside instructional services in RDM (*e.g.*, [371,372]). For the OD theme, ~81% of publications mapped to at least two themes, with the greatest overlaps between OD and OA (~50%) and OD and ORR (~36%). Publications within the OD theme reporting research data services (OD) often mention the use of institutional repositories for data (OD) and scholarly documents (OA).

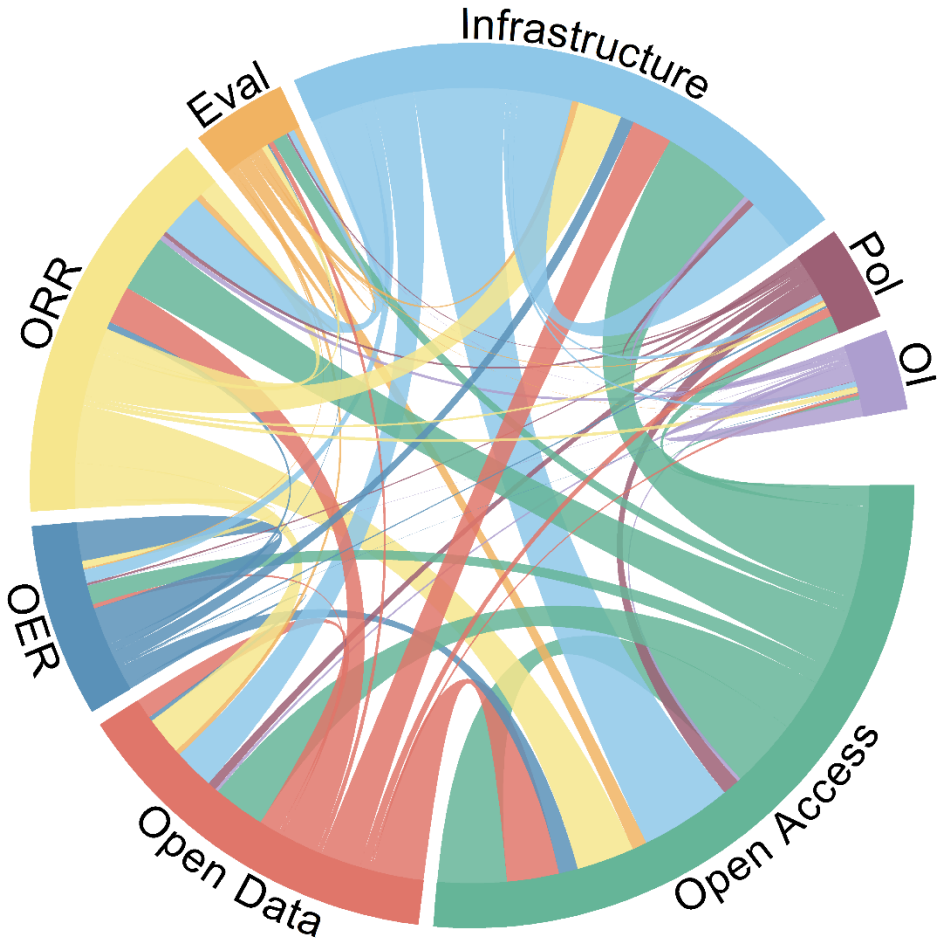

Fig. 8. Chord diagram showing thematic overlap among publications; themes include: Open Access (OA), Open Data (OD), Open Educational Resources (OER), Open Reproducible Research (ORR), Open Innovation (OI), Open and responsible evaluation of science (Eval), open science policy, declarations, and guidelines (Pol), and open science infrastructure and tools (Infrastructure).

The themes with the lowest overlap are Open Innovation (OI) and Open Educational Resources (OER), which may reflect more independent or specialized efforts in these areas, as suggested by the keyword co-occurrence analysis in the previous section. There are examples in the literature demonstrating creative ways to integrate OER across multiple themes. For example, the University of Nevada, Reno incorporated Wikipedia (an OER) into literacy instruction for an undergraduate honors course. They further connected this effort to ORR by having students conduct literature reviews to edit Wikipedia articles and register their projects on Open Science Framework [373].

4. DISCUSSION

This study aimed to explore the activities, strategies, and terminology used by U.S. academic libraries in their engagement with open science. Specifically, we sought to answer two key questions: (i) To what extent have academic libraries shifted from supporting individual components of open science (e.g., open access, open data, open educational resources) to offering comprehensive services throughout the research lifecycle? (ii) What terminology do libraries use to describe their efforts in this area? To identify relevant literature, we conducted a

broad search using traditional bibliographic databases and supplemental sources. We used inclusive search terms to capture intersections between core library services and open science activities, recognizing that not all relevant initiatives are explicitly labeled as "open science." This process yielded 3,752 publications that met our inclusion criteria. A preliminary review of the included studies allowed us to group commonly reported activities into clusters, which were then mapped to the expanded FOSTER taxonomy, adapting the taxonomy to reflect the specific context of academic libraries. Each publication was subsequently coded according to these activity groups, aligning them with the relevant themes from the FOSTER taxonomy. We conducted a theme-level analysis to describe library engagement in each area and performed an overlap analysis to examine shifts towards more comprehensive practices. Finally, we used text analysis to identify the specific terminology libraries employ when discussing open science-related activities.

