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Capillary electrophoresis - A bibliometric analysis

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ABSTRACT

We have explored the history of the field of capillary electrophoresis using bibliometric methods. The analysis shows that 416 prolific researchers are connected in a single, large, co-authorship network based on publications on capillary electrophoresis between 1980 and 2021, with a few pioneers having remained active throughout much of this time period. Looking at research topics revealed electrochemistry, sensors, nanotechnology and metabolomics as 'hot' topics, with fundamental method development being more 'mature', and reveal that capillary electrophoresis technology have matured over a 30-year time period, with research efforts moving from separations to quantitative measurements to biomedical applications. The citation patterns showed the strongest coupling between journals of similar scope. Interactive versions of the bibliometric network visualizations are available on-line at https://tinyurl.com/2z7q7wcx (researcher co-authorship network), https://tinyurl.com/2jmhsgxx (research topic network) and https://tinyurl.com/2lnfzzgn (journal bibliographic coupling citation network).

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1. Introduction

Capillary electrophoresis is a family of analytical separation techniques that have seen wide application, from clinical, environmental, food and forensic analyses of specific compounds to genomics, proteomics and metabolomics measurements of large numbers of similar analytes. The history of and state-of-the-art in capillary electrophoresis have been extensively reviewed in recent years, for example by Harstad et al. [1] and Voeten et al. [2]. The powerful hyphenation of capillary electrophoresis with mass spectrometry has been reviewed by Stolz et al. [3], as has the applications of this hyphenated technique in proteomics [4], metabolomics [5] and glycomics [6]. In this work we performed bibliometric analyses to help answer at least the first four of the "Five Ws" (the "who", "what", "when" and "where") by looking at authors and co-authorships, term frequencies and co-occurrences, publication dates, and journals in publications on capillary electrophoresis.

2. Methods

Bibliometrics [7] is the study of bodies of interrelated documents, for example the scientific literature, and provides well-established methodologies for analyzing and visualizing connections among research topics, researchers, affiliations or journals.

Here we searched the Dimensions database [8] for articles on the topic of "capillary electrophoresis" that are published between 1980 and 2021. We used Dimensions because it includes publications from a large number of sources, it performs disambiguation of researchers, and it allows users to search the full text of publications. We used the following query to perform the Dimensions full data search: ("capillary electrophoresis" OR "capillary affinity electrophoresis" OR "capillary array electrophoresis" OR "capillary gel electrophoresis" OR "capillary sieving electrophoresis" OR "capillary zone electrophoresis" OR "capillary isoelectric focusing" OR "capillary isotachophoresis" OR "capillary electrochromatography") AND (date:[1980-01-01 TO 2021-12-31]). The Dimensions full data search was performed on November 21, 2022.

We then used the VOSviewer software tool [9] to map collaborations (co-authorships), topics (term co-occurrence) and citation patterns (journal bibliographic coupling). Onto these maps, additional information was overlayed, such as average publication year (revealing trends) and number of citations. The VOSviewer

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software tool is freely available on https://www.vosviewer.com/. For a step-by-step tutorial on the use of VOSviewer, including how to display the overlaid information, see a recent book chapter by Van Eck and Waltman [10]. Tutorial videos are also available on the VOSviewer website.

3. Results

The Dimensions full data search returned 203,142 publications of the publication type article published between 1980 and 01-01 and 2021-12-31 (Fig. 1). The number of publications grew exponentially throughout the 1980s and until around 1997, after which the growth has been more uneven but approximately linear. After nearly reaching a plateau 2012–2017, the number of publications per year is now increasing again.

Looking next at the collaborative network (Fig. 2), we see that 416 researchers in the field (with at least 55 co-authored publications in the period 1980–2021) are connected in a single network component, with some regional clusters outside this major component.

