

RSC Mechanochemistry

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Transformation of mechanochemistry from a comminution tool to powerful chemical science: A bibliometric data-driven perspective

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Abstract

Mechanochemistry is advancing rapidly, mainly because it enables necessary chemical transformations that are impossible with solution-based methods. However, it transformed from its beginnings as a comminution and mechanical activation tool that altered raw materials and minerals to its current position as a well-established synthetic tool. This perspective article provides insight into this transformation by discussing publications in the Scopus database classified by subject area and identifying temporal changes in the journals publishing mechanochemical research. A year-wise monitoring of articles retrieved from the Scopus database using the following eight keywords is provided: mechanochemistry, mechanochemical, ball milling, high-energy ball milling, mechanosynthesis, mechanical activation, mechanical alloying, and mechanical milling. Also, the INCOME conference series, a flagship event for the community held every 3 years, was assessed over 10 years based on the occurrence of the mentioned keywords in the contribution titles. The obtained results clearly show a shift from engineering, materials science, and physics and astronomy to chemistry, energy, and environmental sciences. This is also confirmed by shifting the character of the journals publishing mechanochemistry from materials-science-oriented ones (such as Materials Science Forum or Journal of Alloys and Compounds) to chemical journals (ACS Sustainable Chemistry & Engineering, Angewandte Chemie International Edition, and, very recently, RSC Mechanochemistry). Moreover, the keywords mechanical activation and mechanical alloying, which were once among the key terms in the field, have entirely vanished from the contribution titles at the recent INCOME conference. This perspective is a reminder that, in addition to significant developments in emerging fields, the older, established, and sometimes forgotten ones still have something to offer mechanochemistry.

Keywords: mechanochemistry, history, Scopus, conference, publications, bibliometrics

1. Introduction

Most researchers working in mechanochemistry are well aware of the exponential increase in publications in the field over the last few years. This is supported by data from the Scopus database when typing the keywords *mechanochemistry* and *mechanochemical*. By mentioning “keyword”, it is meant that the Scopus search in the initial category “Article title, Abstract, Keywords” was used. This simplification is used throughout the paper. A rapid increase is evident when analysing all publications (Fig. 1a), and is even more apparent for review articles (Fig. 1b) and citations (Fig. 1c). It is peculiar that this rapid onset started earlier for the term *mechanochemical* than *mechanochemistry*, which hints to the fact that the researchers used the adjective first before actually joining their research endeavours with a separate field of mechanochemistry. It is generally accepted that modern mechanochemistry began in the USSR with investigations of the changes caused by milling processes in raw materials, such as minerals, in the last century^{1,2}. However, such studies are very scarce these days. Actually, no research on this topic was found at the recently concluded flagship conference for mechanochemists, the 11th International Conference on Mechanochemistry and Mechanical Alloying (INCOME 2025)³. Rather than publications on



mechanical activation and high-energy milling for creating defects, increasing specific surface area and decreasing particle size, mechanochemical forces are now used for the synthesis of novel, mostly organic compounds^{4, 5}. Also, the recent editorial meant for inorganic mechanochemistry does not mention any revival of the “older branch” of mechanochemistry⁶. When and how did this change take place? This article provides a brief excursion through the bibliography in the Scopus database and selected proceedings of the INCOME conference series, which attest to the apparent shift observed within our unique discipline.