We found that U.S. academic libraries are actively engaged in a wide range of open practices, spanning multiple dimensions of the open science paradigm. Through instructional services, infrastructural support, and advocacy efforts, libraries play a pivotal role in building capacity for our collective engagement in open science. In their instructional roles, libraries offer workshops on data management, coding, open workflows, and scholarly communication, while integrating open-source tools and guiding the use of open licenses. Their infrastructural efforts include managing repositories, offering publishing services, and supporting collaborative research platforms for sharing data, code, and workflows. In advocacy, libraries conduct outreach, promote holistic assessments of research impact, and advance policies that foster open practices. Libraries also contribute to open science-related scholarship through independent and collaborative research. As the role of libraries expands, they must address key challenges, including infrastructural sustainability and faculty and staff capacity building to support their evolving efforts in open practices. One of the key challenges is the need for ongoing professional development to keep pace with rapid technological advancements.

4.1. Opportunities and Challenges

Commonly reported challenges by libraries engaging in open science activities include budgetary constraints (*e.g.*, [161,374,375]), staffing shortages and turnover (*e.g.*, [159,313,376]), and time constraints (*e.g.*, [314,344,377]). Challenges associated with getting buy-in from researchers [43,184,378–381] and institutions [43,184], as well as challenges associated with outreach (or institutional awareness of library services) [182,378,382], and differing needs among researchers making one-size-fits-all approaches impossible [383–385] were also commonly discussed. However, the most pressing challenge reported across all themes of open science activities includes a lack of technical expertise among library staff [167,314,375].

Studies that investigate U.S. academic librarian confidence have shown that the rate of "impostor syndrome" (persistent self-doubt among high-achieving individuals [386]) is quite high, with the majority of librarians reporting symptoms [387,388]. Librarians report that they have had to become data scientists and data curators by necessity [166], they have too many responsibilities [388], and their preparatory education has insufficiently prepared them for their current roles [387,388]. Institutional professional development programs aim to address knowledge gaps and build confidence [299,389]. However, as research needs and corresponding responsibilities of librarians continue to evolve, ongoing professional development opportunities will remain imperative.

While U.S. academic libraries are engaged in activities associated with each of the open science themes described by Silveira *et al*. [17], the level of engagement varies across themes. For example, we found only eleven studies that described engagement with citizen science. While these activities are likely underreported in the literature relative to actual practice, relative to other themes, it appears to have the least emphasis. Giustini *et al*. [18] reported similar findings. Chiu and Chen [390] conducted a study examining LibGuides of U.S. academic institutions classified as R1 and found similarly low engagement (~8% of R1 institutions having a LibGuide on citizen science). They provide recommendations for libraries seeking grant funding to support this work.

Evidence synthesis services appear to be an emerging trend, with ~62% of studies reporting these activities having been published from 2019 forward (despite an ~41% decrease in included publications over this period, Fig. 5). As the volume of published research continues to grow, high quality reviews are becoming increasingly important [391], and librarian-involvement in these reviews has been repeatedly shown to increase the corresponding quality (*e.g.* [273–276]). Synthesizing evidence across multiple studies (*e.g*., *via* scoping/systematic reviews or meta-analyses) can deepen our understanding of research trends, identify gaps in the literature [391], and, for meta-analyses, increase statistical power [392]. This approach also helps identify reproducibility issues by assessing consistency across different studies [393,394] and supports evidence-based decision-making in the domains impacted by the research [395,396]. While offering these services is resource-intensive, they also provide opportunities for high quality research collaborations across institutional departments [397–399].

While we found that many libraries are working to advance the United Nations Sustainable Development Goals (SDGs) [82], we found limited work that shows an explicit connection between SDGs and open science activities. San Diego State University provides an exception [400]; they explicitly connect their work to SDGs by integrating SDGs into their strategic plan and have developed initiatives and partnerships that work to advance these goals. The library analyzed their current practices, mapping them to SDGs, and identified areas where they could further promote resource sharing and equitable access. They further developed a marketing plan to raise visibility for these efforts. This work may provide a good example for institutions looking to more explicitly integrate SDGs into their operations.

Libraries often engage in activities that promote open science without labeling it as such. This is because many library services have always aligned with principles of open science. For example, creating and sharing LibGuides could be considered open educational resources. While library workshops are typically tailored to their institution's population, they are also often offered to the broader public. By recognizing these activities as components of open science, libraries can better highlight their role in promoting open and inclusive research practices.

4.2. Study Limitations and Future Directions

This work has several limitations. First, as noted in Section 2.5, we deviated from systematic review protocol in that we did not use two screeners throughout, and a single person carried out article coding. Relying on a single reviewer can increase the likelihood of bias in screening, coding, and analysis [76]. While we attempted to classify library activities into clearly defined categories,

some subjectivity is inherent in assigning activity codes; this bias may have been reduced by employing two coders and assessing their interrater reliability [401]. Additionally, our coding schema did not account for the quality or depth of engagement in a given activity group; it merely acted as a binary indicator that an activity within that group was reported. Similarly, while thematic overlap within publications suggests a convergence to comprehensive practices in open science, it does not indicate the effectiveness or sustainability of the initiatives described.