Looking at the average publication year overlay reveal some of the pioneers in the field, such as James W. Jorgensen (average publication year 1997.14), Stellan Hjertén (1997.61), Shigeru Terabe (1998.53), Richard N. Zare (1999.18), Barry L. Karger (1999.41), Pier Giorgio Righetti (1999.37), Richard D. Smith (2001.86), Salvatore Fanali (2003.45), Norman J. Dovichi (2004.83), Bezhan Chankvetadze (2007.34), Alejandro Cifuentes (2006.77) and Václav Kašička (2008.71). These are just examples of researchers who in the authors' view are well-known for their contributions to the field of capillary electrophoresis. All of these are, or at least until very recently were, active researchers. This is particularly impressive when considering Stellan Hjertén published his first paper (with electrophoresis inventor and Nobel laureate Arne Tiselius) in 1956 and his most recent work in 2018, 62 years later. Papers published prior to 1980 were not part of the corpus in these analyses, so these average publication years would be even earlier if older papers had been included (even if they are still increasing as the authors publish new articles).

The author disambiguation successfully resolved what would otherwise be a dominating co-authorship cluster of Chinese researchers which including many authors of the same name as another author. Most of these have average publication years in the mid-2010s, though there are exceptions. Author name disambiguation is a well-known issue, especially among these researchers, which without disambiguation leads to overcounting publications for an undercounted number of authors.

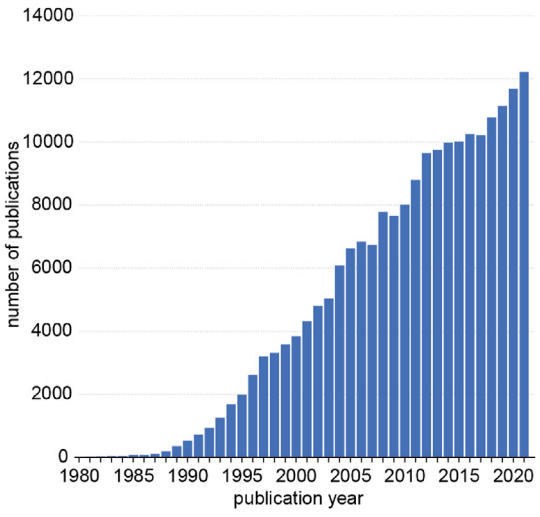

Fig. 1. The number of articles in the Dimensions database matching the search query for each year of publication 1980–2021.

The term co-occurrence map (Fig. 3) splits into two major subnetworks. One subnetwork is enriched in terms related to method development. This can in turn be divided into development of separations and detection, albeit with a significant overlap. The second major subnetwork is enriched in terms related to applications. This can be further separated into terms related to DNA sequencing and other biomedical applications. "Spectrometry", as in "mass spectrometry", is a large node relatively close to the center of the map, suggesting mass spectrometric techniques are used both during development and in applications of capillary electrophoresis.

Overlaying the average publication year reveals 'cold', or perhaps more positively 'mature' research topics, including many of those terms that relate to the development of capillary electrophoresis separations, including "capillary", "buffer", "voltage", "mobility", "separation", "resolution". These all have average publication years in the early 2000s. Terms that relate to quantitative methods such as "determination", "concentration", "limit", "detection" and "range" have average publication years around 2012, followed by terms in the biomedical cluster such as "metabolome", "metabolomics", "early diagnosis", "biomarker", "biomarker discovery" and "novel biomarker" with average publication years around 2015. This suggests a gradual maturation of capillary electrophoresis technology over a three decades (1990–2020) as research and development shifted from improving separations to making sensitive and quantitative measurements, and finally to application in clinical studies. Other terms with average publication years closer to 2000 than today include "DNA sequencing", "sequence analysis", "human genome", "PCR product". This can be explained by the dominance of capillary (array) electrophoresis in DNA sequencing [11,12] during the sequencing of the human genome (and other genomes) in the 1990s [13].

The 'hottest' region in the term map is in the upper left corner and largely consists of terms related to electrochemical sensors, including "electrochemical sensor" itself, "electrocatalytic activity", "differential pulse voltammetry", "nanoparticle", "nanocomposite", "graphene" and "graphite oxide". But also among more mature topics there are hotspots. Some of these, including "next generation sequencing" and "NGS" in the DNA sequencing cluster, may come from papers referring to, or comparing results with, capillary electrophoresis as a superseded technology, rather than being new applications of capillary electrophoresis itself. But others do reveal more recent avenues of research, for example in metabolomics. Finally, there are some special cases, such as "SARS-CoV" with an average publication year very close to 2020, suggesting papers involving capillary electrophoresis and SARS-CoV-2 vastly outnumber those published during the first SARS-CoV outbreak in 2002–2004. This is unsurprising given the vastly different scales of the initial outbreak and the COVID-19 pandemic and the extremely large number of papers on SARS-CoV-2 [14].