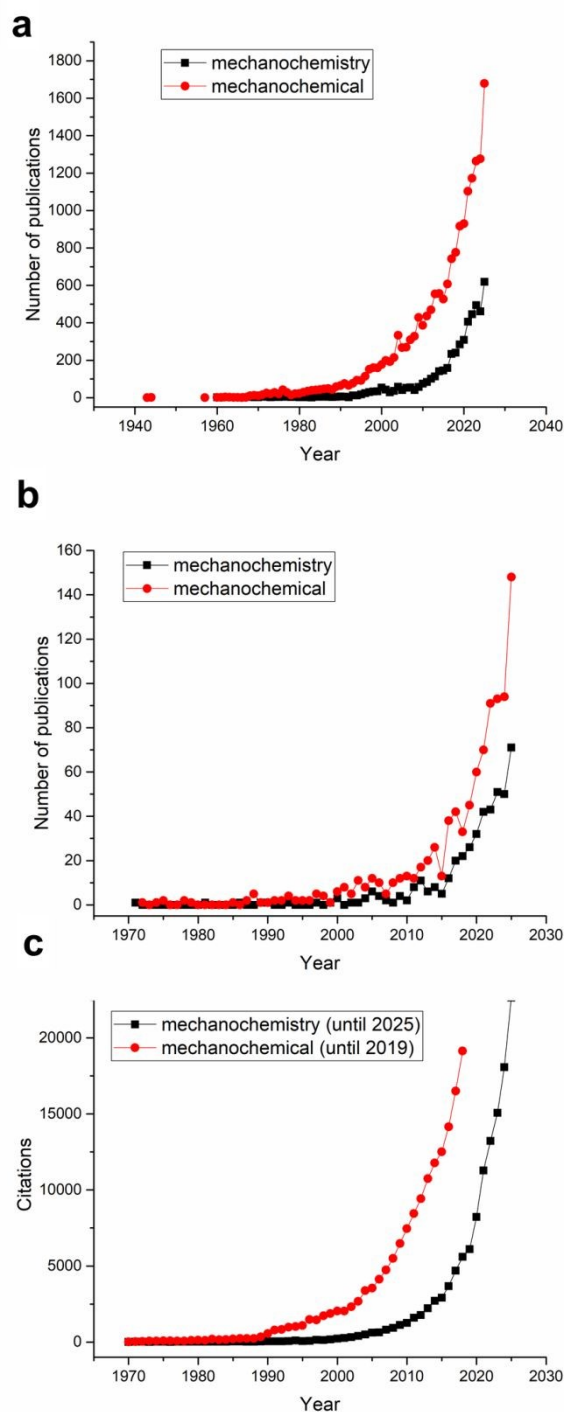


Fig. 1: Analysis of publication and citation activity until the year 2025 according to Scopus database using keywords “mechanochemistry” and “mechanochemical”: (a) number of publications, (b) number of review articles, (c) amount of citations (for keyword “mechanochemical”, the citations



count is presented only until 2019 due to limitation of Scopus database). Data available on February 3, 2026, was used.

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2. Bibliometric analysis documenting a shift in the field

2.1 Keyword “mechanochemistry”

The Scopus database allows classification of published articles by subject area. For publications related to mechanochemistry, eight key subject areas could be identified: **chemistry; chemical engineering; materials science; physics and astronomy; environmental sciences; engineering; energy; and biochemistry, genetics, and molecular biology.**

The first contributions that use the keyword mechanochemistry are biological in origin and report muscle contraction⁷, thus falling into the last subject area. However, in the same year, the first contribution to “chemical” mechanochemistry, namely the disintegration of polystyrene under sonication, was published by Berlin et al.⁸ This group subsequently published a few follow-up studies in the years to come. Thus, from analysing this keyword, polymer mechanochemistry seems to be the oldest branch of mechanochemistry. The first report from V. V. Boldyrev, the first head of the International Mechanochemical Association devoted to the effect of milling on the inorganic solids, was published in 1971¹. Today, significant contributions to this subject area, referencing mechanochemistry, also come from the use of mechanical force to perform chemical reactions.

Most publications from the field of mechanochemistry fall into one or more of the mentioned subject areas. A year-wise classification of the articles provides the first insight into the change described in the first paragraph found when searching for the keyword *mechanochemistry* in the Scopus database. The percentual contribution to each subject area is provided in Fig. 2a. In this case, the statistics for the 30 years from 1994 to 2024 are considered. Already, the first view gives a clear impression that, over time, the number of papers published in the fields of chemistry, energy, and environmental sciences is increasing, while the contributions to the subject areas of engineering, physics and astronomy, and materials science are decreasing. The remaining two subjects (chemical engineering and biochemistry...) appear to be largely intact. This trend is, of course, not straightforward; mainly in the early years, some deviations can be identified. However, when looking at the data, the number of papers must also be taken into account. Namely, it is pretty low before the year 2000 (Fig. 1a), and thus the relevance of the data becomes questionable.

