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Bibliometric Analysis of Critical Materials Innovation Hub Publications 2013–2022

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NEXIGHT GROUP

Disclaimer

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List of Acronyms

CMI	Critical Materials Innovation Hub
DOE	U.S. Department of Energy
DOI	Digital object identifier
FWIC	Field-weighted citation impact
ID	Identification
ii	Ferrous iron, iron(II) or Fe(2+)
iii	Ferric iron, iron(III) or Fe(3+)
REE	Rare earth elements

Executive Summary

The Critical Materials Innovation Hub (the CMI Hub, formerly known as the Critical Materials Institute or CMI) is a U.S. Department of Energy (DOE) Energy Innovation Hub led by Ames National Laboratory and supported by DOE. Established in 2013, the CMI Hub focuses on “technologies that make better use of materials and eliminate the need for materials that are subject to supply disruptions” (Ames National Laboratory 2024). the CMI Hub researchers regularly publish articles that describe their research and its results.

Nexight Group conducted a bibliographic analysis of the CMI Hub’s publications to develop a profile of the CMI Hub’s research community, identify growing and emerging research fronts in critical materials, and describe the impact the CMI Hub’s publications have had on the research community. The analysis focused on 475 the CMI Hub publications from 2013 through 2022 that were covered by the Scopus database. Citation counts and other information on each publication (authors, author affiliation, keywords, references, etc.) were downloaded from Scopus in early December 2022.

We conducted network analyses of articles, authors, and author affiliations (organizations) using Gephi, a network analysis software package. These analyses yielded visualizations of article communities, author communities, and organization communities. We also conducted keyword analyses using VOSviewer, a software tool for visualizing bibliometric networks. VOSviewer was used to create visualizations of bibliometrics networks that showed occurrences and co-occurrences of keywords and to complete bibliographic coupling analysis, which showed connections between articles based on common citations. We analyzed and visualized connections among the CMI Hub publications and self-citations using Litmaps, a literature mapping tool. Finally, we conducted citation analyses including citation counts and normalized measures like percentile ranking and field weighted citation impact.

The analyses yielded numerous compelling results, including the following.

The CMI Hub has developed a large, interconnected research community. The CMI Hub’s 475 publications were produced by 1,039 authors. Of these, 98.7% of the authors are connected to all other the CMI Hub authors through authorships on the CMI Hub publications alone. the CMI Hub’s publications were authored by individuals affiliated with 251 organizations that span six continents and 31 countries. Most publications (76%) were authored by individuals from academia and government/lab. Specifically, through academia (15%), government/lab (17%), or a collaboration of the two (44%).

Keywords indicate growing research fronts. Occurrence and co-occurrence of keywords can indicate a growing research front. Keywords with the highest growth in occurrence include “magnet,” “recovery,” “permanent magnet,” “defect,” “magnetic field,” “microstructure,” “cerium,” “coercivity,” “Ga2O3,” and “additive manufacturing.” Keywords with the highest growth in co-occurrence include “concentration & extraction,” “magnet & magnetic property,” “magnet & permanent magnet,” “alloy & cerium,” “extraction & separation,” “alloy & mechanical property,” “REE (rare earth element) & separation,” “magnet & NdFeB (neodymium-iron-boron),” “sample & tic,” and “alloy & composition.” The average publication year for keywords show recent trends for “lithium-ion batteries,” “gallium compounds,” “magnetic fields,” and “electronic waste.”

Keywords indicate potential emerging research fronts. Keywords having the highest growth in co-occurrences in recent years indicate potential emerging research fronts. Top new co-occurrences of keywords from 2019–2022 include “concentration and extraction,” “concentration and rare-earth elements,” “concentration and recovery,” “ionic liquid and solution,” and “recovery and technology.”

The CMI Hub’s publications are highly cited and impactful. As of December 2, 2022, the CMI Hub’s 475 publications had received 9,747 citations, or 20.5 citations per publication. The average field-weighted citation impact (FWCI) value for the CMI Hub’s publications was 1.51, meaning the CMI Hub’s publications received 51% more citations than expected. Only 21% of the CMI Hub’s publications are below the 50th percentile of Scopus percentile ranking. The average the CMI Hub publication is at the 70th percentile of Scopus percentile ranking. The self-citation rate was 10%, which is comparable to the 9% overall rate and below the 15% physical sciences rate. This suggests that the CMI Hub publications have more impact on the scientific community than the average physical sciences author. The CMI Hub self-reference rate is 5%, which is lower than the overall self-reference rate (15%) and the highly cited physical sciences self-reference rate (10%). This suggests that the CMI Hub draws less upon its own publications to inform its work than either the average author or highly cited physical science authors.

Article-organization communities have varying size and impact. Analysis of articles and organizations considered together resulted in eight primary article-organization communities that had varying indicators of production and impact. The Ames National Laboratory community had the highest number of publications (126). The Oak Ridge National Laboratory community had the highest number of citations (2,322) and patents (14). The Lawrence Livermore National Laboratory community had the highest average FWCI (2.25) for its publications.

The observations outlined above indicate that the CMI Hub publications have played an important role in the development of the literature supporting the critical materials field.

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1. Introduction

The Critical Materials Innovation Hub (the CMI Hub, formerly known as the Critical Materials Institute or CMI) is a U.S. Department of Energy (DOE) Energy Innovation Hub led by Ames National Laboratory and supported by DOE. The CMI Hub focuses on “technologies that make better use of materials and eliminate the need for materials that are subject to supply disruptions” (Ames National Laboratory 2024). Emphasizing an innovative approach, the CMI Hub seeks to achieve three main goals: (1) diversify and expand sources; (2) drive reuse and recycling of materials; and (3) develop substitutes to reduce critical materials use.

Progress toward these goals is shared by the CMI Hub scientists in publications that highlight the CMI Hub collaborations among industry, universities, national laboratories, and other researchers. To better understand the status, trends, and impacts of these efforts, this report addresses the following research questions:

- What is the profile of the CMI Hub’s research community, encompassing its size, geographic distribution, interaction, and areas of research?
- What are the growing and emerging research fronts in the CMI Hub community?
- What impacts have the CMI Hub’s publications had on the broader research community?

To address these research questions, we examined three sets of research literature: the CMI Hub research publications, references in the CMI Hub publications, and citations of the CMI Hub publications (**Figure 1**).

We developed a profile of the CMI Hub’s research community through analysis of both the CMI Hub publications and references in the CMI Hub publications. the CMI Hub publications provided information about authors, their affiliations (organizations), coauthorship, and keywords. Analysis of this information enabled us to demonstrate the CMI Hub’s interconnected communities of authors and organizations, and to describe the research landscape through occurrence and co-occurrence of keywords and analysis of journal fields of study. References in the CMI Hub research publications helped us fill out the profile of the CMI Hub’s research community by identifying the most influential publications on the CMI Hub community. It also helped ground the CMI Hub publications in the broader set of literature.

We identified growing and emerging research fronts through an analysis of how the frequency of keywords in the CMI Hub publications have changed over time. Furthermore, we identified the impacts the CMI Hub’s publications have had on the broader research community by examining the number of citations of the CMI Hub publications and related statistics.

Figure 1. Sets of research literature

2. Project Design

Bibliometric analysis is a popular and rigorous method for assessing a large set of publications to evaluate their impact and trends over time. Scholars employ this method to uncover emerging trends, discover collaboration patterns, and show how authors, publications, scientific terms, and disciplines relate to one another (Donthu et al. 2021). Data for this analysis is objective and includes features such as the number of citations, number of publications, and occurrences of author and index keywords.[1] Interpretation of the data is more subjective in nature.

2.1. Tools

A variety of tools were used to conduct the bibliographic analysis.

Scopus is an abstract and citation database of books, peer-reviewed journals, and conference proceedings that allows researchers to easily filter and search publications. It is the source for citation numbers, key words, authors, organizational affiliations, etc. used in the analysis.

Network maps are an essential component of bibliometric analysis as visualization tools. For this analysis, we used several popular tools for network and citation analysis: Gephi, VOSviewer, and Litmaps. Gephi is an open-source network analysis and visualization software package. It was used to show relationships among articles, authors, and organizations. VOSviewer is a software tool for constructing and visualizing bibliometrics networks. It was used to show relationships among keywords and sources and to conduct bibliographic coupling. Litmaps is a literature mapping tool that creates time-based visualizations of a publication’s citations received. It was used to show connections among the CMI Hub publications over time. These software packages are widely used and useful to uncover trends and patterns in large databases.

Tableau was used to show locations of author-affiliated organizations around the world and connections among them.

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[1] Scopus lists both author and index keywords. VOSviewer can be used to conduct keyword analysis on the author and index keywords from Scopus. VOSviewer can also conduct an analysis of words in an article’s title and abstract.

2.2. Scope

The bibliographic analysis covered the CMI Hub publications from 2013 through mid-2022.[2] Because the CMI Hub was launched in 2013, publications do not exist for the full year. The citation data pulled for this analysis was captured in early December 2022, so citation data does not reflect a full year for 2022.

The bibliometric analysis focused on a population of 475 publications covered by Scopus. A publication was included if it could be found in the Scopus database by searching for the publication's digital object identifier (DOI) or title. The list of 475 publications was developed from a list of 511 publications provided by the CMI Hub. From this list, four duplicates were deleted, and another 35 were added from a search in Scopus where the CMI Hub was an author affiliation. This resulted in a total of 542 publications. Of these, 67 were not covered by Scopus. These were a mix of 13 dissertations, five master's theses, seven conference papers, eight technical reports, 11 internship reports, 18 articles in sources not covered by Scopus, and five articles that could not be found in Scopus even though the source was tracked by Scopus.

2.3. Methods for Characterizing Research Publications

Advancing a research field relies not only on the individual research, but the communication among researchers, which improves the scientific community, particularly through scholarly journals (Liu, Yin, Dunford 2015). To assess these advances, we employ several bibliographic techniques. First, a list of the CMI Hub's 475 articles was created in Scopus. The following information on each article was then obtained from Scopus: author(s), author(s) identification (ID), title, year published, source title, number of citations, digital object identifier (DOI), affiliations, authors with affiliations, abstract, author keywords, index keywords, funding details, references, document type, publication stage, electronic identifier (EID), FWCI, and percentile rank.

The information drawn from Scopus was then used to: (1) summarize publication demographics; (2) analyze author/organization collaboration, networking, and research communities; (3) identify research fronts; and (4) conduct citation analyses.

2.3.1. Publication Demographics

Summary demographics on the CMI Hub publications were developed by aggregating individual article data drawn from Scopus. This includes total number of publications, and number of publications by year, document type, journal, and field of study.

2.3.2. Author Analysis

Scopus' author ID was used to conduct an analysis of authors. An initial list of authors was developed using the author ID. The list was then vetted to identify duplicate names or variations of author names. The final list was used to calculate simple counts of the number of publications for each author. The data were then used in Gephi to develop maps of author communities. Each author is affiliated with one or more organizations.

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[2] The latest publication date of publications in the CMI Hub's list was May 2022.

2.3.3. Organization Analysis

Each article in Scopus is affiliated with one or more organizations through the article's author(s). A list of unique organizations was created and assigned an organization type (government/lab, university, industry, and other). Locations of organizations were obtained through demographic information in articles or through Google Maps. This information was loaded into Tableau to create maps. Summary information on the number of publications by organizations, and organization co-authorships were calculated. Gephi was used to develop network maps of organizations and identify organization communities.

2.3.4. Keyword Analysis

Keyword frequency is considered a primary metric to identify research trends (Huang and Zhao 2019). Keywords are especially useful as they can be analyzed immediately after an article's publication. This type of analysis considers frequency of terms and their networks. While usually looked at retrospectively to assess research trends, keyword analysis can also be used to project research trends into the future (Lu et al. 2021). Keywords may be author-assigned or indexed. Scopus index keywords and words in the title and abstract of articles were used to conduct keyword analyses. Data from Scopus were loaded into VOSviewer, which was then used to create maps showing the prevalence of keywords (occurrences) and their relationships to other keywords (co-occurrences). Data downloaded from VOSviewer was then used to show growth in keywords over time.

2.4. Methods for Assessing Impacts of Research Publications

Data loaded into VOSviewer were also used to conduct bibliographic coupling analysis. This showed connections between articles based on common citations. If two publications both cite a third publication, it is an indicator of a connection and potentially shared subject matter between the two publications.

Citation and keyword analyses are the most used techniques for analyzing trends (Wang, Cheng, and Lu 2014). These methods are used to measure the impact and influence of publications.

2.4.1. Citation Analysis

Citation analysis is an objective measure to evaluate the impact of publications in a field (Stremersch et al. 2007). Citation analysis measures the influence of publications by identifying the relationships among publications across a research field. Data include authors' names, citations, titles, journals, DOIs, and references. Citations reflect linkages between publications (Appio, Cesaroni, and DiMinin 2014). Data obtained from Scopus were used to calculate the total number of citations as well as the number of citations by year and document type.

Citations accumulate over time. To best evaluate the impact of a publication, a time lapse of two or three years from the publication date to the citation count has been suggested by scholars (Abramo et al. 2011). This time-dependency is corroborated by observations from other researchers that demonstrate lower citation counts in recent years (Abramo et al. 2011). As such, data for the most recent publications need to consider their newness; older papers have had more time to accumulate citations, which biases those sources. Co-citation analysis—the frequency with which two documents are cited together—offers a way to study the networks of co-cited sources to study specialty structures of science (Small 1973) as well as to identify the key literature for cross-disciplinary ideas (Trujillo and Long 2018).

2.4.2. Percentile Ranking

We used Scopus to create a distribution of the CMI Hub's publications by percentile ranking. This measure provides a normalized measure of a publication's impact. It compares items of the same age, subject area, and document type over an 18-month window (Elsevier Library Connect and DelaSalle 2016).

2.4.3. Field Weighted Citation Impact

To account for differences in the number of publications and citations received across disciplines, impact of the CMI Hub research is also shown by the field-weighted citation impact (FWCI), a ratio of the total citations received for a document to the expected number of citations for similar documents. Similar documents are ones in the same discipline, of the same type (e.g., article, letter, review), and of the same age.[3] FWCI data obtained from Scopus were used to calculate an average FWCI for the CMI Hub's publications.

2.4.4. Self-Citation

One concern of citation analysis is self-citation, which has the potential to misrepresent research performance (Baccini, De Nicolao, and Petrovich 2019; Peroni et al. 2020). Self-citation is a common practice in which the author references another one of their own publications. While these citations can be useful to reference previously published research, the practice has received some scrutiny as a form of self-promotion. In a global study of self-citations across 27 disciplines, Pandita and Singh (2017) found that that out of a total of over 24 million citations, 34.5% were self-citations, though prevalence varies widely across disciplines. We identified all the references in the CMI Hub's publications and then identified which were one of the CMI Hub's 475 publications. We then uploaded the CMI Hub's article DOI's into Litmaps to create an internal the CMI Hub citation map (the CMI Hub articles that were cited by other the CMI Hub articles). This provides a visualization of the CMI Hub's self-citation.

2.4.5. External Citations

We identified external citations of the CMI Hub's most-cited publications and used Litmaps to create a broader map that includes highly cited non-the CMI Hub articles that cited highly cited the CMI Hub articles.

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[3] Ibid.

2.4.6. Other Indices

Publications are evaluated by various indices including h-index (number of publications cited at least the same number of times as the publication being indexed), i10-index (number of publications with at least 10 citations), and g-index (number of publications that together receive that many citations squared). These were calculated using citation data from Scopus.

2.4.7. Community Production and Impact

Finally, Gephi was used to develop an article-organization network. This allowed us to analyze communities based on their production of articles and citations.

Additional details on methods for analyzing the CMI Hub's publications and their impact are discussed in the following sections.