We relied exclusively on published literature to assess library engagement in open science activities; as not all activities are reported this way, our analysis likely underestimates the extent of library involvement in open science. Moreover, external pressures, resource limitation, or institutional priorities may shape publication patterns—an assessment of these issues is not present in our analysis. Assessments that go beyond published literature (*e.g.*, website analysis, surveys) are necessary to further clarify the magnitude of U.S. academic library engagement in open science initiatives. Ongoing assessments are essential for tracking the evolving role of U.S. academic libraries in promoting open science and for guiding corresponding assessment practices. Automation methods and "living reviews" [402] may offer more efficient means for ensuring our assessments remain comprehensive and current. However, a significant challenge in that pursuit is the lack of standardized terminology related to open science activities. Adopting standardized terms would better ensure that reports of these activities are located and integrated.

CONCLUSIONS

This study investigated the engagement of U.S. academic libraries in open science by analyzing activities, strategies, and terminology described and employed in the literature. A total of 3,752 publications were analyzed. We found that U.S. academic libraries are actively engaged in range of open science activities that span the research lifecycle, primarily focusing on providing instructional services, infrastructure development, and advocacy to advance open practices. Thematic overlap analysis showed that ~50% of publications report activities across multiple themes of open science (*e.g.*, open access, open data, open educational resources), suggesting a shift toward more integrated discussions and practices. Terminology analysis showed that while umbrella terms like, "open science" and "open research" are increasingly used, libraries often frame their activities under more familiar terms, such as "open access" and "scholarly communication." The most frequently reported challenges for carrying out this work include budget constraints, staffing shortages, and technical skills gaps. As research needs continue to evolve, finding sustainable ways to provide services and ensuring ongoing professional development opportunities are available to librarians will remain crucial for supporting and advancing open practices.

CRediT authorship contribution statement

Emily Bongiovanni: Conceptualization, Writing - Review & Editing, Funding acquisition. **Melanie Gainey**: Conceptualization, Methodology, Writing - Review & Editing. **Chenyue Jiao**: Investigation, Writing - Review & Editing. **Kristen Scotti**: Methodology, Investigation, Formal analysis, Software, Visualization, Writing - Original Draft, Writing - Review & Editing. **Emma Slayton**: Conceptualization, Visualization, Writing - Review & Editing.

Data availability

Data and code used in this work is available on our OSF project page (https://osf.io/pv7k2/), except for data files containing extracted text from article PDFs (described in Section 2.6), which

are not included due to copyright and licensing restrictions (the code used to extract text from PDFs is available).

Funding
This work is supported by a Laura Bush 21st Century Librarian Program grant through the Institute of Museum and Library Services (IMLS Grant No. RE-254818-OLS-23).

ACKNOWLEDGEMENTS

The authors thank Sarah Young (Carnegie Mellon University Libraries) for numerous useful discussions and helpful insights regarding review methodologies. The authors also thank the rest of the Open Science Primer IMLS team (Chasz Griego, Lauren Herckis, Lencia Beltran, Nicky Agate, Sabrina Brown, and Thomas Hughes) for sharing feedback and helpful insights throughout this work.