In the bibliographic coupling citation analysis (Fig. 4), we see clusters based on the topics considered within the scope of the journals. Electrochemistry and sensors dominate in one cluster (blue). Mass spectrometry journals are clustered with proteomics journals (cyan). Food (yellow) and environmental (brown) chemistry journals also form their distinct clusters. General interest journals such as *Nature*, *PNAS* and *PLoS One* are clustered with clinical and forensics and genetics journals, suggesting applications of capillary electrophoresis in these fields have reached the broadest audiences.

We also see strong couplings between journals of similar scope from different publishers, e.g., between broad analytical chemistry journals such as *Analytical and Bioanalytical Chemistry* (Springer)

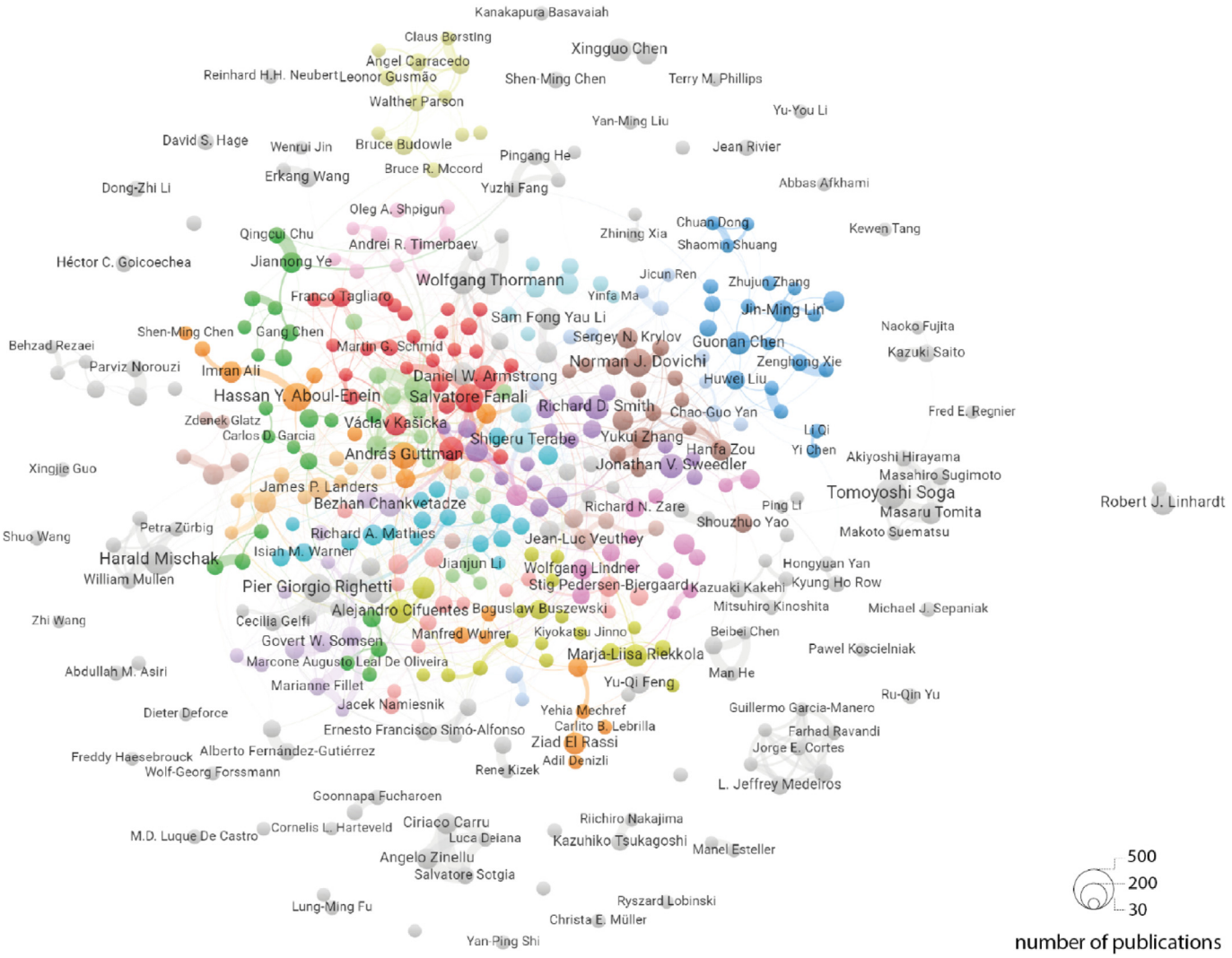

Fig. 2. VOSviewer visualization of the co-authorship network of researchers publishing on capillary electrophoresis in the period 1980–2021, including many of the contributors to this Special Issue. Researchers with at least 55 co-authored publications are included in the visualization. The area of the circles is proportional to the number of publications. An interactive version of this visualization with overlays is available on https://tinyurl.com/2z7q7wcx.

and *Journal of Chromatography A* (Elsevier), and between *Analytical Chemistry* (ACS) and *Electrophoresis* (Wiley). The same holds for more applied journals, such as between *Journal of Agricultural and Food Chemistry* (ACS) and *Food Chemistry* (Elsevier), and between *Clinical Chemistry and Laboratory Medicine* (de Gruyter) and *Clinical Chemistry* (Oxford University Press). This journal (*Trends in Analytical Chemistry*) has the strongest bibliographic coupling with *Journal of Chromatography A*, followed by *Analytical Chemistry*. However, a caveat in these analyses is that it is not uncommon for journals to change publisher, with some, such as the *Journal of the