2.4.8. Limitations

Bibliographic analysis contains some limitations. The Scopus database focuses largely on journals. As a result, our analysis did not include 67 the CMI Hub publications not covered by Scopus (dissertations, theses, conference papers, reports, and some articles). An additional five articles could not be located in Scopus even though their journal were tracked in Scopus. While Scopus was not able to evaluate all the publications, the effect is minimal given that the types of publications not included typically have limited impact. Still, Scopus is regarded as an authoritative tool, especially effective for citations analysis. Additional research employing use of additional tools, such as Web of Science, may yield marginal benefits as Scopus and Web of Science are not all-inclusive of each other.

Another limitation is that while highly cited papers are useful to chart the development of a field and the influence of a particular publication (Garfield 1979), reasons for a citation are not considered. A publication may be cited for a variety of reasons, including giving credit to experts, providing examples of previous work, to reinforce a point, or even an as an example of a flawed approach. In this way, the "impact" of citation counts has a specific meaning rooted in how publications relate to each other though not necessarily other measures of impact. Another dimension of citation counts is the prestige of the journal. While a journal's impact factor can measure its impact, it does not account for a particular article's impact. For example, an article published in a lower-impact journal could be more heavily cited than an article in a higher-impact journal: Impact factor is a measure of a journal's citation impact, but not for an individual article's citation impact (Belter 2015).

Despite these limitations, bibliometric analysis is widely applied, as it effectively measures performance across an entire publication set, offering a collective evaluation that reveals the importance of research in a field based on objective data as well as the forward trends of the discipline.

3. Results

The results provide an overall perspective of the critical materials field and its status, trends, and impacts. Specifically, these results present a profile of the CMI Hub's research community and the growing and emerging research fronts in critical materials. Results are organized into: (1) characterizing the CMI Hub research; (2) identifying the research upon which the CMI Hub research is built; and (3) identifying impacts of the CMI Hub research through bibliometric analyses.

3.1. Characterization of Research Publications

The CMI Hub scientists have shared their research results in presentations and publications that highlight collaborations among industry, universities, and national laboratories, as well as early career researchers. We analyzed characteristics of the publications including document type, publication year, source, author, author affiliation (organization), and keywords.

3.1.1. Document Type

Publications tracked in the Scopus database are assigned one of 13 document types described in the Scopus Content Coverage Guide. the CMI Hub's publications were predominantly articles (86%), but there were also a significant number of reviews and conference papers, as well as a handful of editorials, notes, data papers, letters, errata, and a retraction (**Table 1**).

Table 1. Number of the CMI Hub Publications by Scopus Document Type

Document Type	Definition*	Number of the CMI Hub Publications
Article	Original research or opinion	410
Article in Press	Accepted article made available online before official publication	0
Book	A whole monograph or entire book	0
Chapter	A book chapter	9
Conference Paper	Original article reporting data presented at a conference or symposium	19
Data Paper	Searchable metadata documents describing an online accessible dataset, or group of datasets	1
Editorial	Summary of several articles; or provides editorial opinions or news	4
Erratum	Report of an error, correction, or retraction of a previously published paper	2
Letter	Letter to or correspondence with the editor	1
Note	Note, discussion or commentary	4
Retracted Article	Published articles that the author(s) or publisher has requested to retract	1

Review	Significant review of original research, also includes conference papers	24
Short Survey	Short or mini review of original research	0

*Definitions are from the Scopus Content Coverage Guide available at https://www.elsevier.com/solutions/scopus/how-scopus-works/content. The guide also contains characteristics of each document type. For instance, "Notes are short items not readily suited to other item types … Discussions and commentaries that follow an article are defined as notes … Notes also include questions and answers, as well as comments on other (often translated) articles."

3.1.2. Publication Year

Figure 2 shows the distribution of the CMI Hub publications by year published. It shows a rise in publications over the first 5 (to 65) years and then a rough leveling off thereafter (around 60 per year). Note the data for 2022 do not include documents published in the last half of the year. The latest publication date of publications in the CMI Hub's list was May 2022. The average number of publications per year is 47.5, with a low of 2 (2013) and a high of 67 (2020). The average when 2013 and 2022 values are removed (because they are partial years) is 54.2.

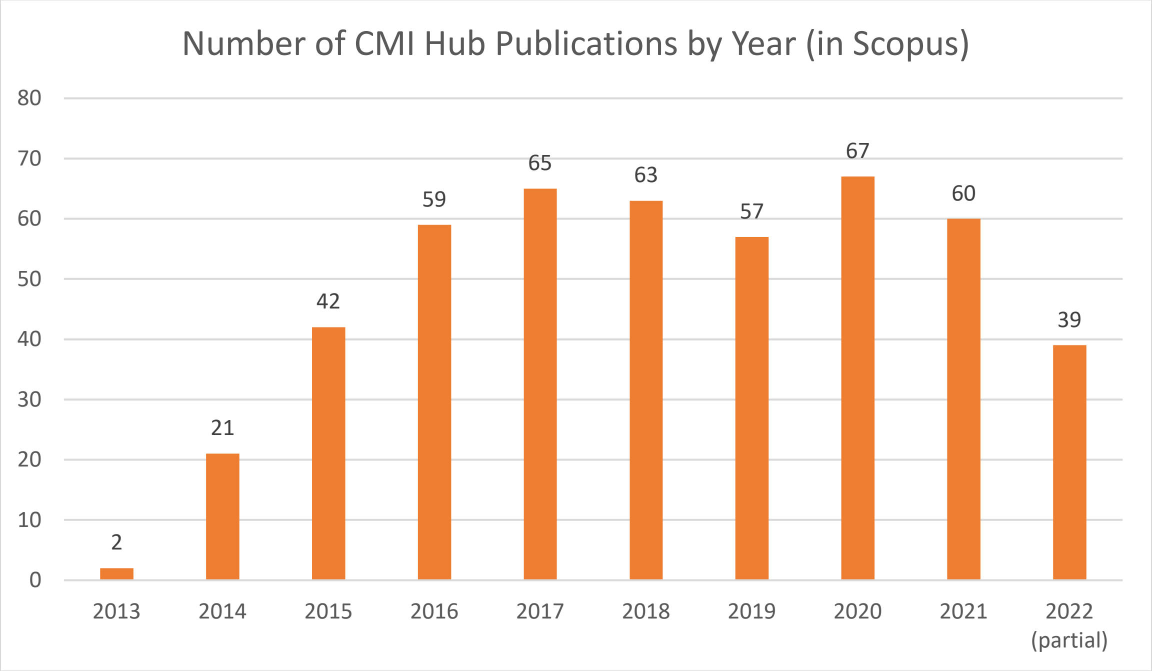

Figure 2. Number of the CMI Hub publications by year

3.1.3. Sources

The CMI Hub's articles were published in 185 different sources (i.e., journals), with the ten most frequent shown in **Table 2**. The top ten sources cover 130 (27%) of the CMI Hub's publications. We also included journal impact factors, which measure the average number of citations received in a year (e.g., 2022) divided by citable items (articles and reviews) published in the journal during the previous two years (e.g., 2020 and 2021).[4]

Table 2. Top 10 Sources in Which the CMI Hub Articles Are Published

Source	Number of CMI Hub Publications	Impact Factor (2022)
JOM	19	2.6
Physical Review B	17	3.7
Journal of Magnetism and Magnetic Materials	16	2.7
Resources, Conservation and Recycling	14	13.2
ACS Sustainable Chemistry and Engineering	12	8.4
Environmental Science and Technology	11	11.4
Minerals, Metals and Materials Series	11	0.4
Inorganic Chemistry	10	4.6
Journal of Applied Physics	10	3.2
Journal of Materials Chemistry C	10	6.4

Each source is associated with multiple fields of study, including a top-ranked field. The most popular fields of study for the sources in which the CMI Hub's documents are published are show in Table 3. The most common fields of study are condensed matter physics, general physics and astronomy, general engineering, metals and alloys, and mechanical engineering.

Table 3. Top 10 Fields of Study Associated Sources in Which the CMI Hub Articles Are Published

Field of Study	Number of the CMI Hub publications*
Condensed Matter Physics	42
General Physics and Astronomy	28
General Engineering	24
Metals and Alloys	21

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[4] Most journal impact factors were generated from the journal impact search engine Bioxbio, available at https://www.bioxbio.com. Impact factor for *Inorganic Chemistry* is from ACS Publications https://pubs.acs.org/journal/inocaj, accessed March 27, 2024. Impact factor for *Journal of Magnetism and Magnetic Materials* is from Science Direct https://www.sciencedirect.com/journal/journal-of-magnetism-and-magnetic-materials, accessed March 27, 2024.

Mechanical Engineering	19
General Materials Science	18
General Chemistry	17
Materials Chemistry	16
Economics and Econometrics	15
Industrial and Manufacturing Engineering	15

* Counts are based on the highest ranked field for each source in Scopus.

Figure 3 shows a network map for the 35 sources cited 75 or more times. The network consists of three large clusters: The red cluster includes topics on chemistry, the green cluster topics on physics, and the blue cluster assorted topics on policy and law, electrochemistry, materials chemistry, and materials science.

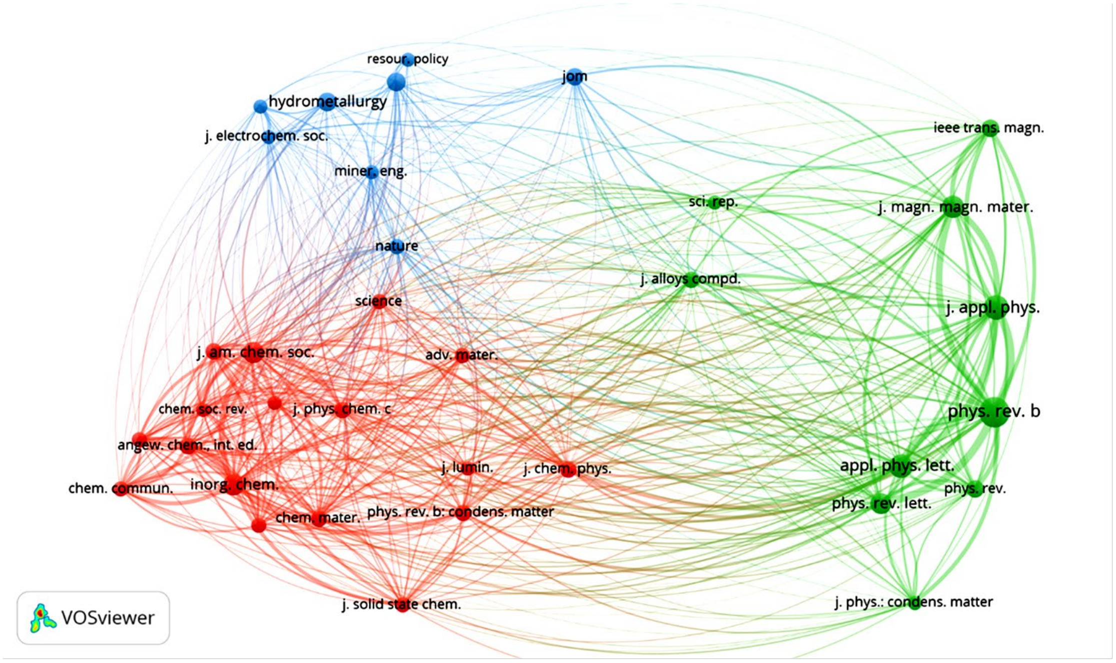

Figure 3. Cocitation network of sources (75 or more citations)

3.1.4. Bibliographic Coupling

Bibliographic coupling identifies article groupings with similar topics or subject matter. It is used to analyze relationships among cited publications to better understand the development of themes in a field. Bibliographic coupling links two articles together based on the articles they cite. The method operates on the assumption that publications that share references are linked in their content. This is a useful method to uncover the present state of the research field (Donthu et al. 2021). Data include authors' names, titles, journals, DOIs, and references.

Two articles are "bibliographically coupled" if they both cite the same document. The more documents that both articles cite, the stronger the link between the two articles. If two articles cite the same five documents, for example, then their coupling strength would be five (**Figure 4**).

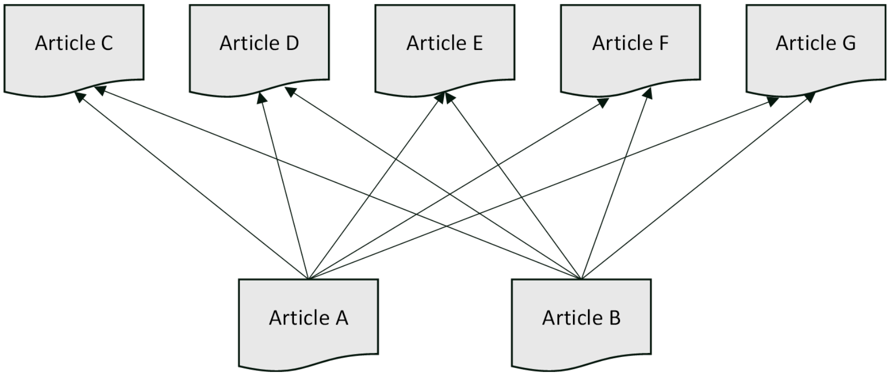

Figure 4. Concept of bibliographic coupling

Citations in the two bibliographically coupled articles do not change over time and therefore the coupling strength of the two articles is static. In that sense, bibliographic coupling is considered retrospective.

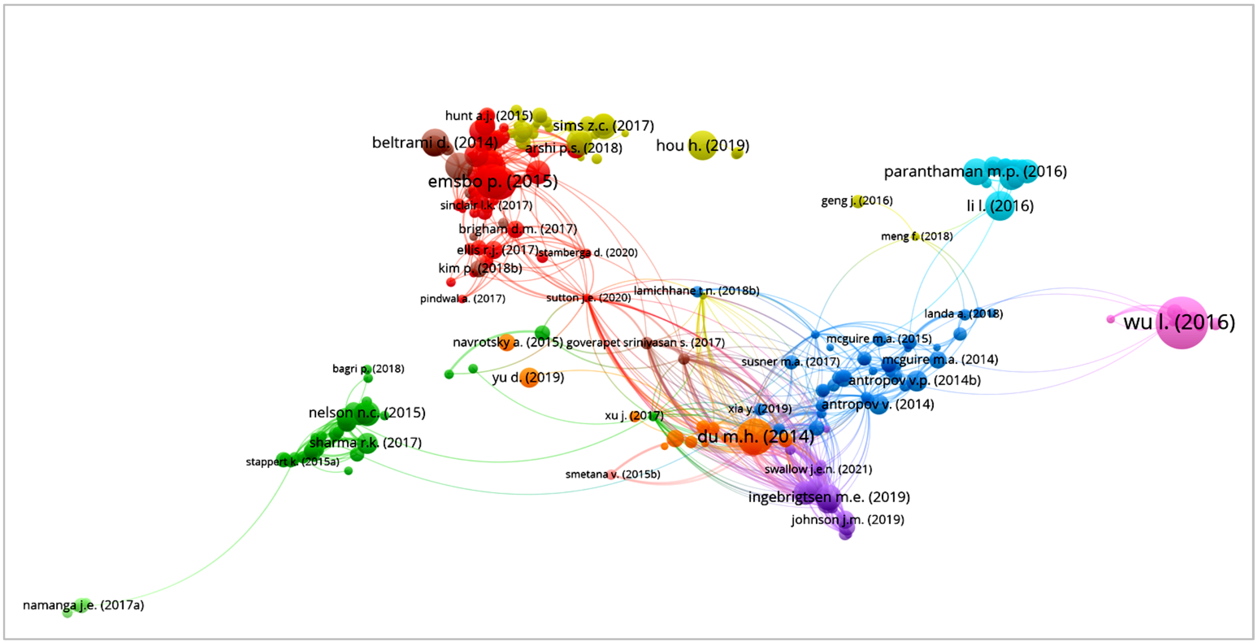

Figure 5. Bibliographic coupling network

We conducted bibliographic coupling on the CMI Hub articles connected to the entire network of the CMI Hub articles (i.e., that shared connections, whether direct or indirect, between authors and were not “islands”) and that received at least 10 citations. Interpreting a bibliographic coupling network involves understanding the connections between documents based on their shared references. Each document is represented as a node in the network. Node size corresponds to the number of citations an article received, and different colors represent the shared thematic focus of each cluster. The links between nodes indicate shared references, and the more references they share, the stronger (thicker) the link. Nodes with many connections (a high degree of centrality) share many references with other articles. Clusters of tightly interconnected nodes identify research areas or subfields. Dense regions may signify cohesive research areas and sparse regions could indicate less interconnected topics.