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SUPPLEMENTAL

Table S 1. Search queries

Database	Query	Search date
WOS Core Collection	(TS=((("research librar*" OR "academic librar*" OR "university librar*" or "college librar*") AND ("open science" OR "science 2.0" OR "open research" OR "open scholarship" OR "open knowledge" OR "e-research" OR "e research" OR "electronic research" OR "e-science" OR "e science" OR "electronic science" OR "e-scholarship" OR "e scholarship" OR "electronic scholarship" OR "open access" OR "open-access" OR "scholarly communication" OR "publish*" OR "repositor*" OR "ETD" OR "electronic theses and dissertations" OR open NEAR/1 data OR "data sharing" OR "data manage*" OR "FAIR" OR "metadata" OR "data reuse" OR "big data" OR "data librar*" OR "data service" OR "data visualization" OR "data curation" OR "cloud comput*" OR "cyberinfrastructure" OR "cyber infrastructure" OR "open education*" OR "OER" OR "open text*" OR "alt*text" OR "textbook afford*" OR "citizen science" OR "open assessment" OR "open metric" OR "alt*metric" OR "bibliometric" OR "open source" OR "collaborati*" OR "open reproducible" OR "reproducible research" OR "transparent research" OR "open workflow" OR "geographic Information Science" OR "GIS" OR "digital humanities" OR "digital scholarship" OR "archives" OR "digitization" OR "innovation" OR "makerspace" OR "maker space" OR "creative commons" OR "research commons" OR "information commons" OR "evidence synthesis" OR "knowledge synthesis" OR "data synthesis" OR "systematic review" OR "research synthesis" OR "review service" OR "research service" OR "professional develop*" OR "training" OR "needs assessment" OR "focus group" OR "learning communit*" OR "communit* of practice" OR "workshop" OR "literacy" OR "embedded" OR "instruction" OR "teach" OR "sustainable" OR "SDG" OR diversity NEAR/1 equity OR "DEI" OR "DEIA" OR "accessibil*")))) AND LA=(English) and USA (Countries/Regions) Refinements: FY2010-present	5/6/2024
Scopus	TITLE-ABS-KEY(("open science" OR "science 2.0" OR "open research" OR "open scholarship" OR "open knowledge" OR "e-research" OR "e research" OR "electronic research" OR "e-science" OR "e science" OR "electronic science" OR "e-scholarship" OR "e scholarship" OR "electronic scholarship" OR "open access" OR "open-access" OR "scholarly communication" OR "publish*" OR "repositor*" OR "ETD" OR "electronic theses and dissertations" OR (open pre/2 data) OR "data sharing" OR "data manage*" OR "FAIR" OR "metadata" OR "data reuse" OR "big data" OR "data librar*" OR "data service" OR "data visualization" OR "data curation" OR "cloud comput*" OR "cyberinfrastructure" OR "cyber infrastructure" OR "open education*" OR "OER" OR "open text*" OR "alt*text" OR "textbook afford*" OR "citizen science" OR "open assessment" OR "open metric" OR "alt*metric" OR "bibliometric" OR "open source" OR "collaborati*" OR "open reproducible" OR "reproducible research" OR "transparent research" OR "open workflow" OR "geographic Information Science" OR "GIS" OR "digital humanities" OR "digital scholarship" OR "archives" OR "digitization" OR "innovation" OR "makerspace" OR "maker space" OR "creative commons" OR "research commons" OR "information commons" OR "evidence synthesis" OR "knowledge synthesis" OR "data synthesis" OR "systematic review" OR "research synthesis" OR "review service" OR "research service" OR "professional develop*" OR "training" OR "needs assessment" OR "focus group" OR "learning communit*" OR "communit* of practice" OR "workshop" OR "literacy" OR "embedded" OR "instruction" OR "teach" OR "sustainable" OR "SDG" OR (diversity w/2 equity) OR "DEI" OR "DEIA" OR "accessibil*") AND ("research librar*" OR "academic librar*" OR "university librar*" or "college librar*")) AND PUBYEAR > 2009 AND PUBYEAR < 2025 AND (LIMIT-TO (AFFILCOUNTRY,"United States")) AND (LIMIT-TO (LANGUAGE,"English"))	5/6/2024
LISTA	TI ((("open science" OR "science 2.0" OR "open research" OR "open scholarship" OR "open knowledge" OR "e-research" OR "e research" OR "electronic research" OR "e-science" OR "e science" OR "electronic science" OR "e-scholarship" OR "e scholarship" OR "electronic scholarship" OR "open access" OR "open-access" OR "scholarly communication" OR "publish*" OR "repositor*" OR "ETD" OR "electronic theses and dissertations" OR (open N2 data) OR "data sharing" OR "data manage*" OR "FAIR" OR "metadata" OR "data reuse" OR "big data" OR "data librar*" OR "data service" OR "data visualization" OR "data curation" OR "cloud comput*" OR	5/6/2024

Database	Query	Search date
	"cyberinfrastructure" OR "cyber infrastructure" OR "open education*" OR "OER" OR "open text*" OR "alt*text" OR "textbook afford*" OR "citizen science" OR "open assessment" OR "open metric" OR "alt*metric" OR "bibliometric" OR "open source" OR "collaborati*" OR "open reproducible" OR "reproducible research" OR "transparent research" OR "open workflow" OR "geographic Information Science" OR "GIS" OR "digital humanities" OR "digital scholarship" OR "archives" OR "digitization" OR "innovation" OR "makerspace" OR "maker space" OR "creative commons" OR "research commons" OR "information commons" OR "evidence synthesis" OR "knowledge synthesis" OR "data synthesis" OR "systematic review" OR "research synthesis" OR "review service" OR "research service" OR "professional develop*" OR "training" OR "needs assessment" OR "focus group" OR "learning communit*" OR "communit* of practice" OR "workshop" OR "literacy" OR "embedded" OR "instruction" OR "teach" OR "sustainable" OR "SDG" OR (diversity N2 equity) OR "DEI" OR "DEIA" OR "accessibil*") AND ("research librar*" OR "academic librar*" OR "university librar*" or "college librar*"))) OR AB ((("open science" OR "science 2.0" OR "open research" OR "open scholarship" OR "open knowledge" OR "e-research" OR "e research" OR "electronic research" OR "e-science" OR "e science" OR "electronic science" OR "e-scholarship" OR "e scholarship" OR "electronic scholarship" OR "open access" OR "open-access" OR "scholarly communication" OR "publish*" OR "repositor*" OR "ETD" OR "electronic theses and dissertations" OR (open N2 data) OR "data sharing" OR "data manage*" OR "FAIR" OR "metadata" OR "data reuse" OR "big data" OR "data librar*" OR "data service" OR "data visualization" OR "data curation" OR "cloud comput*" OR "cyberinfrastructure" OR "cyber infrastructure" OR "open education*" OR "OER" OR "open text*" OR "alt*text" OR "textbook afford*" OR "citizen science" OR "open assessment" OR "open metric" OR "alt*metric" OR "bibliometric" OR "open source" OR "collaborati*" OR "open reproducible" OR "reproducible research" OR "transparent research" OR "open workflow" OR "geographic Information Science" OR "GIS" OR "digital humanities" OR "digital scholarship" OR "archives" OR "digitization" OR "innovation" OR "makerspace" OR "maker space" OR "creative commons" OR "research commons" OR "information commons" OR "evidence synthesis" OR "knowledge synthesis" OR "data synthesis" OR "systematic review" OR "research synthesis" OR "review service" OR "research service" OR "professional develop*" OR "training" OR "needs assessment" OR "focus group" OR "learning communit*" OR "communit* of practice" OR "workshop" OR "literacy" OR "embedded" OR "instruction" OR "teach" OR "sustainable" OR "SDG" OR (diversity N2 equity) OR "DEI" OR "DEIA" OR "accessibil*") AND ("research librar*" OR "academic librar*" OR "university librar*" or "college librar*"))) OR KW ((("open science" OR "science 2.0" OR "open research" OR "open scholarship" OR "open knowledge" OR "e-research" OR "e research" OR "electronic research" OR "e-science" OR "e science" OR "electronic science" OR "e-scholarship" OR "e scholarship" OR "electronic scholarship" OR "open access" OR "open-access" OR "scholarly communication" OR "publish*" OR "repositor*" OR "ETD" OR "electronic theses and dissertations" OR (open N2 data) OR "data sharing" OR "data manage*" OR "FAIR" OR "metadata" OR "data reuse" OR "big data" OR "data librar*" OR "data service" OR "data visualization" OR "data curation" OR "cloud comput*" OR "cyberinfrastructure" OR "cyber infrastructure" OR "open education*" OR "OER" OR "open text*" OR "alt*text" OR "textbook afford*" OR "citizen science" OR "open assessment" OR "open metric" OR "alt*metric" OR "bibliometric" OR "open source" OR "collaborati*" OR "open reproducible" OR "reproducible research" OR "transparent research" OR "open workflow" OR "geographic Information Science" OR "GIS" OR "digital humanities" OR "digital scholarship" OR "archives" OR "digitization" OR "innovation" OR "makerspace" OR "maker space" OR "creative commons" OR "research commons" OR "information commons" OR "evidence synthesis" OR "knowledge synthesis" OR "data synthesis" OR "systematic review" OR "research synthesis" OR "review service" OR "research service" OR "professional develop*" OR "training" OR "needs assessment" OR "focus group" OR "learning communit*" OR "communit* of practice" OR "workshop" OR "literacy" OR "embedded" OR "instruction" OR "teach" OR "sustainable" OR "SDG" OR (diversity N2 equity) OR "DEI" OR "DEIA" OR "accessibil*") AND ("research librar*" OR "academic librar*" OR "university librar*" or "college librar*"))) Refinements: FY2010-present, English	