American Society for Mass Spectrometry*, having changed more than once in the analyzed time period (from Elsevier to Springer to ACS). When overlaying average publication year on the journals and consistent with the above observations, we see that journals publishing on method development in analytical chemistry, including the journal of this name, *Journal of Chromatography A* and *B*, and *Electrophoresis* have published on capillary electrophoresis for a very long time, with average years of publication between 2004 and 2006. Contrastingly, journals in electrochemistry and sensors have average publication years between 2014 and 2017, consistent with the more recent average publication year for the terms related to these topics in Fig. 3.

The interactive VOSviewer visualizations are available at https://tinyurl.com/2z7q7wcx (Fig. 2), https://tinyurl.com/2jmhsgxx (Fig. 3) and https://tinyurl.com/2lnfzzgn (Fig. 4).

4. Discussion

The bibliometric analyses show that it is feasible to study the development of a scientific field spanning decades and tens of thousands of publications. To our knowledge, this is the first comprehensive bibliometric and co-authorship analysis of the field of capillary electrophoresis. The co-authorship network exhibits geographical patterns of collaboration, but also many international collaborations, in particular within Europe. There are still active researchers who published important work before 1980 - in a few cases as far back as the 1960s. However, as modern capillary electrophoresis is generally regarded as having taken off with capillary zone electrophoresis and the work of Jorgenson and Lukacs in 1981 [15], our analyses have captured at least the modern era of the field.

When studying the history of a field, looking at a simple metric such as average publication year for authors, terms and journals, reveal major trends. For capillary electrophoresis, one such major trend is the gradual transition from fundamental method