Figure 5 shows the network of the CMI Hub articles resulting from a bibliographic coupling analysis of the CMI Hub articles. The graph depicts large central nodes for the most cited articles. These include Wu et al. (2016), Du (2014), and Emsbo et al. (2015), each of which exhibits high centrality metrics in its own cluster. These can be interpreted as influential or central documents within the network, playing a key role in connecting clusters or bridging different research areas. The network is fairly diffused, with nine visually distinct clusters. Articles in clusters share references among themselves more than with articles outside their clusters.

Some articles are highly cited but share few references with other articles, such as Wu et al. (2016). Other articles received comparatively fewer citations yet exhibit a large number of bibliographic coupling relationships, such as Sutton et al. (2020) in the red cluster.

3.1.5. Authors

There were 1,039 individual authors of the CMI Hub’s 475 publications. The authors (lead and coauthors) with the most the CMI Hub publications are listed in **Table 4**.

Table 4. Authors with the Most the CMI Hub Publications

Author	Organization(s)	Number of the CMI Hub Publications
Mudring, A.-V.	Ames National Laboratory, Iowa State University, Stockholm University, Ruhr-Universität Bochum	49
Nlebedim, I.C.	Ames National Laboratory	49
Rios, O.	University of Tennessee	41
Paranthaman, M.P.	Oak Ridge National Laboratory	33

Parker, D.S.	Oak Ridge National Laboratory	27
Varley, J.B.	Lawrence Livermore National Laboratory	25
McCall, S.K.	Lawrence Livermore National Laboratory	24
Kramer, M.J.	Ames National Laboratory	22
Navrotsky, A.	Arizona State University	22
Riman, R.E.	Rutgers University	21

3.1.6. Coauthorship

Co-authorship examines the interactions among authors and their affiliations as a reflection of scholarly collaboration (Cisneros et al. 2018). These interactions allow for improved and more sophisticated research. Their linkages form a network that is useful for showing how scholars cluster by theme and over time (Donthu et al. 2021). Data include the number of articles coauthored and the affiliated organizations.

We conducted a coauthorship analysis to identify links among the CMI Hub authors. The analysis found that 1,026 (98.7%) of the CMI Hub's 1,039 authors are connected to one another through the CMI Hub's publications alone.

Figure 6 represents the CMI Hub's network of authors color-coded by author community. Each node represents an author, and each line represents co-authorship between two authors. Node size is a function of its centrality to the network. It is based on the number of shortest paths passing through the node for all paths in the network. Nodes (i.e., authors) of a community are more closely connected to each other than they are to other nodes in the network.

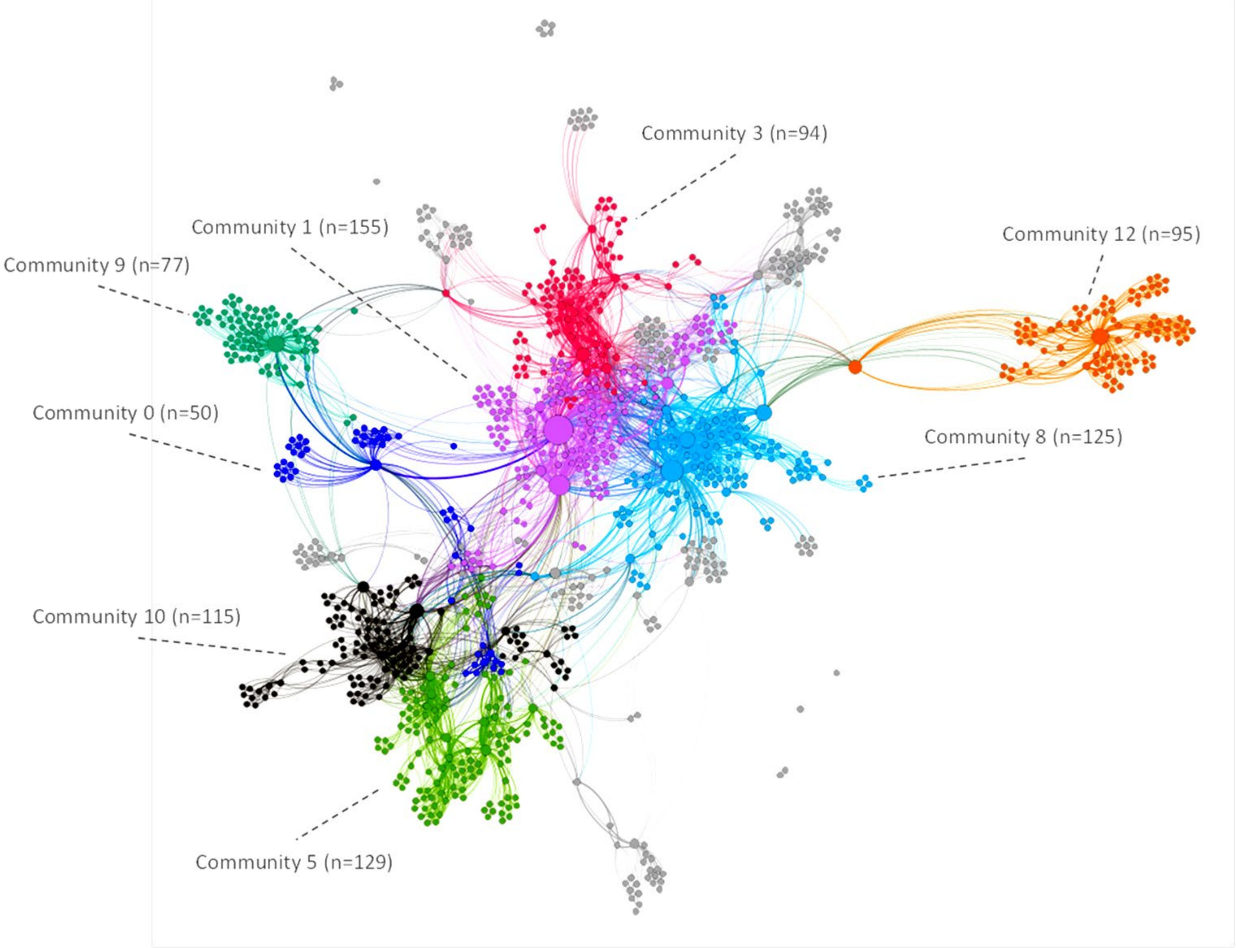

Figure 6. Author communities

Table 5 lists the top five most frequent keywords for communities of at least 50 authors. Some common keywords, such as “rare earths” and “binary alloys,” are associated with multiple communities.

Table 5. Top Five Keywords for Each Author Community

Community 0	Community 1	Community 3	Community 5
Rare earths	Permanent magnets	Binary alloys	Rare earths
Recycling	3D printers	Cobalt alloys	Life cycle (assessment)
Electronic waste	Neodymium alloys	Magnetic anisotropy	Recycling
Leaching	Rare earths	Permanent magnets	Adsorption
Metals			

	Iron alloys	Single crystals	Magnet(s)

Community 8	Community 9	Community 10	Community 12
Aluminum alloys Cerium alloys Rare earths Binary alloys Heat treatment	Ionic liquid(s) X-ray diffraction Crystal structure Luminescence Nanoparticle(s)	Rare earths Ligands Density function theory Extraction Adsorption	Gallium compounds Scanning transmission electron microscopy Energy gap Defects Density functional theory

3.1.7. Organization Analysis

The file of 475 articles from Scopus contained 940 uniquely named organizations (unlike author IDs, affiliation IDs are not included in Scopus files). Often, the same organization was listed multiple times due to variations in naming conventions. For example, “Virginia Polytechnic Institute and State University” was also listed as “Virginia Tech.” Sometimes sub-units within an organization were listed. For instance, within Virginia Tech, the Department of Biomedical Engineering and Mechanics, Department of Mechanical Engineering, and Macromolecules Innovation Institute were listed. We cleansed the data by removing variations in organization naming and using only the highest organization level (e.g., name of the university, not the department within the university). Finally, we did not use the CMI Hub as an organization because it was not consistently co-listed with Ames National Laboratory, Idaho National Laboratory, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, Iowa State University, or the Colorado School of Mines (the CMI Hub’s primary partners). After data cleansing, we were left with 251 unique organizations associated with the 475 the CMI Hub publications.

3.1.8. Organization Types

Each organization was classified as one of four organization types: government (includes federal laboratories), industry, university, and other (e.g., nonprofits and organizations whose type was not clear). Of the 251 organizations, 154 (61%) are universities, 55 (22%) are industry, 28 (11%) are government/lab, and 14 (6%) are other.

3.1.9. Organization Locations

The location of each organization was obtained from Google Maps. Organization locations were used to create a map of organizations publishing the CMI Hub articles, color-coded by organization type (**Figure 7**). The organizations span six continents and 31 countries. Most organizations publishing articles are in the United States and Western Europe, with some in India, China, Japan, and South Korea. Distribution by organization type across countries was fairly uniform.

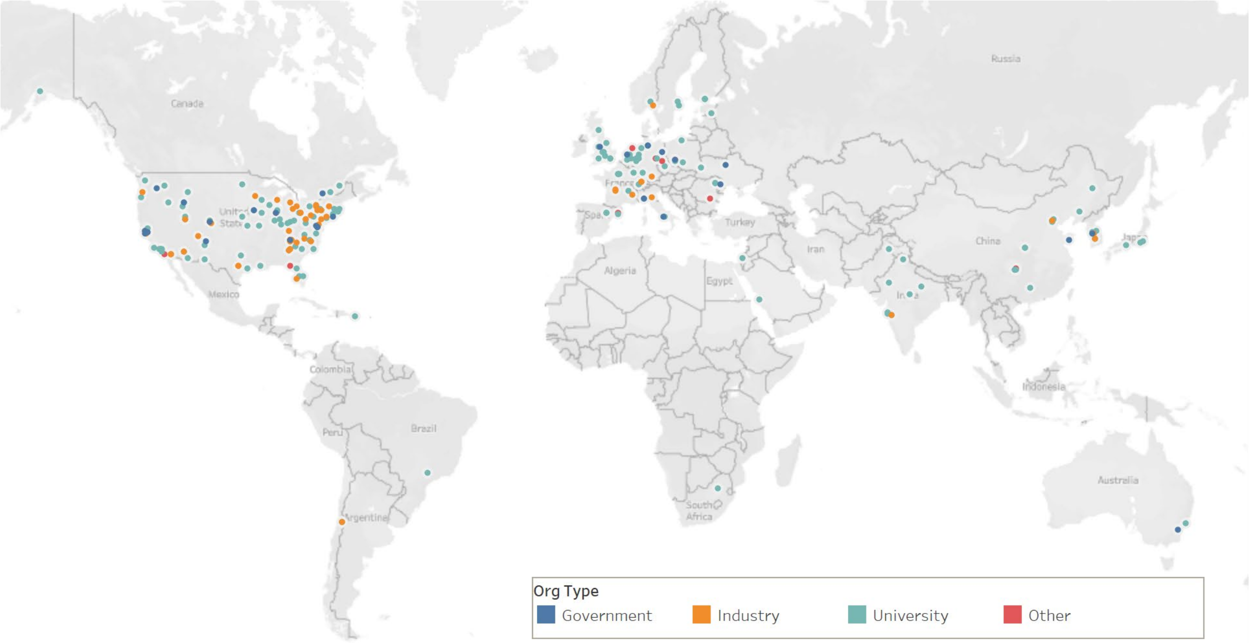

Figure 7. Map of organizations authoring the CMI Hub publications

In the United States, out of 131 organizations, 53% are universities, 32% are industry, and 11% government/national lab, and 4% are other. For the 120 non-U.S. organizations, 71% are universities, 11% are industry, and 11% are government, and 8% are other.[5] Notably, 16 organizations are based in Germany, 10 of which (63%) are universities. Fourteen organizations are based in China, 11 of which (79%) are universities. Ten organizations are based in South Korea, seven of which (70%) are universities.

3.1.10. Publications by Organization and Organization Type

Table 5 shows organizations with the most publications. The list includes four national labs (Ames National Laboratory, Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, and Idaho National Laboratory) and six universities (Iowa State

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[5] Data do not add to 100% because some organizations are categorized as "other."

University, University of Tennessee, Colorado School of Mines, Purdue University, University of California, Davis, and Ruhr-Universität Bochum[6]).

Table 6. Organizations with the Most the CMI Hub Publications

Organization	Number of CMI Hub Publications
Ames National Laboratory	169
Oak Ridge National Laboratory	140
Iowa State University	98
Lawrence Livermore National Laboratory	92
Idaho National Laboratory	50
University of Tennessee	46
Colorado School of Mines	40
Purdue University	34
University of California, Davis	27
Ruhr-Universität Bochum	25

Figure 8 provides a breakdown of how many of the CMI Hub's 475 articles were authored or co-authored by each combination of organization type. The value in each cell reflects the number or articles published by the type of organization(s) indicated by the heading(s) associated with the cell. Cell headings are located at the top left and top right. Headings that overlap indicate collaboration by organization types with those headings. For instance, the cell furthest to the left contains the value 80, which represents the number of articles published solely by a government organization (including national laboratories). The cell with the value 72 is the number of articles published solely by a university. The cell with the value 207 is the number of articles published that have author(s) affiliated with government and universities. Fifty-one articles were coauthored by the three organization types of government, university, and industry.

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[6] All 25 publications by Ruhr Universität Bochum were coauthored A.V. Mudring, who was also affiliated with Ames National Laboratory and Iowa State University. In many instances coauthors were also affiliated with Ruhr Universität Bochum.

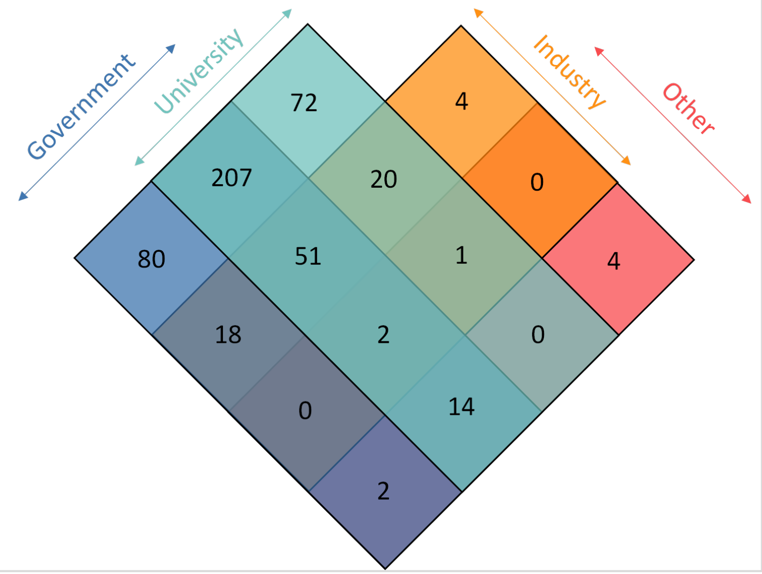

Figure 8. Number of articles authored and coauthored by organization type

Of the 475 publications, 160 (34%) were authored by a single organization type while 66% were authored by multiple organization types. Most publications (86%) were either from academia (15%), government (17%), a collaboration of academia and government (44%), or a collaboration of academia, government, and industry (11%).