Database	Query	Search date
LISA	Searched for:noft((("open science" OR "science 2.0" OR "open research" OR "open scholarship" OR "open knowledge" OR "e-research" OR "e research" OR "electronic research" OR "e-science" OR "e science" OR "electronic science" OR "e-scholarship" OR "e scholarship" OR "electronic scholarship" OR "open access" OR "open-access" OR "scholarly communication" OR "publish*" OR "repositor*" OR "ETD" OR "electronic theses and dissertations" OR (open PRE/2 data) OR "data sharing" OR "data manage*" OR "FAIR" OR "metadata" OR "data reuse" OR "big data" OR "data librar*" OR "data service" OR "data visualization" OR "data curation" OR "cloud comput*" OR "cyberinfrastructure" OR "cyber infrastructure" OR "open education*" OR "OER" OR "open text*" OR "alt*text" OR "textbook afford*" OR "citizen science" OR "open assessment" OR "open metric" OR "alt*metric" OR "bibliometric" OR "open source" OR "collaborati*" OR "open reproducible" OR "reproducible research" OR "transparent research" OR "open workflow" OR "geographic Information Science" OR "GIS" OR "digital humanities" OR "digital scholarship" OR "archives" OR "digitization" OR "innovation" OR "makerspace" OR "maker space" OR "creative commons" OR "research commons" OR "information commons" OR "evidence synthesis" OR "knowledge synthesis" OR "data synthesis" OR "systematic review" OR "research synthesis" OR "review service" OR "research service" OR "professional develop*" OR "training" OR "needs assessment" OR "focus group" OR "learning communit*" OR "communit* of practice" OR "workshop" OR "literacy" OR "embedded" OR "instruction" OR "teach" OR "sustainable" OR "SDG" OR (diversity NEAR/2 equity) OR "DEI" OR "DEIA" OR "accessibil*") AND ("research librar*" OR "academic librar*" OR "university librar*" OR "college librar*"))) AND la.exact("English") AND location.exact("United States--US") AND yr(2010-2029)	5/6/2024
IEEE Xplore Digital Library	("All Metadata":"research librar*" OR "All Metadata":"academic librar*" OR "All Metadata":"university librar*" OR "All Metadata":"college librar*") Refinement(s): FY2010-2025	5/7/2024
Library Science Database	noft((("open science" OR "science 2.0" OR "open research" OR "open scholarship" OR "open knowledge" OR "e-research" OR "e research" OR "electronic research" OR "e-science" OR "e science" OR "electronic science" OR "e-scholarship" OR "e scholarship" OR "electronic scholarship" OR "open access" OR "open-access" OR "scholarly communication" OR "publish*" OR "repositor*" OR "ETD" OR "electronic theses and dissertations" OR (open PRE/2 data) OR "data sharing" OR "data manage*" OR "FAIR" OR "metadata" OR "data reuse" OR "big data" OR "data librar*" OR "data service" OR "data visualization" OR "data curation" OR "cloud comput*" OR "cyberinfrastructure" OR "cyber infrastructure" OR "open education*" OR "OER" OR "open text*" OR "alt*text" OR "textbook afford*" OR "citizen science" OR "open assessment" OR "open metric" OR "alt*metric" OR "bibliometric" OR "open source" OR "collaborati*" OR "open reproducible" OR "reproducible research" OR "transparent research" OR "open workflow" OR "geographic Information Science" OR "GIS" OR "digital humanities" OR "digital scholarship" OR "archives" OR "digitization" OR "innovation" OR "makerspace" OR "maker space" OR "creative commons" OR "research commons" OR "information commons" OR "evidence synthesis" OR "knowledge synthesis" OR "data synthesis" OR "systematic review" OR "research synthesis" OR "review service" OR "research service" OR "professional develop*" OR "training" OR "needs assessment" OR "focus group" OR "learning communit*" OR "communit* of practice" OR "workshop" OR "literacy" OR "embedded" OR "instruction" OR "teach" OR "sustainable" OR "SDG" OR (diversity NEAR/2 equity) OR "DEI" OR "DEIA" OR "accessibil*") AND ("research librar*" OR "academic librar*" OR "university librar*" OR "college librar*"))) Refinements: FY2010-2024, US	5/7/2024
Education Collection	noft((("open science" OR "science 2.0" OR "open research" OR "open scholarship" OR "open knowledge" OR "e-research" OR "e research" OR "electronic research" OR "e-science" OR "e science" OR "electronic science" OR "e-scholarship" OR "e scholarship" OR "electronic scholarship" OR "open access" OR "open-access" OR "scholarly communication" OR "publish*" OR "repositor*" OR "ETD"	5/7/2024