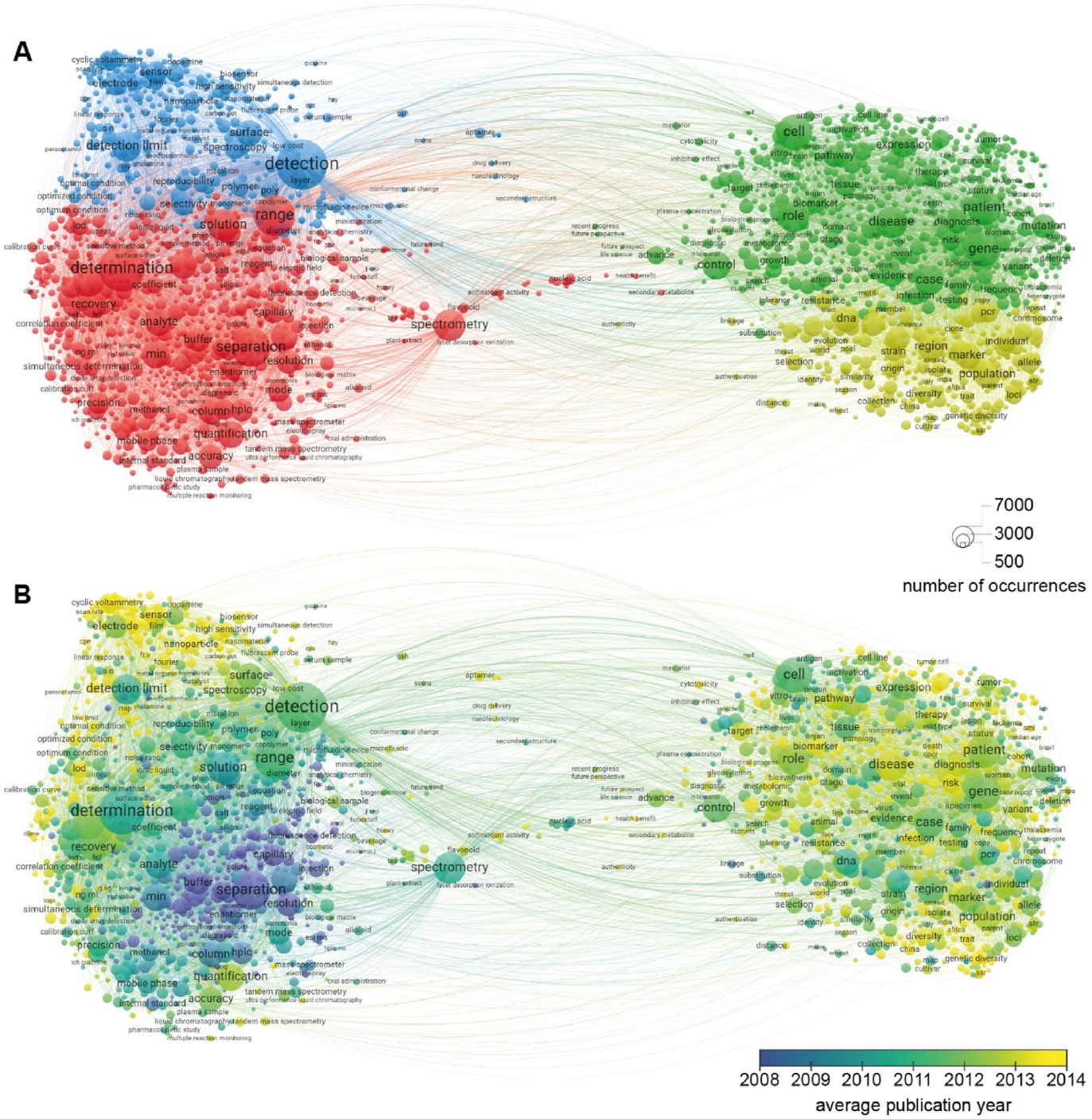

Fig. 3. VOSviewer visualization of terms co-occurring in the titles and abstracts of capillary electrophoresis publications (A), first separating into method development (left) and applications (right), with clusters broadly corresponding to method development in capillary electrophoresis (red), detection methods and electrochemistry (blue), biomedical applications (green) and DNA sequencing (yellow). Overlaying publication years reveal which topics are 'hot' and which are not (B). The clustering and layout are independent on publication year. Terms identified in at least 220 titles and abstracts are included in the visualization. The area of the circles is proportional to the number of occurrences. An interactive version of this visualization is available on https://tinyurl.com/2jmhsgxx.

development - first to separate and then to quantify analytes - to applications in biomedical research. The latter were dominated by DNA sequencing in the 1990s and early 2000s but have since shifted more toward metabolomics and clinical studies. In recent years, we also see an increasing overlap between capillary electrophoresis, sensors and new nanomaterials. These are still methods being researched and developed but may see increasing practical application in the future. As single-cell analyses are becoming more common in transcriptomics, proteomics and metabolomics, capillary electrophoresis and related techniques will likely see increasing application in sample handling and separation.