It should be noted that some authors had multiple affiliations, often with different organization types (e.g., a federal lab and a university). The collaborations indicated in **Figure 8** do not distinguish between, for instance, an article authored by two individuals from different organization types and another article authored by one individual affiliated with two organization types.

Of the CMI Hub's 475 Scopus-tracked publications, 75% were authored by multiple organizations (or authors affiliated with multiple organizations). **Figure 9** depicts the geographic extent of this collaboration.

Figure 9. Map of organization coauthorships

The CMI Hub has coauthored 167 publications with 118 organizations in 30 other countries. Of these, the greatest number have been with organizations in Germany (32 publications), China (21), Poland (16), India (12), and Norway (10). Coauthorships are extensive and diverse in both type and geography. To illustrate, King Abdullah University of Science and Technology (Saudia Arabia) is linked with Lawrence Berkeley National Laboratory, the National Institute of Standards and Technology, and the University of Arizona. North Dakota State University is linked with Oak Ridge National Laboratory, Shaanxi University of Science and Technology (China), the University of Science and Technology (China), the University of Naples Federico II (Italy), the University of Tennessee, and Washington State University. The organizations most frequently linked by coauthorships are in **Table 6**.[7]

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[7] There is no significance to whether an organization is listed as Organization 1 or Organization 2.

Table 7. Most Frequent Organization Coauthorship (or Coaffiliation)

Number of Articles Coauthored or Coaffiliated	Organization 1	Organization 2
86	Ames National Laboratory	Iowa State University
40	Oak Ridge National Laboratory	University of Tennessee
36	Ames National Laboratory	Oak Ridge National Laboratory
24	Iowa State University	Ruhr-Universität Bochum
21	Oak Ridge National Laboratory	Lawrence Livermore National Laboratory
19	Ames National Laboratory	Lawrence Livermore National Laboratory
18	Ames National Laboratory	Ruhr-Universität Bochum
17	OLI Systems, Inc.	Rutgers University
16	Oak Ridge National Laboratory	Eck Industries, Inc.
15	Oak Ridge National Laboratory	Iowa State University
15	Rutgers University	University of California, Davis

3.1.11. Organization Networks

Gephi was used to construct a network of organizations based on co-authorships and then to identify organization communities within the network. Cleansed data on organizations (nodes) and their coauthorships (edges) were loaded into Gephi. As with authors, Gephi's Force Atlas algorithm was used to position nodes. **Figure 10** shows the network of 251 organizations authoring the CMI Hub's publications. Each node represents an organization. Node size is an indicator of the node's centrality to the entire network. It is based on the number of shortest paths passing through the node for all paths in the network. Node color represents a community as identified by Gephi's Modularity Class algorithm. Nodes of a community are more closely connected to each other than they are to other nodes in the network.

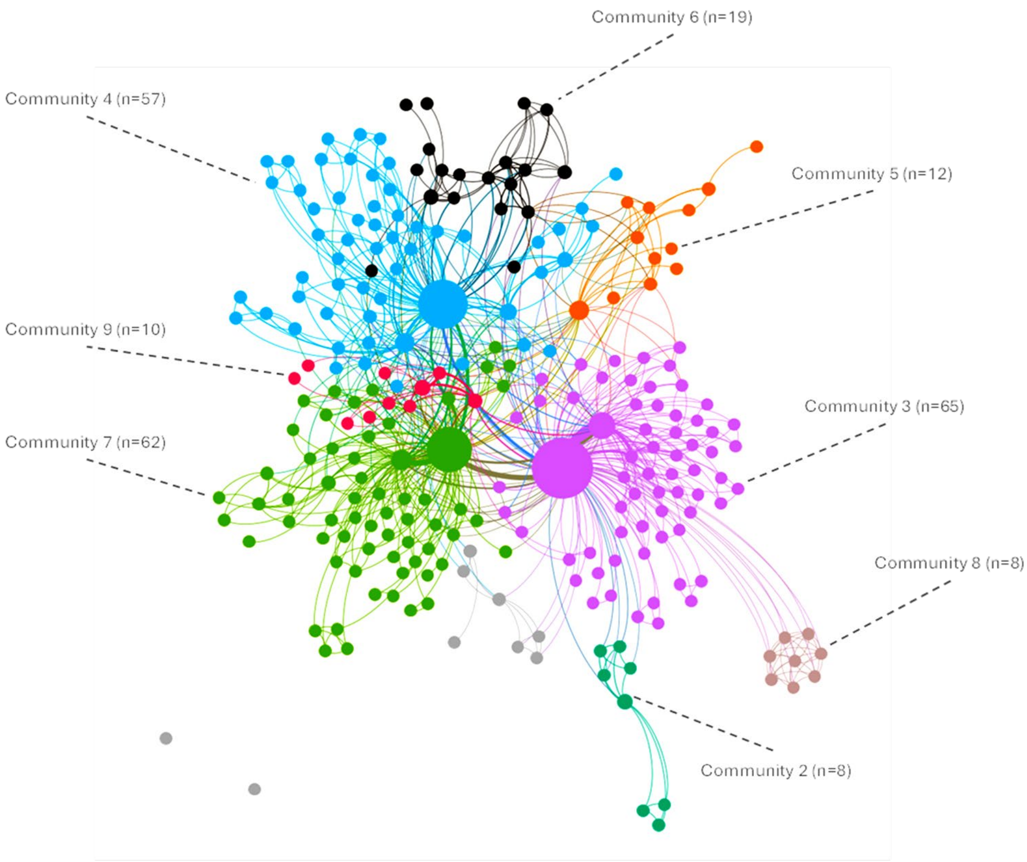

Figure 10. Network of organizations authoring the CMI Hub publications

Organizational networks tend to coordinate and collaborate to grow expertise within a particular discipline or topic. These networks are ongoing, and communities may change with time. Community 3 (n=65), Community 7 (n=62), and Community 4 (n=57) have the greatest degree of centrality.

Table 8 lists the three organizations in each community that are most central to the entire network. The eight most populous communities are displayed.

Table 8. Top Three Organizations in Each Community That Are Most Central to the Entire Network

Community 2	Community 3	Community 4	Community 5
Academy of Sciences Moldova Escola Universitària Salesiana de Sarrià Universidad de Zaragoza	Ames National Laboratory Iowa State University Ruhr-Universität Bochum	Lawrence Livermore National Laboratory Idaho National Laboratory Purdue University	Colorado School of Mines U.S. Geological Survey Lawrence Berkeley National Laboratory
Community 6	**Community 7**	**Community 8**	**Community 9**
Yale University Universitat Bern GE Global Research	Oak Ridge National Laboratory University of Tennessee Florida Polytechnic University	Institute for Basic Science (South Korea) Seoul National University Ewha Womans University	Rutgers University University of California, Davis OLI Systems, Inc

3.1.12. Keyword Analysis

Keyword analysis can identify research fronts—existing, growing, and emerging (Soriano, Álvarez, and Valdés 2018; Verma and Gustafsson 2020). Keyword co-occurrence analysis is often used to analyze strengths between links for a large number of documents (Shi, Miao, and Si 2019). Analyzing the co-occurrence of keywords reveals relationships within the discipline and the research frontiers. Two types of keywords were contained in Scopus: indexed keywords and author keywords. Indexed keywords are chosen by Scopus and standardized based on Scopus's licensed thesauri. Author keywords are selected by authors based on what are presumably the most important words that reflect the substance of the article. The index and author keywords are supplemented by an analysis of words contained in an article's title and abstract. Of the CMI Hub's 475 articles, 54% contained author keywords, 86% had index keywords, and 98% had words in the title and abstract (some publications did not include an abstract). Because of the missing author keywords, our analysis focused on index keywords and words in the title and abstract.

We conducted an occurrence and co-occurrence analysis of index keywords using VOSviewer. The occurrence analysis counted the number of articles in which a word appeared as an index keyword (e.g., the number of articles in which “magnets” appeared as an index keyword). The co-occurrence analysis counted the number of articles in which a pair of words appeared as index keywords (e.g., “magnets” and “recycling”). VOSviewer produced a network map depicting keywords as nodes, occurrence of a keyword as the size of the node, and co-occurrence of keywords as lines between nodes. Keywords that co-occur are clustered together, with clusters of nodes receiving the same color. Another version of the graphic colored the nodes by the mean publication year of the documents in which the keyword occurs. These clusters are useful for understanding the structure of research in a field and how it develops.

A similar occurrence and co-occurrence analysis of title and abstract words was conducted using Gephi. This allowed us to visually explore and interpret the networks to identify patterns and structures.

Growth in occurrence or co-occurrence of keyword(s) can indicate *growing* research fronts (Li et al. 2016; Yuan et al. 2022). We analyzed occurrence and co-occurrence of words in an article’s title/abstract over rolling four-year periods to identify indicators of growing research fronts.

New co-occurrence of keywords can indicate emerging research fronts. We identified the top new co-occurrences of words in an article’s title/abstract over the period 2019–2022. Conversely, this approach also allows us to identify research fronts that are receding.

We analyzed the occurrence and co-occurrence of index keywords and words in the title and abstract. This was followed by analysis of the trends in keywords over time.

3.1.13. Index Keywords

The most frequent occurrences of index keywords are presented in **Table 7**.

Table 9. Most Frequent Index Keywords

Index Keyword	Number of Occurrences
Rare Earths	151
Binary Alloys	67
Permanent Magnets	51
Magnets	49

Recycling	47
Neodymium Alloys	43
Iron Alloys	41
Cobalt Alloys	35
Magnetism	32
Aluminum Alloys	32

A total of 4,012 keywords appeared in the dataset, including variations of the same word or term (e.g., “rare earth” and “rare earths”). To display the relationships more clearly, we set a selection condition in VOSviewer to display keywords with a frequency of five or more occurrences. This resulted in a screening of 283 keywords. The total number of links between keywords is 7,884.

Figure 11 depicts the occurrence and co-occurrence of index keywords. Each node represents a keyword (or phrase), node size reflects the number of occurrences of the keyword, the line represents a co-occurrence of two keywords, color is the community associated with the keyword, and the proximity of nodes to one another reflects the degree of co-occurrence. The figure only includes index keywords with at least five occurrences.

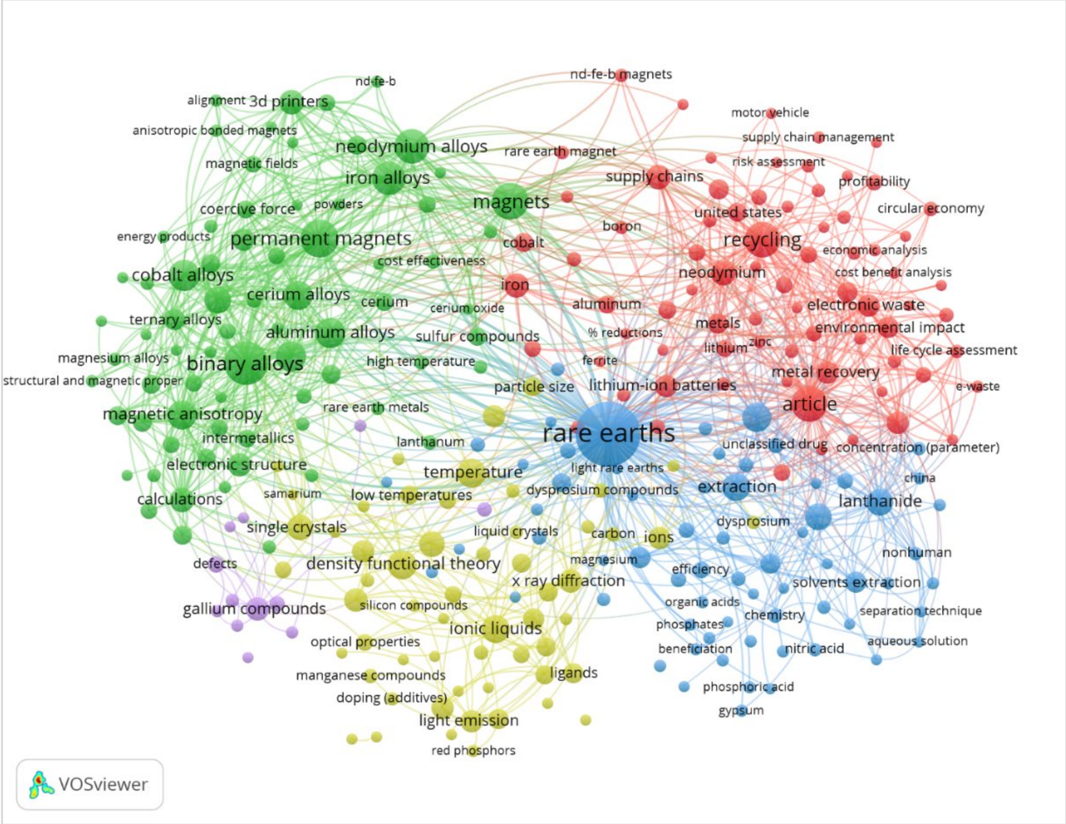

Figure 11. Occurrence and co-occurrence of index keywords

The figure reveals five clusters with a notable correlation between the keywords in each cluster. The clusters are interpreted as follows.

Red Cluster

This is the largest of the five clusters, representing 27% of the keywords. The most frequently used keyword is "recycling." Other common terms are "supply chains," "electronic waste," and "lithium-ion batteries." Several elements and materials are listed, including zinc, lithium, aluminum, boron, cobalt, and iron. The cluster also shows a high occurrence for the word "article." It is not clear why this keyword is indexed with such frequency. The red cluster is the third most integrated with other clusters, with 71% of its co-occurrences involving other clusters. It is most associated with the blue cluster, which is indicated by their proximity. The red cluster is least associated with the purple cluster, and the two are the least associated of any of the clusters. This is indicated by their distance from one another.

Green Cluster

This is the second largest cluster, representing 26% of the keywords. Frequent keywords in this cluster include "magnets," "permanent magnets," and "binary alloys." Magnets are also closely associated with the red cluster. Several alloys/elements are represented, the most prominent of which are neodymium, iron, cobalt, aluminum, and cerium. The cluster also contains some of the most frequently occurring keywords, as indicated by the number of relatively large bubbles in the figure. The green cluster is the least integrated with the other clusters, with only 66% of co-occurrences involving other clusters. It is most associated with the red cluster and least associated with the purple cluster.

Blue Cluster

This is the third largest cluster, representing 23% of the index keywords analyzed. The most frequently used keyword is “rare earth,” which was also the most frequent keyword across the publications. Other common terms in this cluster include “extraction,” “leaching,” and “lanthanide.” The blue cluster is the one most integrated with other clusters—77% of its co-occurrences involve a word external to the cluster. It is most associated with the red cluster and has few associations with the purple cluster.

Yellow Cluster

This cluster is the second smallest, representing 20% of the keywords. The frequency of keywords is less in this cluster compared to the others. Frequent keywords include “ionic liquids,” “ions,” “temperature,” “low temperatures,” “density functional theory,” and “single crystals.” The yellow cluster is the second most integrated with other clusters, with 76% of its co-occurrences involving other clusters. It is most integrated with the green cluster and least integrated with purple.

This is the smallest cluster by far, representing only 4% of the keywords. Frequent keywords include “gallium compounds,” “defects,” and “energy gap.” It is the second least integrated with other clusters, with only 66% of co-occurrences involving other clusters. It is most associated with the green cluster and least associated with the red cluster.

Figure 12 shows the occurrence and co-occurrence of index keywords by mean publication year of the documents in which the keyword occurs. The layout is the same as in Figure 11 and size still reflects number of occurrences, but color now represents the mean publication year of the keyword. Although the publication year of the CMI Hub publications ranges from 2013 to 2022, the mean publication year for keywords runs from late 2016 to early 2021.