Database	Query	Search date
	OR "electronic theses and dissertations" OR (open PRE/2 data) OR "data sharing" OR "data manage*" OR "FAIR" OR "metadata" OR "data reuse" OR "big data" OR "data librar*" OR "data service" OR "data visualization" OR "data curation" OR "cloud comput*" OR "cyberinfrastructure" OR "cyber infrastructure" OR "open education*" OR "OER" OR "open text*" OR "alt*text" OR "textbook afford*" OR "citizen science" OR "open assessment" OR "open metric" OR "alt*metric" OR "bibliometric" OR "open source" OR "collaborati*" OR "open reproducible" OR "reproducible research" OR "transparent research" OR "open workflow" OR "geographic Information Science" OR "GIS" OR "digital humanities" OR "digital scholarship" OR "archives" OR "digitization" OR "innovation" OR "makerspace" OR "maker space" OR "creative commons" OR "research commons" OR "information commons" OR "evidence synthesis" OR "knowledge synthesis" OR "data synthesis" OR "systematic review" OR "research synthesis" OR "review service" OR "research service" OR "professional develop*" OR "training" OR "needs assessment" OR "focus group" OR "learning communit*" OR "communit* of practice" OR "workshop" OR "literacy" OR "embedded" OR "instruction" OR "teach" OR "sustainable" OR "SDG" OR (diversity NEAR/2 equity) OR "DEI" OR "DEIA" OR "accessibil*") AND ("research librar*" OR "academic librar*" OR "university librar*" OR "college librar*")))	
	Refinements: FY2010-2024, US	

Table S 2. Manual journal searches. Total = 534

Source	Search Date	Number
Against the Grain	3/7/2024	5
Association for Information Science and Technology	3/9/2024	4
Association of Research Libraries	3/7/2024	4
Behavioral and Social Sciences Librarian	3/7/2024	2
Bulletin of the Association for Information Science and Technology	3/7/2024	1
Charleston Library Conference	3/8/2024	16
Code4Lib Journal	3/8/2024	34
Collaborative Librarianship	3/8/2024	6
Collection Management	3/8/2024	2
College and Research Libraries News	3/8/2024	59
College and Research Libraries	3/7/2024	12
College and Undergraduate Libraries	3/7/2024	4
Digital Library Perspectives	3/8/2024	7
DLib Magazine	3/9/2024	21
Evidence Based Library and Information Practice	3/7/2024	1
Georgia Library Quarterly	3/7/2024	4
IASSIST Quarterly	3/8/2024	5
Information Technology and Libraries	3/7/2024	3
Insights: the UKSG Journal	3/7/2024	1
International Association of Scientific and Technological University Libraries (IATUL)	3/8/2024	16
International Journal of Digital Curation	3/8/2024	31
International Journal of Librarianship	3/7/2024	1
International Journal of Open Educational Resources	3/9/2024	21
Issues in Science and Technology Librarianship	3/8/2024	51
Journal of Academic Librarianship	3/7/2024	28
Journal of Access Services	3/7/2024	1
Journal of Business and Finance Librarianship	3/8/2024	4
Journal of Digital Information	3/7/2024	3
Journal of Electronic Publishing	3/8/2024	8
Journal of Electronic Resources in Medical Libraries	3/8/2024	5
Journal of Electronic Resources Librarianship	3/8/2024	4
Journal of eScience Librarianship	1/18/2024	9
Journal of Librarianship and Scholarly Communication	1/18/2024	27
Journal of Library Administration	3/8/2024	6
Journal of Library Metadata	3/8/2024	2
Journal of Map and Geography Libraries	3/8/2024	4
Journal of the Medical Library Association	3/8/2024	19
Journal of Web Librarianship	3/8/2024	8
Library Connect	3/8/2024	2
Library Journal	3/8/2024	12