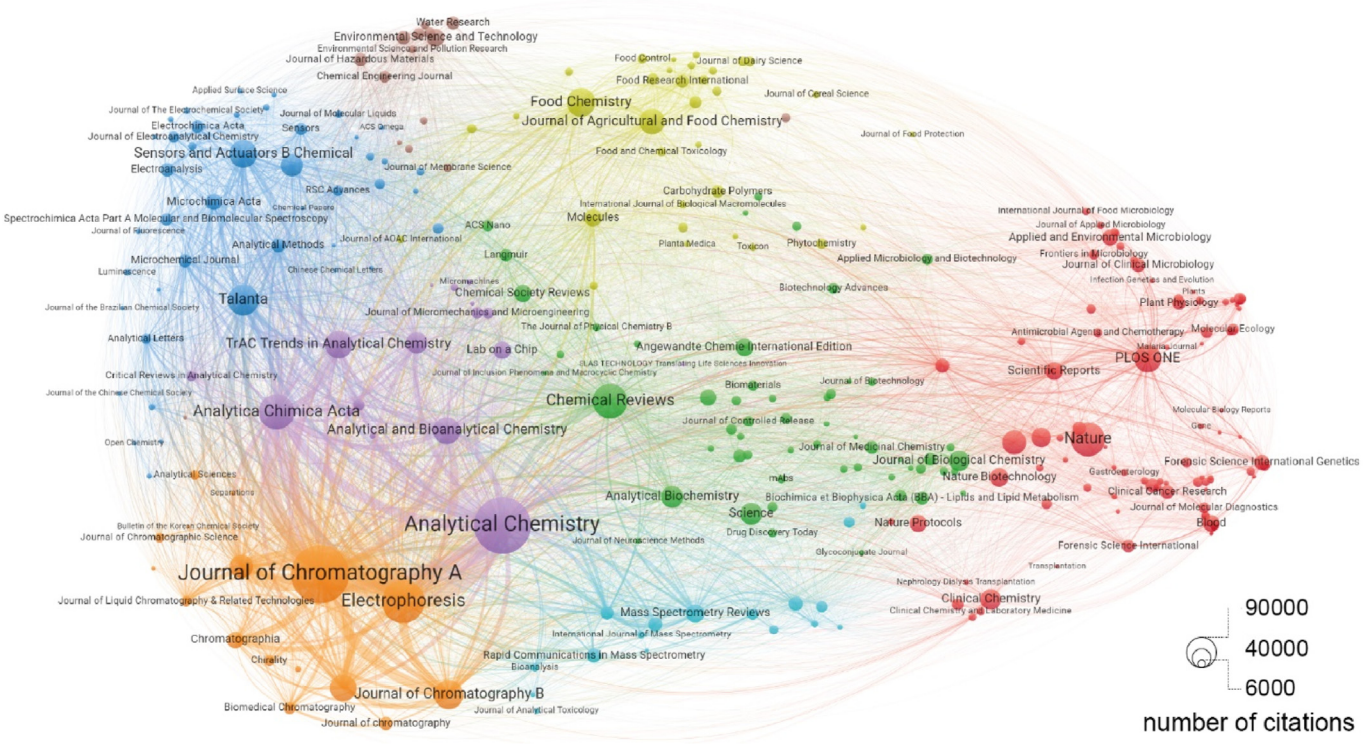

Fig. 4. VOSviewer visualization of the bibliographic coupling citation network of journals publishing on capillary electrophoresis in the period 1980–2021. Journals with at least 100 publications and 1000 citations are included in this visualization. The area of the circles is proportional to the number of citations An interactive version of this visualization is available on https://tinyurl.com/2lnfzzgn.

5. Conclusions

Large-scale bibliometric analysis of an entire corpus of analytical chemistry literature combined with a powerful visualization engine reveals major research trends and important contributors to a field. Here we used these resources to analyze the capillary electrophoresis literature for this Special Issue. However, the same methodology can in principle be applied to the study of any topic for which there is a significant body of literature. The tools are easy to use, but interpretation of the resulting visualizations benefits from familiarity with the topic.

Author contributions

Magnus Palmblad: Conceptualization, Methodology, Formal analysis, Writing - Original draft preparation, Supervision. Nees Jan van Eck: Data curation, Methodology, Software, Writing - Reviewing and Editing. Jonas Bergquist: Validation, Writing - Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The interactive visualizations showin in Figure 2, 3 and 4 have been made available online.

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