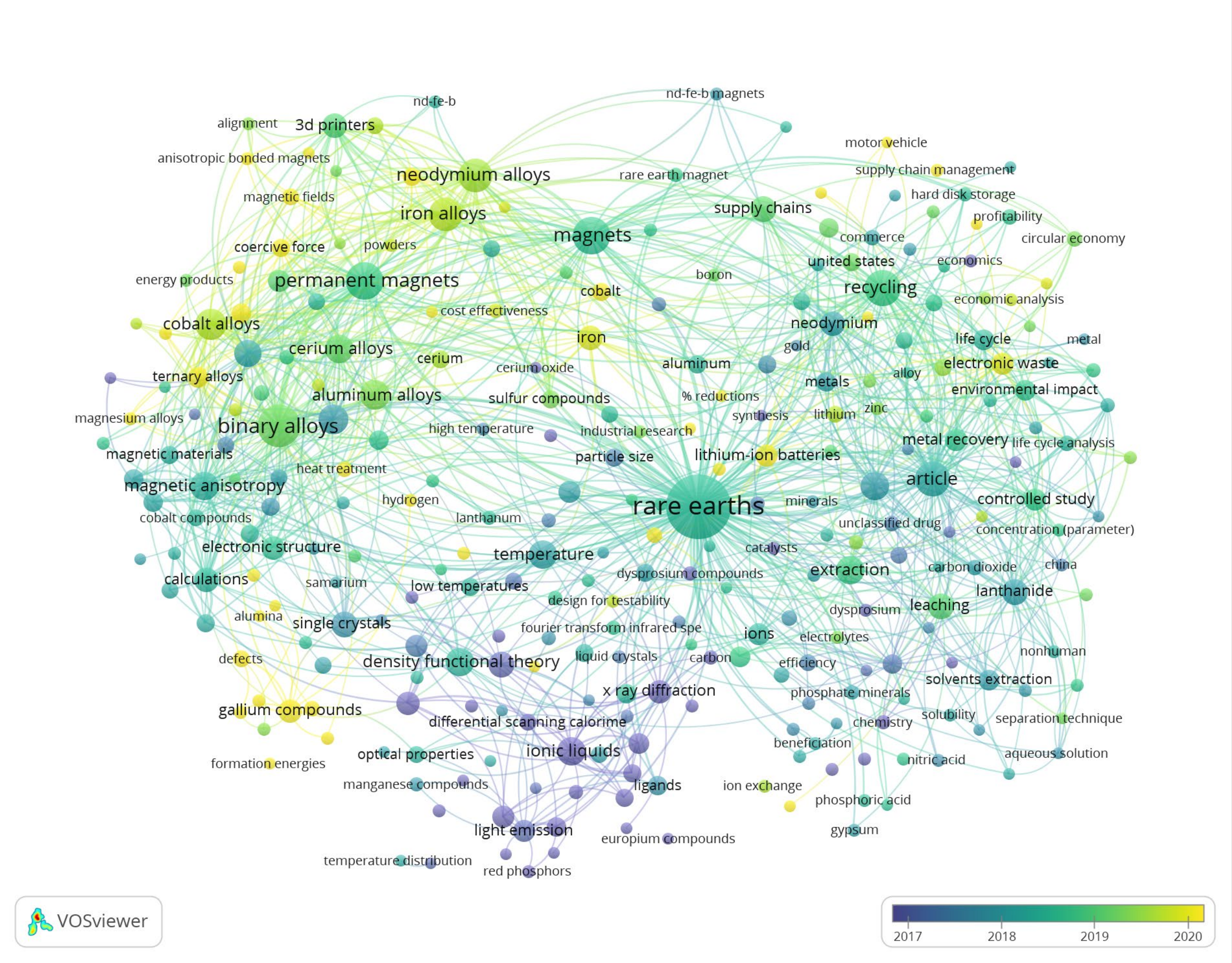

Figure 12. Occurrence and co-occurrence of index keywords by mean publication year

The overlay visualization by year, in a range of purple to yellow, shows trends over time. More recent trends, indicated by the yellow nodes, include “lithium-ion batteries,” “gallium compounds,” “magnetic fields,” and “electronic waste.” The purple nodes indicate topics that trended slightly earlier in time and include “ionic liquids” and “light emission.” The most common keywords—"rare earths,” “binary alloys,” and “magnets”—are in the middle of the color scale, indicating prevalence in the center of the time scale or perhaps across multiple time periods.

3.1.14. Title and Abstract Keywords

Another view of the subject areas of the CMI Hub research can be found through analysis of words in each article’s title and abstract. The advantage to this over index keywords is that 98% of the CMI Hub’s articles had a title and abstract while only 86% had index keywords. **Table 8** shows the most frequent keywords in the titles and abstracts of the CMI Hub’s articles. The top two keywords (magnet and REE) were also at or near the top of the list of index keywords, confirming that these were prevalent using both techniques. The keyword “phase” does not say much on its own. It was sometimes paired with the words "transition," "transformation," "diagram," and "boundary" but these represented a very small fraction of all occurrences. The keyword "technology" is 10th on the list but is generic and does not provide much additional information.

Table 10. Frequency of Keywords in Title and Abstract

Title and Abstract Keywords	Number of Occurrences
Magnet	184
REE	156
Recovery	153
Phase	121
Metal	119
Compound	110
Extraction	100
Production	98
Magnetic Property	96
Technology	90

Figure 13 depicts the occurrence and co-occurrence of 157 keywords in the title and abstract. Like Figure 11, each node represents a keyword (or phrase), node size reflects the number of occurrences of the keyword, the line represents a co-occurrence of two keywords, color is the community associated with the keyword, and the proximity of nodes to one another reflects the degree of co-occurrence.

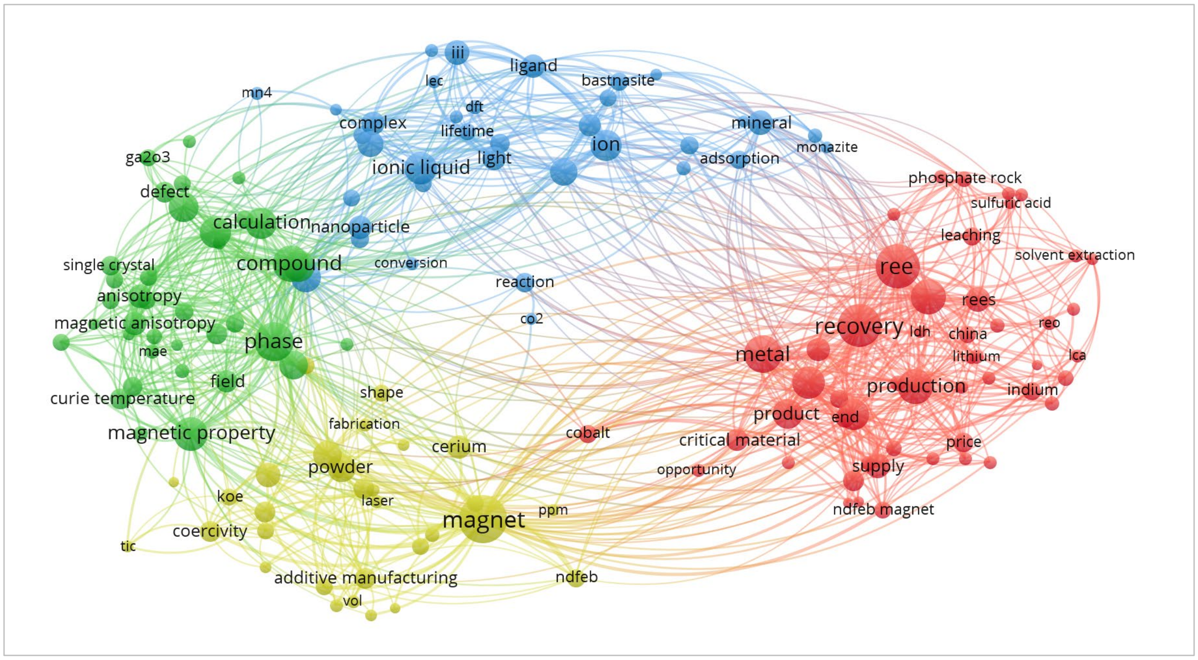

Figure 13. Occurrence and co-occurrence of keywords in the title and abstract

This figure reveals four clusters with the following characteristics.

Red Cluster

This is the largest of the four clusters with 51 words representing 32% of the 157 words analyzed. The cluster appears set apart from the other three clusters. This is because the red cluster has the highest rate of internal co-occurrence—38% of all co-occurrences involving this cluster are between two words within the cluster. Conversely, the cluster's 62% rate of external co-occurrences (involving a word from another cluster) is the lowest of the four clusters. Finally, the cluster contains some of the most frequent occurrences of words across the entire population, including "REE" (rare-earth element), "recovery," "metal," and "production." The red cluster here is somewhat similar to the red cluster for index keywords. This cluster has "metal" and "recovery" while the index keywords have "metal recovery." The keyword "lithium" is found in both.

Green Cluster

This cluster has 39 words (25% of the total). It has the highest external co-occurrence rate (18%) when measured as a percentage of all co-occurrences (instead of co-occurrences only involving the cluster). The cluster's most frequent occurrences include "phase," "compound," and "magnetic property." This cluster is like the green cluster of the index keywords. They both have magnetic anisotropy and calculation in common. However, single crystal found here is found in the yellow cluster for index keywords.

Blue Cluster

This cluster has 36 words (23% of the total). It has the second highest external co-occurrence rate (71%). It is most associated with the red and green clusters. Its 2% co-occurrence rate with the yellow cluster is the lowest of all the clusters. Its most frequent occurrences are “ionic liquid,” “ion,” and “synthesis.” This cluster is like the yellow cluster of the index keywords. They both have ion, ionic liquid, and ligand keywords in common, to name a few.

Yellow Cluster

This is the smallest of the four clusters, with 31 words (20% of the total). It is the most integrated with the other three clusters, with a 27% internal co-occurrence rate and a 73% external co-occurrence rate. The cluster’s most frequent occurrences include “magnet” (also the most frequent word overall), “powder,” and “cerium.” This cluster is like the green cluster of the index keywords. They both have magnet, powder, and cerium in common.

Table 9 below depicts the top 10 most frequent keyword co-occurrences across the titles and abstracts. The highest number of co-occurrences is between “iii” and “ion.” This is almost entirely accounted for by a single article.[8] The term “iii” is most often used along with the lanthanides in general (lanthanides[iii]), or specific lanthanides (like La[iii], Sm[iii], Gd[iii], or Er[iii]). In some instances, it refers to other elements, and in only a few instances as a separator between a list of items.

Table 11. Frequency of Title and Abstract Keyword Co-Occurrence

Title and Abstract Keywords	Number of Co-Occurrences
iii [9]& Ion	265
Extraction & REE	154
Recovery & REE	142
REE & REEs	124
Metal & Recovery	121
Extraction & Recovery	120
Demand & Supply	112

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[8] Balance 2019 accounted for most of the co-occurrences of “iii” and “ion.”

[9] “iii” is shorthand for an ionic state. Some elements generally have a single ion, such as sodium or magnesium elements. However, iron, for example, can naturally take multiple ionic states, so it is called Fe (II) or Fe (III), which also means Fe(2+) or Fe(3+).

Magnet & Magnetic Property	112
Magnet & NdFeB	109
Magnet & Powder	98

3.1.15. Keyword Growth

Growth in particular keywords can indicate a growing research front. **Figure 14** shows the ten keywords with the highest growth in occurrence in the title and abstract over rolling four-year periods. Occurrence of a keyword is measured as a percentage of all keywords for each rolling four-year period. The average occurrence of all 157 keywords was 0.6% of the total occurrence of all keywords (dotted line). The keyword “magnet” exhibited the highest growth—starting at 0% of all keywords in 2014–2017 and 2015–2018 but then growing each subsequent rolling 4-year period and reaching its peak of 9.5% in 2019–2022. The keyword “recovery” started at 4.3% in 2014–2017 and, after declining to 4.0%, grew to 6.9% in 2019–2022.

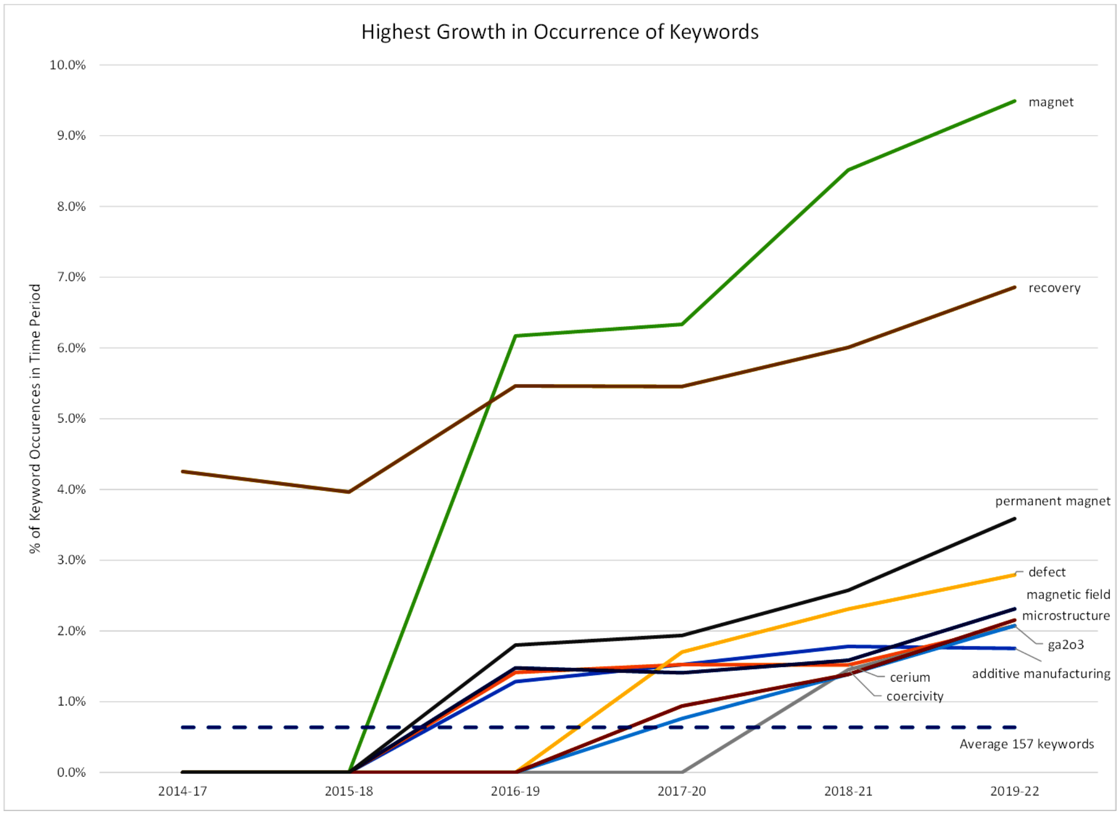

Figure 14. Growing research fronts as indicated by keyword growth

New co-occurrences of keywords can indicate emerging research fronts. **Table 10** identifies the top new co-occurrences of title/abstract keywords over the period 2019–2022. The average number of co-occurrences for keywords over 2019–2022 was 10.4. The top ten co-occurrences are well above that, ranging from 43 to 107 co-occurrences. The top 10 co-occurrences fall at or above the 96th percentile for all co-occurrences in 2019–2022. Note that some keywords, such as “condition,” “technology,” and “solution,” are combined with multiple words as they have broader applicability.