Source	Search Date	Number
Library Management	3/8/2024	1
Library Resources and Technical Services	3/8/2024	1
Library Trends	3/8/2024	2
Medical Reference Services Quarterly	3/8/2024	14
New Review of Academic Librarianship	3/8/2024	1
OCLC Systems and Services	3/8/2024	2
OLA Quarterly	3/8/2024	4
Pennsylvania Libraries: Research and Practice	3/8/2024	2
portal: Libraries and the Academy	3/7/2024	11
Practical Academic Librarianship: The International Journal of the SLA	3/7/2024	2
Qualitative and Quantitative Methods in Libraries	3/7/2024	4
Reference and User Services Quarterly	3/7/2024	2
Reference Services Review	3/7/2024	2
Science and Technology Libraries	3/7/2024	10
Serials Librarian	3/7/2024	13
Serials Review	3/7/2024	8
Technical Services Quarterly	3/7/2024	1
Virginia Libraries	3/7/2024	1

Table S 3. Zotero codes/tags

Code	Description
access	Ensuring library-created and/or managed content (e.g., within repositories, websites) adheres to best practices of accessibility (including offering mobile-compatible interfaces). Utilizing principles of Universal Design for Learning in teaching/workshops/events. Offering workshops, training, etc., in online or hybrid environments.
CARE	Implementing CARE (Collective benefit, Authority to control, Responsibility, Ethics) in practices (including collections and archives)
citizenSci	Offering or facilitating sharing of infrastructure/resources, offering RDM support and/or curation services for participatory activities
commons	Building/maintaining spaces used as innovation hubs/commons, including makerspaces
compute	Providing cyberinfrastructure for cloud and/or high performance computing, including conducting needs assessments and trade studies/market analyses related to cyberinfrastructure
dataCollab	Facilitating data collaboration opportunities among researchers
dataCur	Participating in data curation activities, advising on data privacy, governance, and policy, providing data quality checks and implementing error-checking systems. Assisting with and/or creating and managing metadata for datasets; ensuring compliance with metadata schemas and standards
DEIdata	Teaching citation justice and ethics and equity in data collection and sharing
DEIfund	Employing equitable funding dissemination practices (e.g., APC fees, OER funds)
DEIprogram	Ensuring collections, displays, and exhibits (physical and digital) reflect DEI goals/objectives, conducting metadata and diversity collection audits, creating and evaluating programming related to DEI principles, and implementing DEI-knowledgeable outreach; offering focused support and resources to marginalized populations. Incorporating SDG/DEI metrics in strategic plans, policies, and initiatives (including hiring practices); creating DEI task forces and committees

Code	Description
digHum	Providing support for digital projects, including training/instruction in: sharing, locating, and reusing resources, digital preservation and digitization, text-mining
digital	Creating OA content by digitizing historical collections and hosting collections on IR or other publicly accessible spaces
discovery	Facilitating discovery of Open Access materials (e.g., via metadata, search engine optimization, linked open data, integration of IR with discovery system, indicating access in metadata, Open Access Button integration within discovery system, Open Athens)
dmpComply	Tracking compliance with data management plans
dmpHelp	Providing guidance and/or assisting researchers in developing data management plans
DOI	Managing persistent identifiers for scholarly documents
ELN	Providing access/infrastructure/training for use of electronic lab notebooks
evidSyn	Providing evidence synthesis services, including advising search strategies, providing advice re: best practices, and conducting reviews (collaboratively or independently)
EZID	Establishing/maintaining persistent identifiers for datasets
fundAPC	Creating, maintaining, and assessing APC funding programs
funding	Acknowledged funding from any source
funding_internal	Acknowledged funding from internal (university) source
funding_external	Acknowledged funding external to the institution
fundOER	Creating, managing, and assessing OER funding programs
GIS	Providing GIS services and/or training
hack	Hosting hackathons, wikipedia edit-a-thons, map-a-thons, and the like to promote and provide training in best practices in reproducible and open workflows
IRdata	Creating, maintaining and/or managing an institutional data repository; assisting researchers in identifying appropriate external data repositories
IRoer	Creating, maintaining, and/or managing an institutional repository for OER
IRoss	Building/maintaining an institutional repository that accepts software; advising re: external access to OSS repositories
IRpromote	Promoting the use of repositories among researchers via outreach/promotional activities and/or offering mediated deposit services; providing recommendations for appropriate thematic, consortium, and/or preprint repositories
IRscholar	Building, maintaining, and/or managing an institutional repository for university-generated scholarly works
literacy	Providing instruction/training in information and/or digital literacy, meta or trans-literacies (or, a combination of defined literacies; e.g., digital, visual, spatial, media, data, cyber)
manageAPC	Managing and monitoring costs associated with APCs
metricsJour	Establishing and/or monitoring journal quality indicators/metrics
metricsLib	Open assessment of library-provided services related to Open Science objectives, including instruction/training; assessing impact of services, including identifying appropriate success metrics and creating and sharing reports assessing progress/impact
metricsPromote	Promoting use of holistic measures to assess scholarly output (institutional or individual-level)
metricsScholar	Providing altmetric and bibliometric services and training; publishing research metrics (e.g., using data dashboards or via publications); profiling scholars to increase research reach
needsDigital	Conducting needs assessments related to digital preservation
needsLiteracy	Conducting needs assessments related to literacy instruction
needsOER	Conducting needs assessments related to OER
needsORR	Conducting needs assessments related to ORR