Table 12. Top New Occurrences of Keywords in 2019–2022

Keywords	Number of Co-Occurrences
Concentration & Extraction	107
Concentration & REE	78
Concentration & Recovery	66
Ionic Liquid & Solution	65
Recovery & Technology	58
Condition & Extraction	52
Aluminum Alloy & Cerium	44
Complex & Concentration	44
Magnet & Technology	44
Concentration & Condition	43
Concentration & Solution	43

Growth in the co-occurrence of keywords can provide additional insight into growth areas. **Figure 16** shows the highest growth in the co-occurrence of words in an article title/abstract over rolling four-year periods. The highest growth was seen in the co-occurrence of “concentration & extraction,” “magnet & magnetic property,” “magnet & permanent magnet” and “extraction & separation.” The co-occurrence of “alloy & cerium” showed a substantial increase in 2015–2018 but has declined since then.

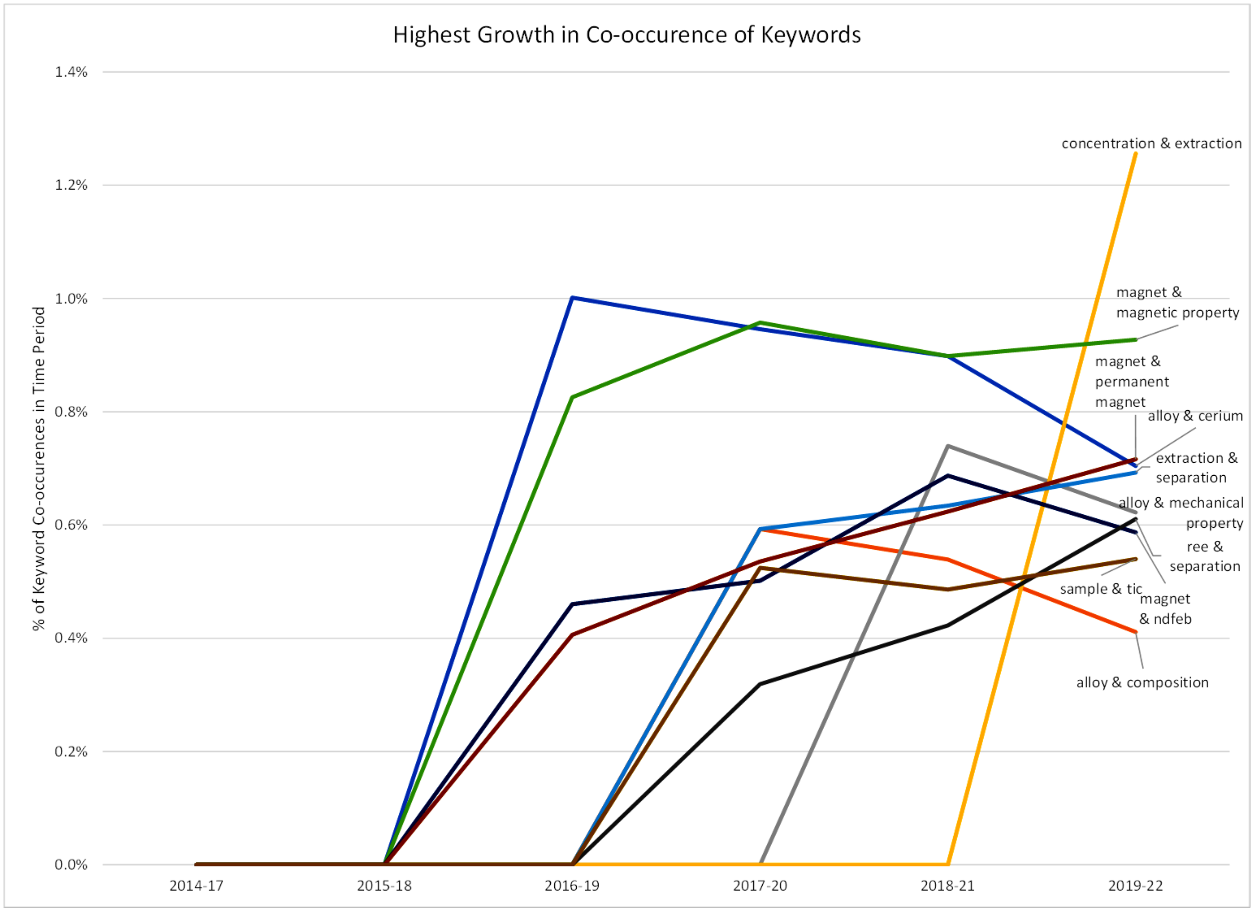

Figure 15. Keyword co-occurrence in sliding timeframes

3.2. Foundations of the CMI Hub Research Publications

3.2.1. Citation Analysis

The CMI Hub's 475 articles included 22,314 citations to 16,197 unique documents. About 83% (13,510) of the documents were cited once by the CMI Hub. The remaining 17% (2,687 documents) were cited 2 to 58 times by the CMI Hub publications. The most frequently cited documents are provided in **Table 11**.

Table 13. Documents Most Frequently Cited by the CMI Hub Publications

Rank	Document Cited by the CMI Hub Publications	Times Cited by the CMI Hub
1	Kresse, G., and J. Furthmüller. 1996. "Efficient Iterative Schemes for Ab initio Total-Energy Calculations Using a Plane-Wave Basis Set." *Physical Review B* 54(16): 11169–11186. https://doi.org/10.1103/physrevb.54.11169.	58
1	Perdew, J. P., K. Burke, and M. Ernzerhof. 1996. "Generalized Gradient Approximation Made Simple." *Physical Review Letters* 77(18): 3865. https://doi.org/10.1103/PhysRevLett.77.3865.	58
3	U.S. Department of Energy. 2011. *Critical Materials Strategy*. Washington, D.C.: U.S. Department of Energy. https://www.energy.gov/sites/prod/files/edg/news/documents/criticalmaterialsstrategy.pdf.	55
4	Blochl, P.E. 1994. "Projector Augmented-Wave Method." *Physical Review B* 50(24): 1795–17979. https://doi.org/10.1103/PhysRevB.50.17953.	53
5	Binnemans, K., P.T. Jones, B. Blanpain, T. Van Gerven, Y. Yang, A. Walton, and M. Buchert. 2013. "Recycling of Rare Earths: A Critical Review." *Journal of Cleaner Production* **51:** 1–22. https://doi.org/10.1016/j.jclepro.2012.12.037.	42
6	Kresse, G. and D. Joubert. 1999. "From Ultrasoft Pseudopotentials to the Projector Augmented-Wave Method." *Physical Review B* 59(3): 1758. https://doi.org/10.1103/PhysRevB.59.1758.	39
7	Kresse, G. and Furthmüller, J. 1996. "Efficiency of Ab-Initio Total Energy Calculations for Metals and Semiconductors Using a Plane-Wave Basis Set." *Computational Materials Science* 6(1): 15–50. https://doi.org/10.1016/0927-0256(96)00008-0.	34
8	Xie, F., T. A. Zhang, D. Dreisinger, and F. Doyle. 2014. "A Critical Review on Solvent Extraction of Rare Earths From Aqueous Solutions." *Minerals Engineering* 56**:** 10–28. https://doi.org/10.1016/j.mineng.2013.10.021.	30
9	Kresse, G. and J. Hafner. 1993. "Ab Initio Molecular Dynamics for Liquid Metals." *Physical review B* 47(1): 558–561. https://doi.org/10.1103/PhysRevB.47.558.	26
10	Alonso, E., A. M. Sherman, T. J. Wallington, M. P. Everson, F. R. Field, R. Roth, and R. E. Kirchain. 2012. Evaluating Rare Earth Element Availability: A Case With Revolutionary Demand From Clean Technologies. *Environmental Science and Technology* 46(6): 3406–3414. https://doi.org/10.1021/es203518d.	24

10	Blaha, P., K. Schwarz, G. K. Madsen, D. Kvasnicka, and J. Luitz. 2001. *WIEN2K. An Augmented Plane Wave+ Local Orbitals Program for Calculating Crystal Properties.* Vienna University of Technology, Austria.	24

Documents cited by the CMI Hub span a broad period, from 1794 to 2022 (**Figure 17**).[10] Most were published from 2010 to 2019. Among the documents most frequently cited by the CMI Hub publications, four are in this time increment. As scientific research in the field of critical materials advances quickly, it is expected that cited sources are timely but also include seminal research articles or foundational books for background.

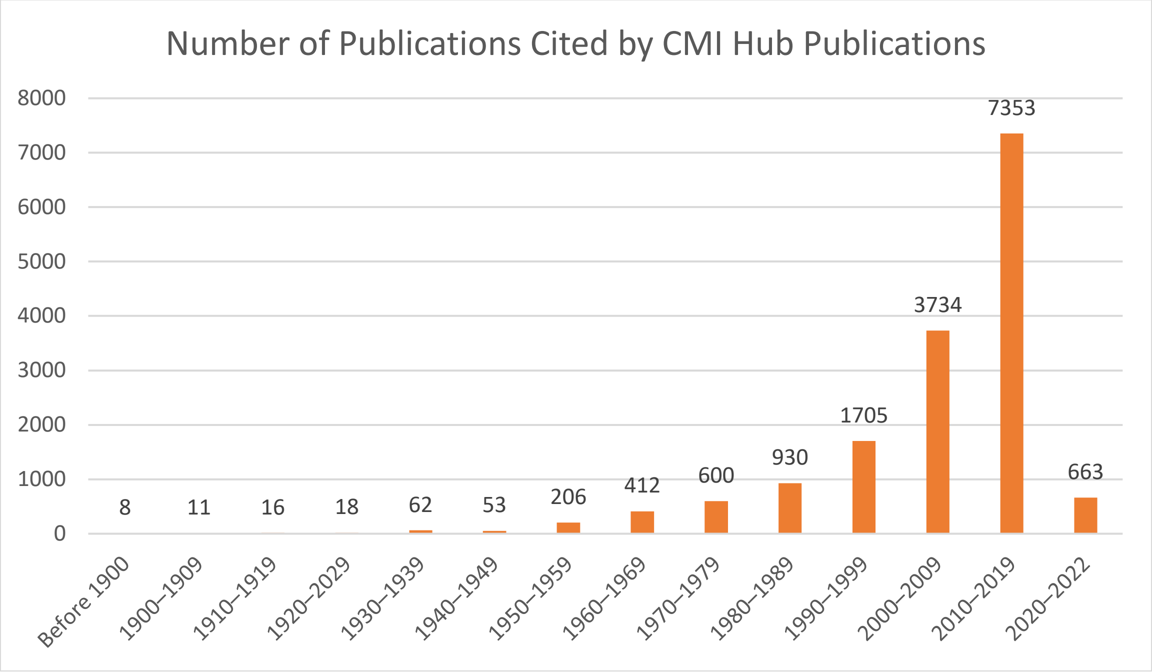

Figure 16. Number of publications cited by the CMI Hub by year of cited publication

3.3. Impacts of the CMI Hub Research Publications

3.3.1. Number of Citations

Bibliometric analysis is based on the idea that a publication’s impact is measured by the number of citations as well as the prestige of other journals that have cited it. As such, citations are useful to ascertain influence across papers as well as the scholarly

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[10] The earliest work cited by a the CMI Hub publication is J. Gadolin’s 1794 *Undersökning af en svart tung stenart ifrån ytterby stenbrott i roslagen, kongl*. *Vetenskaps Academiens Nya Handlingar*, 15, pp. 137-155. [Examination of a black heavy rock from Ytterby quarry in Roslagen. *New Proceedings of the Academy of Sciences.*]

measure of a paper's impact on scientific research in a field. Counts may be measured by author, institution, or location. Generally, higher counts translate to higher impact.

As of Dec. 2, 2022, the CMI Hub's 475 Scopus publications had received 9,747 citations, or 20.5 citations per publication. [11] One of the factors influencing how many citations a publication receives is how long it has been since it was published. **Table 12** shows how the number of citations has changed over time for the CMI Hub's publications. As expected, citation rates are generally higher for older publications.

Table 14. Number of Citations per Year and per Publication

Year Published	Number of Publications	Number of Citations	Number of Citations per Publication
2013	2	16	8.0
2014	21	1,154	55.0
2015	42	1,180	28.1
2016	59	2,010	34.1
2017	65	1,551	23.9
2018	63	1,468	23.3
2019	57	1,315	23.1
2020	67	661	9.9
2021	60	348	5.8
2022 (Partial)	39	44	1.1
Total	475	9,747	20.5

Another factor impacting citations is the document type. Review articles typically have high citation rates. Indeed, the CMI Hub's 24 review articles received an average of 63.4 citations each. The core of the CMI Hub's publications are research articles. These 410 articles received an average of 19.3 citations each. Data on citations by document type are provided in **Table 13**.

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[11] As of March 2024, the number of citations of the 475 publications had grown to 13,400.

Table 15. Number of Publications and Citations by Scopus Document Type

Document Type	Number of Publications	Number of Citations	Number of Cites per Publication
Article	410	7,908	19.3
Chapter	9	21	2.3
Conference Paper	19	175	9.2
Data Paper	1	0	0.0
Editorial	4	42	10.5
Erratum	2	2	1.0
Letter	1	58	58.0
Note	4	12	3.0
Retracted Article	1	7	7.0
Review	24	1,522	63.4
Total	475	9,747	20.5

The 10 most frequently cited the CMI Hub publications are listed in **Table 14**. A high citation count can indicate an article is important to the research community, has utility to the field, and is having an impact. However, citation counts can be affected by the type of article, the journal in which it is published, and the time since publication. Five of the ten publications are review articles, which tend to have higher citation counts than other document types. Five of the articles are from journals with high impact factors: *Chemical Reviews* (two articles; impact factor 62.1), *Chemical Society Reviews* (impact factor 46.2), *Science* (impact factor 56.9), and *Chemical Engineering Journal* (impact factor 15.1).[12] Eight of the articles were published in 2014–2016, the first few years of the CMI Hub's existence. These articles have had more time to garner citations than more recent articles.

To help mitigate the effect of elapsed time on the number of citations, the table also shows the citation density of each publication (i.e., the number of citations divided by the number of years since publication). When this is used as a measure, the ranking of Hou et al.'s (2019) article jumps from sixth to third. While the two publications with the most citations also have the highest citation densities, two other publications have

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[12] Impact factors were generated from the journal impact search engine Bioxbio, available at https://www.bioxbio.com.

notably high citation densities. Hou et al. (2019) and Wu et al. (2018) have higher rankings for citation density than for the number of citations. This suggests that their lower citation values are likely due to the shorter period they have had to accumulate citations.

Table 16. 10 Most Frequently Cited the CMI Hub Publications

Publication	Document Type	Number of Citations	Citation Density
Wu L., A. Mendoza-Garcia, L. Q. Li, and S. Sun. 2016. “Organic Phase Syntheses of Magnetic Nanoparticles and Their Applications.” *Chemical Reviews* 116(18): 10473–10512. https://doi.org/10.1021/acs.chemrev.5b00687.	Review	421	70.2
Du, M. H. 2014. “Chemical Trends of Mn4+ Emission in Solids.” *Journal of Materials Chemistry C* 2: 2475–2481. https://doi.org/10.1039/C4TC00031E.	Article	198	62.3
Emsbo P., P. I. McLaughlin, G. N. Breit, E. A. du Bray, and A. E. Koenig. 2015. “Rare Earth Elements in Sedimentary Phosphate Deposits: Solution to the Global REE Crisis?” *Gondwana Research* 27(2): 776–785. https://doi.org/10.1016/j.gr.2014.10.008.	Review	181	25.9
Izatt R. M., S. R Izatt, R. L. Bruening, N. E. Izatt, and B. A. Moyer. 2014. “Challenges to Achievement of Metal Sustainability in our High-Tech Society.” *Chemical Society Reviews* 43: 2451–2475. https://doi.org/10.1039/C3CS60440C.	Review	169	21.1
Li L. A. Tirado, I. C. Nlebedim, O. Rios, B. Post, V. Kunc, R. R. Lowden, E. Lara-Curzio, R. Fredette, J. Ormerod, T. A. Lograsso, and M. P. Paranthaman. 2016. “Big Area Additive Manufacturing of High Performance Bonded NdFeB Magnets.” *Scientific Reports* 6: 36212. https://doi.org/10.1038/srep36212.	Article	135	22.5
Hou H., E. Simsek, T. Ma, N. S. Johnson, S. Qian, C. Cisse, D. Stasak, N. Al Hasan, L. Zhou, Y. Hwang, R. Radermacher, V. I. Levitas, M. J. Kramer, M. A. Zaeem, A. P. Stebner, R. T. Ott, J. Cui, and I. Takeuchi. 2019. “Fatigue-Resistant High-Performance Elastocaloric Materials Made by Additive Manufacturing.” *Science* 366(6469): 1116–1121. https://doi.org/10.1126/science.aax7616.	Article	133	44.3
Wu S., L. Wang, L. Zhao, P. Zhang, H. El-Shall, B. Moudgil, X. Huang, and L. Zhang. 2018. “Recovery	Review	120	30.0

of Rare Earth Elements From Phosphate Rock by Hydrometallurgical Processes – A Critical Review.” *Chemical Engineering Journal* 335: 774–800. https://doi.org/10.1016/j.cej.2017.10.143.			
Beltram, D., G. Cote, H. Mokhtari, B. Courtaud, B. A. Moyer, and A. Chagnes. 2014. “Recovery of Uranium From Wet Phosphoric Acid by Solvent Extraction Processes.” *Chemical Reviews* 114(24): 12002–12023. https://doi.org/10.1021/cr5001546.	Review	119	14.9
Paranthama, M. P., C. S. Shafer, A. M. Elliott, D. H. Siddel, M. A. McGuire, R. M. Springfield, J. Martin, R. Fredette, and J. Ormerod. 2016. “Binder Jetting: A Novel NdFeB Bonded Magnet Fabrication Process.” *JOM* 68: 1978–1982. https://doi.org/10.1007/s11837-016-1883-4.	Article	107	17.8
Li Y., O. Rios, J. K. Keum, J. Chen, and M. R. Kessler. 2016. “Photoresponsive Liquid Crystalline Epoxy Networks With Shape Memory Behavior and Dynamic Ester Bonds.” *ACS Applied Materials and Interfaces* 8(24): 15750–15757. https://doi.org/10.1021/acsami.6b04374.	Article	101	16.8

The highest number of citations and the highest citation density occurred for the same publication: Wu et al. (2016), titled “Organic Phase Syntheses of Magnetic Nanoparticles and Their Applications” in *Chemical Reviews*. The subject matter among the most cited articles includes magnetic nanoparticles, manganese ion emission energy, potential of phosphorites as a primary source for rare earth elements, and metal sustainability.

3.3.2. Percentile Ranking of Publications

Scopus provides a percentile ranking for a publication based on the number of citations it receives and considers the date of publication, document type, and disciplines associated with its source. A graphical depiction of the percentile rankings for the CMI Hub’s publications is provided in **Figure 18**. The data indicate that no the CMI Hub publications are below the 26th percentile and only 21% are below the 50th percentile. The average the

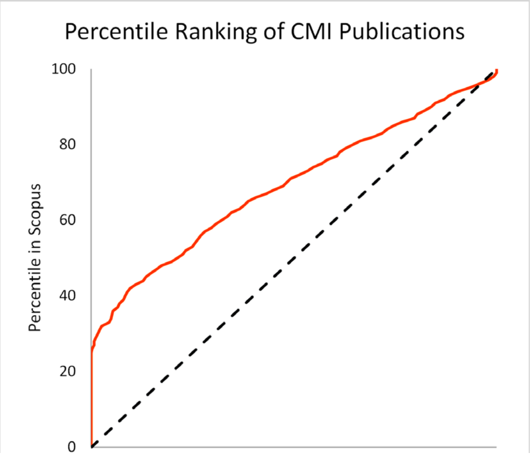

Figure 17. Percentile Ranking of the CMI Hub Publications

CMI Hub publication is at the 70th percentile.[13] The dotted line indicates what the CMI Hub's percentile would look like if the CMI Hub's publications matched the overall percentile distribution in Scopus. That is, 20% of the CMI Hub's publications were at the 20th percentile, 40% were at the 40th percentile, etc. the CMI Hub's publications are clearly above this line.

3.3.3. Field-Weighted Citation Impact

The Field-Weighted Citation Impact (FWCI) is the ratio of the number of citations received by a publication to the number of citations expected for similar documents. Similar documents are ones in the same discipline, of the same type (e.g., article, letter, review) and of the same age (Elsevier Library Connect and Delasalle 2016). the CMI Hub's publications had an average FWCI of 1.51, meaning that on average the CMI Hub's publications received 51% more citations than expected. The distribution of the CMI Hub's FWCI scores are shown in **Figure 19**. Note that 209 publications had a FWCI of less than 1, while 122 publications had a FWCI of 1 to less than 2. (Publications with an FWCI of an exact whole number are counted in the upper bin. For example, a FWCI of 2.0 is counted in the "2–3" bin not the "1–2" bin.)

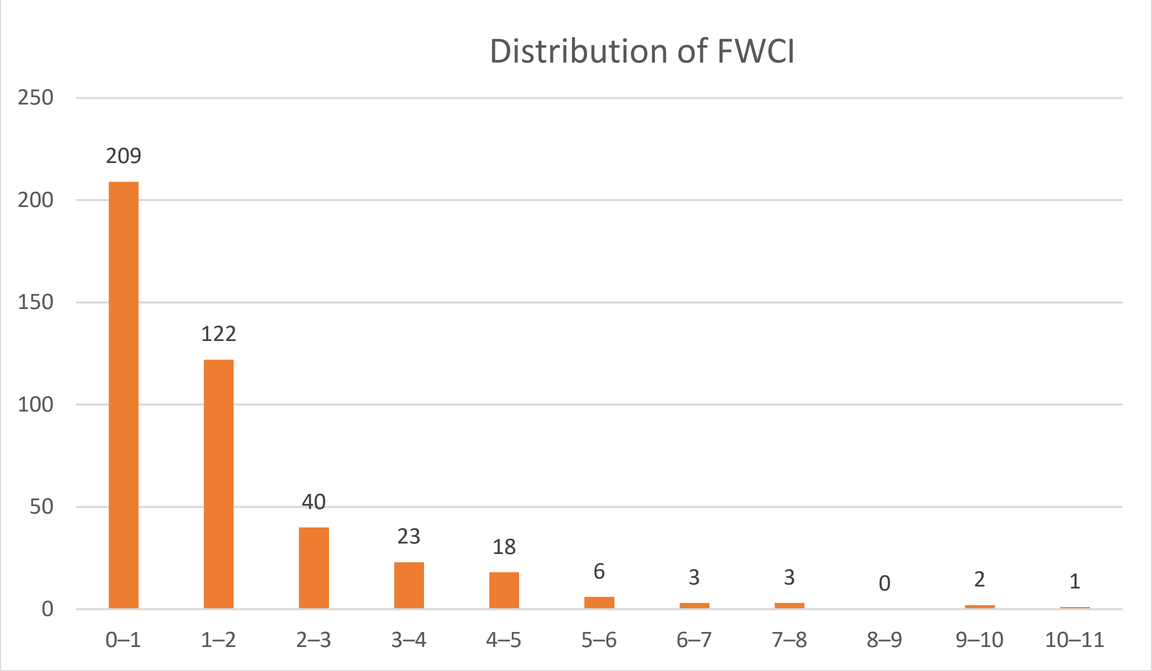

Figure 18. Distribution of FWCI for the CMI Hub publications

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[13] Note that not all publications have a percentile ranking.

Table 15 lists the CMI Hub publications with the ten highest FWCI scores. Six of the 10 are research articles and four are conference papers. The prevalence of conference papers may be due to their easier accessibility as they are often open source. Three articles are in the top 10 FWCI and top ten citations (Hou et al. 2019, Du 2014, and Paranthaman et al. 2016).

Table 17. Publications With the 10 Highest FWCI

Publication	Document Type	FWCI	Citations
Ingebrigtsen, M. E., A. Y. Kuznetsov, B. G. Svensson, G. Alfieri, A. Mihaila, U. Badstubner, A. Perron, L. Vines, and J. B. Varley. 2019. "Impact of Proton Irradiation on Conductivity and Deep Level Defects in β-Ga2O3." ***APL Materials*** **7: 022510. https://doi.org/10.1063/1.5054826.**	Article	10.05	100
Peelaers, H., J. L. Lyons, J. B. Varley, C. G. Van de Walle. 2019. "Deep Acceptors and Their Diffusion in Ga2O3." ***APL Materials*** **7: 022519. https://doi.org/10.1063/1.5063807.**	Article	9.32	91
Sims, Z. C., D. Weiss, O. Rios, H. B. Henderson, M. S. Kesler, S. K. McCall, M. J. Thompson, A. Perron, and E. E. Moore. 2020. "The Efficacy of Replacing Metallic Cerium in Aluminum-Cerium Alloys With LREE Mischmetal." In: Tomsett A. (eds) ***Light Metals 2020*****. The Minerals, Metals & Materials Series. Springer, Cham. https://doi.org/10.1007/978-3-030-36408-3_30.**	Conference Paper	9.23	7
Jin, H., P. Afiuny, T. McIntyre, Y. Yih, and J. W. Sutherland. 2016. "Comparative Life Cycle Assessment of NdFeB Magnets: Virgin Production Versus Magnet-to-Magnet Recycling." ***Procedia CIRP*** **48: 45–50. https://doi.org/10.1016/j.procir.2016.03.013.**	Conference Paper	7.88	35
Antropov, A., L. Ke, and D. Aberg. 2014. "Constituents of Magnetic Anisotropy and a Screening of Spin-Orbit Coupling in Solids." ***Solid State Communications*****. 194: 35–38. https://doi.org/10.1016/j.ssc.2014.06.003.**	Conference Paper	7.04	61
Hou, H., E. Simsek, T. Ma, N. S. Johnson, S. Qian, C. Cisse, D. Stasak, N. Al Hasan, L. Zhou, Y. Hwang, R. Radermacher, V. I. Levitas, M. J. Kramer, M. A. Zaeem, A. P. Stebner, R. T. Ott, J. Cui, and I. Takeuchi. 2019. "Fatigue-Resistant High-Performance Elastocaloric Materials Made by Additive Manufacturing."	Article	7.02	133

***Science* 366(646): 1116–1121. https://doi.org/10.1126/science.aax7616.**			
Du, M. H. 2014. "Chemical Trends of Mn4+ Emission in Solids." *Journal of Materials Chemistry C* 2: 2475 –2481. https://doi.org/10.1039/C4TC00031E.	Article	6.98	198
Paranthaman, M. P., C. S. Shafer, A. M Elliott, D. H. Siddel, M. A. McGuire, R. M. Springfield, J. Martin, R. Fredette, and J. Ormerod. 2016. "Binder Jetting: A Novel NdFeB Bonded Magnet Fabrication Process." *JOM* 68: 1978–1982. https://doi.org/10.1007/s11837-016-1883-4.	Article	6.93	107
Vaccarezza, V. and C. Anderson. 2019. "Beneficiation and Leaching Study of Norra Karr Eudialyte Mineral." In: Kim, H., et al. *Rare Metal Technology 2018*. TMS 2018. The Minerals, Metals & Materials Series. Springer, Cham. https://doi.org/10.1007/978-3-319-72350-1_4.	Conference Paper	6.00	9
Frodason, Y. K., K. M. Johansen, L. Vines, and J. B. Varley. 2020. "Self-Trapped Hole and Impurity-Related Broad Luminescence in Beta-Ga2O3." *Journal of Applied Physics* 127: 075701. https://doi.org/10.1063/1.5140742.	Article	5.82	57

3.3.4. Self-Citation

Citation values are influenced by, among other things, citations to one's own work. An author can increase the number of their citations by citing their previous publications. There are two metrics that measure this effect: self-citation rate and self-reference rate. The *self-citation rate* is the percentage of citations an author's publications receive that are from the author themselves. Authors with lower self-citation rates are generally seen to demonstrate more impact on the scientific community, all other things equal. The *self-reference rate* is the percentage of citations an author makes that refer to their own publications. It is seen as an indicator of how much an author draws upon their own work to inform their current work. The self-citation rate and the self-reference rate both use the same numerator (the number of citations to one's own work) but the denominators are different. The self-citation rate uses the total citations one's publication receives while the self-reference rate uses the total number of references in one's own publications.

Benchmark values for self-citation rates vary by discipline (Aksnes 2003) and gender[14], and the number of citations a paper or author receives. Self-citation rates are about 9% overall, 15% for the physical sciences, and 3% for highly cited physical sciences (i.e., the top 1% by citations in the field). Highly cited papers and authors have lower self-citation rates because the denominator (number of citations) is much larger.

We calculated a self-citation rate where the CMI Hub was the author. That is, for the 475 CMI Hub publications, the number of times those publications cited other CMI Hub publications, divided by the total number of citations the 475 publications received. We found a CMI Hub self-citation rate of 10%, which is slightly higher than the 9% overall rate but below the 15% physical sciences rate (Szomszor et al. 2020) (**Figure 20**). This suggests that the CMI Hub publications have more impact on the scientific community than the average physical sciences author.

We also calculated a self-reference rate for the CMI Hub's publications using the CMI Hub as the author, that is, for the 475 CMI Hub publications, the number of times those publications cited other the CMI Hub publications divided by the total number of references in the 475 publications. We found a CMI Hub self-reference rate of 5%, which is lower than the overall self-reference rate (15%) and the highly cited physical sciences self-reference rate (10%). This suggests that the CMI Hub draws less upon its own publications to inform its work than either the average author or highly cited physical science authors.

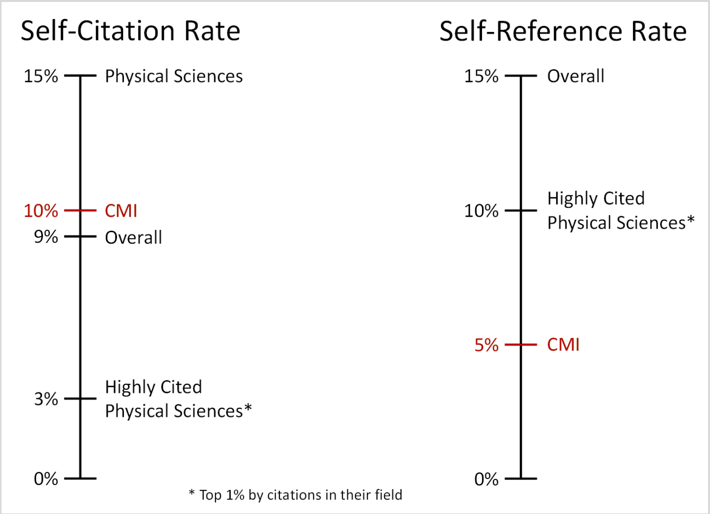

Figure 19. the CMI Hub Self-Citation Relative to Benchmarks

One way to visualize self-citations is through a self-citation map. **Figure 21** is self-citation map for the CMI Hub. The circles represent the CMI Hub's publications and lines the CMI Hub's citations to its own publications. Circle size reflects the total number of citations the publication received, as does the vertical axis (log scale). The horizontal

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[14] King et al. (2017) found that in the last two decades of data, men self-cited 70% more than women.

axis reflects publication date with each year given width to allow for ordering of publications based on predecessor and successor citations. Citation counts are from the Litmaps tool and may differ slightly from Scopus.

Since citation counts tend to grow over time, older publications tend to have larger circles that are placed higher on the y-axis than do more recent publications. Wu (2016) had about 400 citations, yet only a handful of them appear to be from other the CMI Hub authors. Hou (2019) had about 100 citations, none of which were from other the CMI Hub authors. These cases reinforce the notion that most the CMI Hub's citations are from outside the CMI Hub community.