Code	Description
needsRDM	Conducting needs assessments related to RDM
needsSC	Conducting needs assessments for scholarly communication activities related to open access, including conducting needs assessments related to institutional repositories
needsSDG	SDG/DEI needs assessment
OApromote	Promoting OA practices among researchers, providing OA support (including locating open access materials), and organizing events aimed at promoting OA activities
ODcreate	Creating and sharing open data
ODpromote	Promoting the sharing and reuse of data, including: Advocating for, and promoting, the use of data repositories among researchers, promoting open data practices through events, workshops, etc., and locating appropriate datasets for reuse; providing guidance on data citation practices, and utilizing open data in training/teaching and/or library operations
OERcreate	Creating OER content
OERpromote	Promoting the sharing and reuse of OER, including providing training in creating and using OER content, licensing options and curating, preserving, and evaluating OER content, and utilizing OER in instructional and outreach roles
OIsupport	Providing support for entrepreneurship and innovation; e.g., patent searches/licensing, economic development/commercialization support, market/industry research, use of business databases
OPRpromote	Advocating for, and promoting, use of open peer-review journals/services
ORCID	Promoting/providing researcher identification services (e.g., ORCID)
ORRpromote	Providing infrastructure and/or training in reproducible workflows, open workflow platforms; e.g., Results Reproduction Service (R-Squared), OSF, protocols.io, Github, and advising best practices with respect to reproducibility guidelines, testing, and preservation. Promoting reproducible practices, including: Advocating for, and promoting, open workflows among researchers, promoting ORR practices through events, workshops, etc., and recommending tools that enable ORR
OSScreate	Creating/modifying and/or customizing OSS for library operations and/or scholarly purposes
OSSlicensing	Offering guidance regarding creation of OSS and corresponding licensing
OSSpromote	Utilizing OSS in instructional/training spaces to promote use and/or utilizing and/or evaluating OSS in own scholarly work/library operations
polAI	Participating in the development and/or promotion of institutional policies related to open practices, AI
polData	Participating in the development and/or promotion of institutional policies related to open practices, data
polDig	Participating in the development and/or promotion of institutional policies related to open practices, digital preservation
polHelp	Helping researchers to understand open science guidelines/requirements of funders
polOA	Participating in the development and/or promotion of institutional policies related to open practices, Open Access
polOER	Participating in the development and/or promotion of institutional policies related to open practices, Open Educational Resources
polOSS	Participating in the development and/or promotion of institutional policies related to open practices, Open-Source Software
profDev	Participating in (or offering) professional development related to Open Science activities
profDev_trainer	Providing professional development opportunities to external libraries
profDevSDG	Providing and/or participating in SDG/DEI professional development for library employees
pub	Providing publishing services

Code	Description
reproShared	Creating, maintaining and/or managing a shared repository (accepts contributions from external users)
reproTest	Carrying out reproducibility studies
resCollab	Research collaborations between libraries and other university departments
RRID	Providing support/infrastructure for research instrumentation identification within shared laboratory/ core facilities (e.g., Research Resource Identifiers, RRID)
sustainEnviron	Employing environmentally sustainable practices/activities
tCitMan	Providing training/instruction in citation management tools
tCode	Providing code support and instruction/training in data analysis and/or visualization
tCopy	Supporting the management of authors' rights: providing guidance and promoting use of open licensing awareness & understanding, promoting copyright literacy, and providing guidance on embargo periods
tEthics	Creating & conducting research ethics-related training sessions
textAfford	Creating/managing textbook affordability, alt-text, textbook reserve programs
tOSS	Provide training re: use of open code repositories (for code reuse and sharing)
tRDM	Providing RDM training and guidance; advising best practices, promoting FAIR principles, and providing guidance/instruction/training; providing instruction in data literacy
tSC	Providing training/instruction in activities related to scholarly communication, including: funding options, publishing options, preparation of posters, oral presentation skills, and grant writing
tSearch	Providing training/instruction on conducting literature reviews and corresponding searches
xEdu	Source: ProQuest Education Collection
xIEEE	Source: IEEE Xplore Digital Library
xJSearch	Source: Journal hand searching
xLISA	Source: Library and Information Science Abstracts
xLISTA	Source: Library, Information Science, and Technology Abstracts
xLSD	Source: Library Science Database
xOpenAlex	Source: Open Alex
xOSF	Source: Open Science Framework
xProtocols	Source: Protocols.io
xRefTrace2	Source: Reference Tracing
xScholar	Source: Google Scholar
xScopus	Source: Scopus
xWOS	Source: WOS Core Collection

Table S 4. Zotero field codes

Field code	Description
Extra	Paper ID
Loc. in Archive	Source type (e.g., journal, conference, …)
Library Catalog	University name