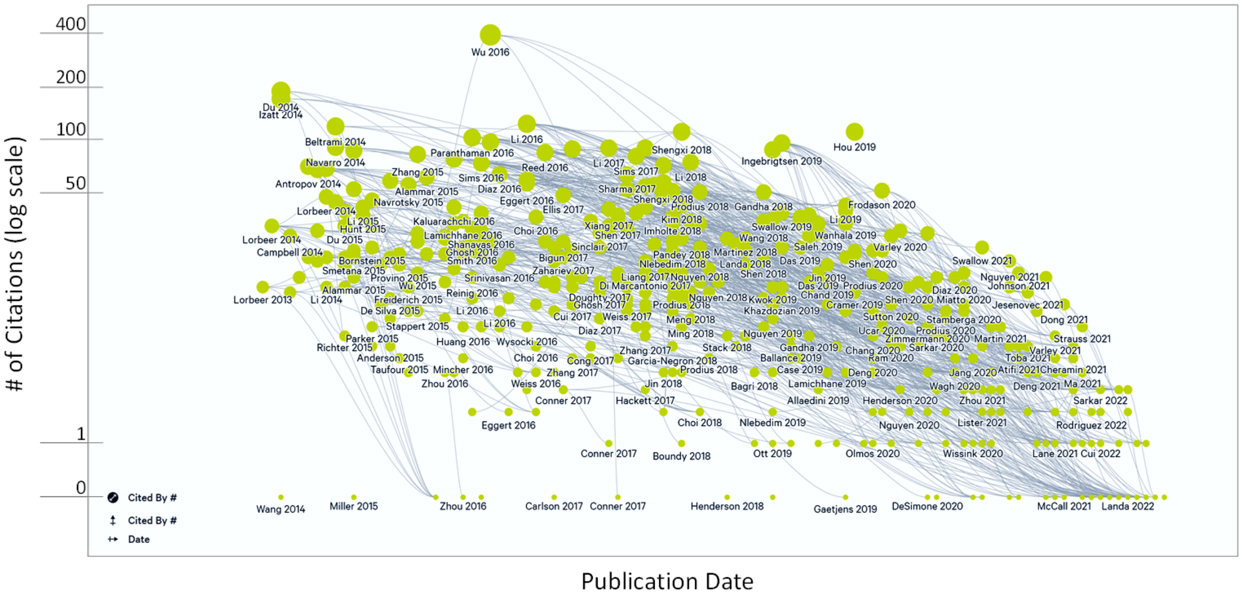

Figure 20. The CMI Hub self-citation map

3.3.5. Other Citation Indices

Three other citation indices are often used to capture author production: the h-index, i10-index, and the g-index. These are measures of influence (h-index) and impact (g-index, i10-index). The h-index is the number of publications (h) by an author that have been cited at least h times. the CMI Hub has 45 publications cited at least 45 times, meaning its h-index is 45. The i10-index is the number of publications with at least 10 citations. the CMI Hub has 235 publications cited at least 10 times, meaning its i10-index is 235. The g-index is the largest number of publications (g) that together receive at least g^2 citations. the CMI Hub has 69 publications that together have received at least 69^2 (4,761) citations, so the CMI Hub's g-index is 69. We offer these indices as a point of reference. They are typically applied to individual authors. They have some downsides, such as being biased against early career researchers and not being normalized by field. Some universities and research organizations publish one or more of these indices. However, they are biased by the size of research organization.

3.3.6. Community Production and Impact

We conducted a network analysis where both organizations and the articles they author were members of the network. We used Gephi to assign all 251 organizations and 475 articles to communities. A community is a cluster of nodes that are more densely connected to each other than to the overall network. Gephi identified 15 communities; the eight most populous communities are identified in **Figure 23.** Organizations are represented by circles and articles by squares. Node size reflects the centrality of the node to the entire network. The most central organizations to the network are identified for each community. The three organizations in each community that are the most central to the overall network are identified.

Table 16 identifies the top five index keywords associated with each article-organization community. "Rare earths" are one of the top five keywords in every community except Community 3.

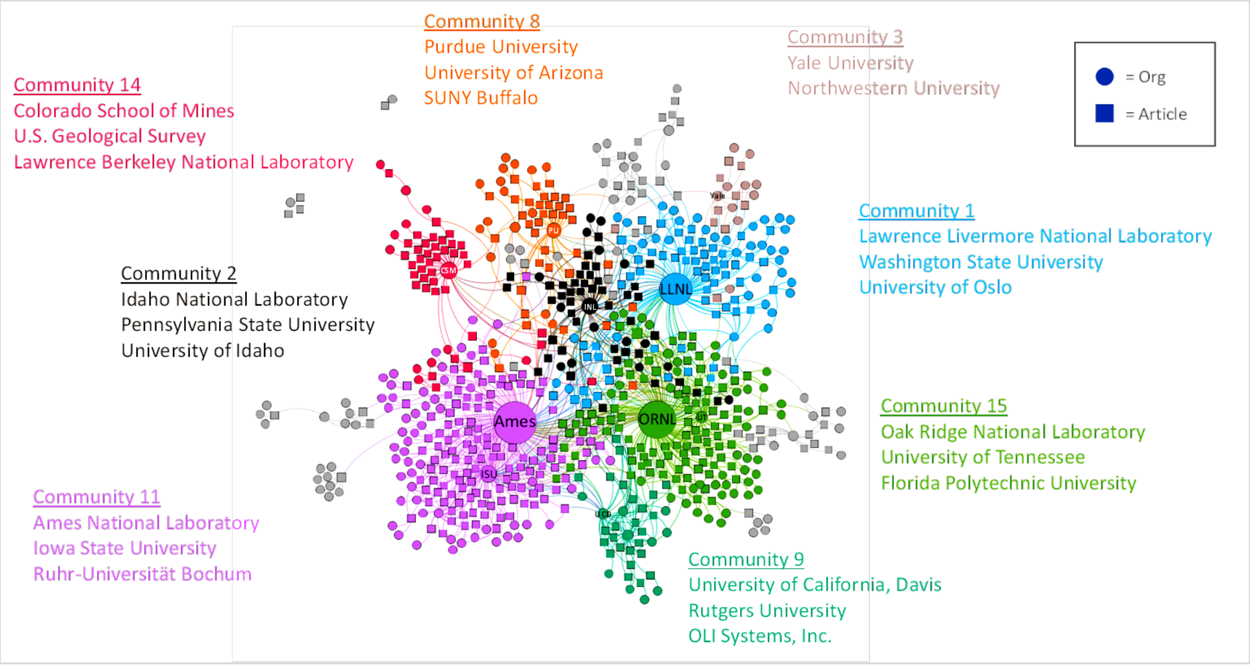

Figure 21. Article-organization communities

Table 18. Top Keywords Associated With Each Article-Organization Community

Community (Number)	Top Five Index Keywords
Ames National Laboratory(11)	Binary alloys, rare earths, ionic liquids, cobalt alloys, permanent magnets
Oak Ridge National Laboratory (15)	Aluminum alloys, binary alloys, cerium alloys, rare earths, permanent magnets
Lawrence Livermore National Laboratory (1)	Gallium compounds, binary alloys, rare earths, density function theory, defects
Idaho National Laboratory (2)	Rare earths, recycling, rare earth elements, extraction, metal recovery
Colorado School of Mines (14)	Rare earths, costs, leaching, recycling, flotation
Purdue University (8)	Rare earths, life cycle, magnets, rare earth elements, recycling
University of California, Davies (9)	Rare earths, rare earth elements, electrolytes, fluorine compounds, mixed solvent electrolytes
Yale University (3)	Phonons, recycling, electric power factor, human, lithium

We calculated the production and impact of each community in terms of articles, citations, FWCI, and patents (**Table 17**). Patents, another key indicator for assessing the quality, or impact, of research (Narin and Hamilton 1996), were assigned to a community based on the organization(s) of the inventor(s) associated with the patent. If the organizations fell across multiple communities, then each community received partial credit for the patent.

The table shows a few things. First, the Ames community had the most organizations and the most articles. The Oak Ridge community had the second most organizations and articles and had the most patents. The Lawerence Livermore community had the third highest number of articles and the highest FWCI.

Table 19. Community Production and Impact

Community (Number)	Organizations	Articles	Citations	FWCI	Patents
Ames National Laboratory (11)	56	126	2,189	1.17	5 (all), 6 (pt)
Oak Ridge National Laboratory (15)	45	94	2,322	1.51	6 (all), 8 (pt)
Lawrence Livermore National Laboratory (1)	38	61	1,305	2.25	1 (all), 9 (pt)
Idaho National Laboratory (2)	16	43	764	1.42	2 (all), 7 (pt)
Colorado School of Mines (14)	12	39	698	1.57	3 (pt)
Purdue University (8)	18	36	644	1.80	---
University of California, Davis (9)	11	25	512	1.52	---
Yale University (3)	10	10	201	1.80	---
Others	45	41	1,112	1.32	1 (pt)
All	251	475	9,747	1.51	29

We then created a scatter plot of FWCI against the number of publications for each community (Figure 24). Almost all communities had FWCIs above one, indicating an above-average citation impact and that the research is likely considered influential by other researchers. Communities that had FWCI scores below one had relatively few publications. Looking at the communities with the most publications (Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, and Ames National Laboratory), as the count of publications increases, the average FWCI decreases. This suggests that it may be difficult to maintain a high FWCI as the number of publications increases. While maintaining a high FWCI as the number of publications increases can be challenging, researchers may focus on quality over quantity of publications and staying attuned to the field dynamics (e.g., some fields have higher citation rates than others, and emerging fields tend to have fewer established works to cite) to sustain a strong citation impact over time.

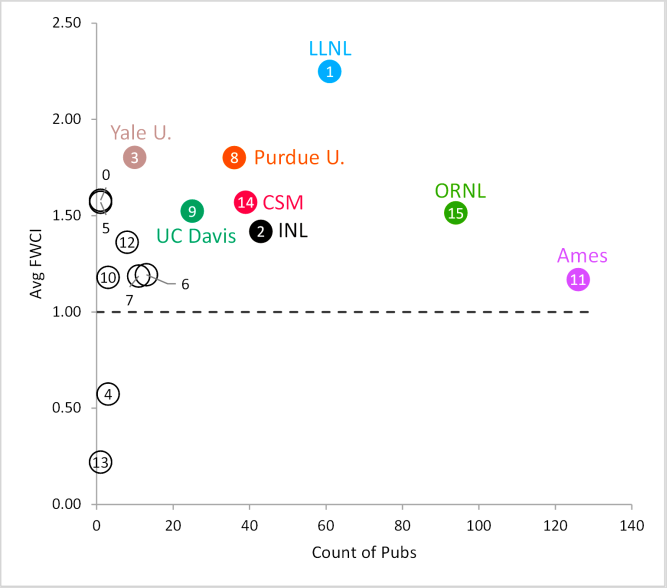

Figure 22. FWCI and publication count for article-organization communities, where LLNL=Lawrence Livermore National Laboratory, INL=Idaho National Laboratory, ORN=Oak Ridge National Laboratory, Ames=Ames National Laboratory, UC Davies=University of California , Davis, CSM=Colorado School of Mines, and U.=University

4. Conclusions

This research utilized a bibliometric analysis to generate a profile of the CMI Hub research community and the growing and emerging research fronts in critical materials. Specifically, it 1) characterized the CMI Hub research, 2) identified the foundational research upon which the CMI Hub research is built, and 3) identified impacts of the CMI Hub research through a bibliometric analysis.

Three categories of research literature were considered: (1) the CMI Hub publications, consisting primarily of articles, conference papers, and reviews of original research; (2) publications cited in the CMI Hub publications, representing the foundation of the CMI Hub research; and (3) citations of the CMI Hub publications, reflective of the impact of the CMI Hub publications.

4.1. Observations and Conclusions

The analysis yielded the following observations and conclusions.

The CMI Hub has developed a large, interconnected research community. Across 475 publications, the CMI Hub has developed a research community of 1,039 authors. Of these, 98.7% of the authors are connected to all other the CMI Hub authors through authorships on the CMI Hub publications alone. Network analysis showed 81% of authors belonging to eight communities ranging in size from 50 to 155 authors. the CMI Hub's publications were authored by individuals affiliated with 251 organizations. The organizations span six continents and 31 countries. The country with the most publications, besides the United States, is Germany. Seventy-five percent of the CMI Hub's 475 Scopus-tracked publications were authored by multiple organizations (or authors affiliated with multiple organizations). Most publications (76%) were authored by individuals from academia and government/lab. Specifically, through academia (15%), government/lab (17%), or a collaboration of the two (44%). Industry was also an author on 13% of the publications, usually in collaboration with government/lab, academia, or both. A network analysis of organizations placed them into nine communities. The organizations most central to the network were Ames National Laboratory, Oak Ridge National Laboratory, and Lawrence Livermore National Laboratory.

The CMI Hub's publications are based on a broad set of literature. the CMI Hub's publications include 22,314 citations to 16,197 unique documents published from 1794 to 2022. The decade with the highest number of citations by the CMI Hub was 2010 to 2019. The ten most frequently cited documents were published from 1993 to 2014. The U.S. Department of Energy's *Critical Materials Strategy* is the third most cited document by the CMI Hub.

Keywords indicate growing research fronts. Of the ten keywords having the highest growth in occurrence, nine had no occurrences in the CMI Hub publications from 2014–2017. Keywords with the highest growth include "magnet," "recovery," "permanent magnet," "defect," "magnetic field," "microstructure," "cerium," "coercivity," "Ga_2O_3," and "additive manufacturing." Using an overlay visualization, we could discern trends over time based on the average publication year for keywords. Recent trends include "lithium-ion batteries," "gallium compounds," "magnetic fields," and "electronic waste." Topics that trended slightly earlier in time include "ionic liquids" and "light emission." Co-occurrence of keywords have also evolved. Of the ten co-occurrences of keywords that had the highest growth, none had co-occurrences in 2014–2017. The highest growth in co-occurrence includes "concentration & extraction," "magnet & magnetic property," "magnet & permanent magnet," "alloy & cerium," "extraction & separation," "alloy & mechanical property," "REE & separation," "magnet & NdFeB," "sample & tic," and "alloy & composition."

Keywords indicate potential emerging research fronts. Keywords having the highest growth in co-occurrences in recent years indicate potential emerging research fronts. Top new co-occurrences of keywords over the period 2019 to 2022 include concertation and extraction, concentration and rare-earth elements, concentration and recovery, and ionic liquid and solution, and recovery and technology.

The CMI Hub's publications are highly cited and impactful. As of December 2, 2022, the CMI Hub's 475 publications had received 9,747 citations, or 20.5 citations per publication. The average FWCI value for the CMI Hub's publications was 1.51, meaning the CMI Hub's publications received 51% more citations than expected. Only 21% of the CMI Hub's publications are below the 50th percentile of Scopus percentile ranking. The average the CMI Hub publication is at the 70th percentile of Scopus percentile ranking.

The self-citation rate was 10%, which is slightly higher than the 9% overall rate but below the 15% physical sciences rate. This suggests that the CMI Hub publications have more impact on the scientific community than the average physical sciences author. The CMI Hub self-reference rate is 5%, which is lower than the overall self-reference rate (15%) and the highly cited physical sciences self-reference rate (10%). This suggests that the CMI Hub draws less upon its own publications to inform its work than either the average author or highly cited physical science authors.

Article-organization communities have varying size and impact. Analysis of articles and organizations considered together resulting in eight primary article-organization communities that had varying indicators of production and impact. The Ames National Laboratory community had the highest number of publications (126). The Oak Ridge National Laboratory community had the highest number of citations (2,322) and patents (14). The Lawrence Livermore National Laboratory community had the highest average FWCI (2.25) for its publications.

The observations outlined above indicate that the CMI Hub publications have played an important role in the development of the literature supporting the critical materials field.

5. References

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