To demonstrate this change more clearly, the chemistry, environmental sciences, and energy subject areas were grouped under the term “new”. In contrast, the engineering, materials science, and physics and astronomy subject areas were grouped under the term “old”. The rest is grouped under “steady” subject areas. In this way, increasing the contribution of the *new* and decreasing the contribution of the *old* subject areas is undeniable (Fig. 2b). The overall number of publications published within *new*, *old* and *steady* subject areas is presented in Fig. 2c. Much higher increase in the number of papers published in the recent years in the *new* group compared to the *old* one can be clearly seen.



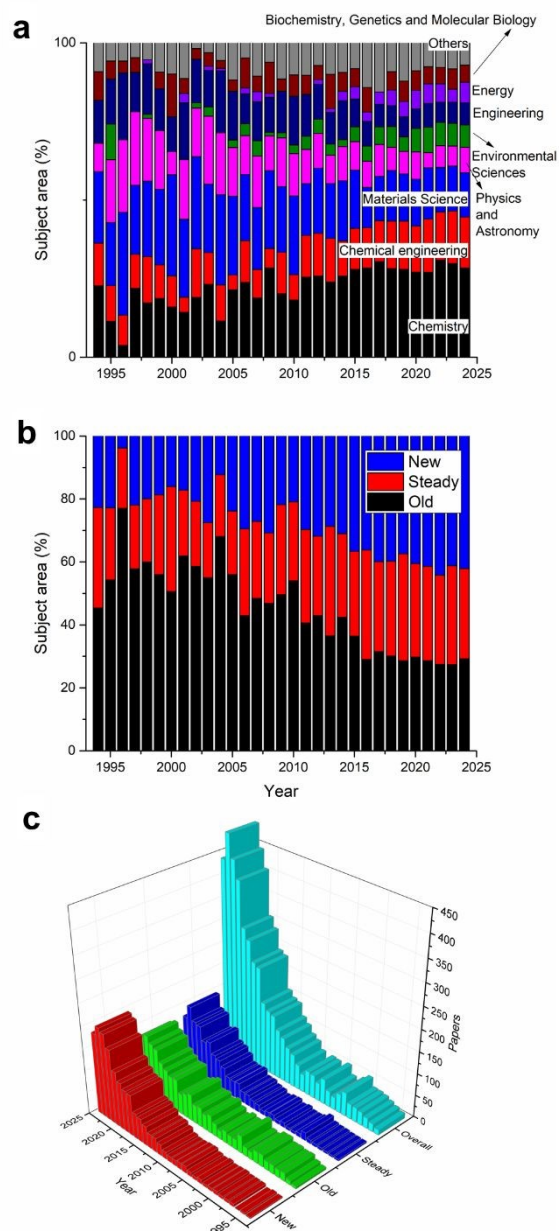


Fig. 2: Analysis of the publications using keyword "mechanochemistry": (a) year-wise contribution (in percent) to subject areas, (b) year-wise statistics (in percent) on the papers published in the new (*chemistry, environmental sciences and energy*), old (*engineering, materials science, and physics and astronomy*) and steady (*biochemistry, genetics and molecular biology, chemical engineering and others*) subject areas, (c) overall number of papers classified into new, old and steady subject areas. Data until the year 2024 available in the Scopus database on February 3, 2025, was used.

2.1.1. Analysis of journals publishing mechanochemical research

The output from the Scopus database for the *mechanochemistry* keyword was also analysed to identify journals that publish mechanochemical research. The first-ever publication describing polymer degradation was published in 1960 in the journal *Polymer Science USSR*⁸. The keyword 'mechanochemistry' is also found in a 1962 publication in the prestigious Nature journal; however,



this is in the context of biological research. Between 1965 and 1969, three articles of biological origin were published in the journal *Circulation Research*. Until 1970, only 23 publications altogether were identified for the *mechanochemistry* keyword in Scopus. Between 1970 and 1974, the contributions appeared in diverse journals, dominated by biological ones, but some reports on polymer mechanochemistry and the pioneering paper on inorganic mechanochemistry¹ were also published during this time.

From 1975 onward, the analysis becomes more interesting, as more journals began publishing in the field; thus, this year was also selected as the starting point for the figures below (Fig. 3). It is now necessary to clarify how the journals analysed in Fig. 3 were selected. Initially, the contributions of 42 journals were analysed over a five-year period (the total number of papers published in 2020-2024, 2015-2019, etc.). The journals for analysis were selected either if they published at least 23 papers (corresponding to approx. 0.5% of all contributions (4430) registered in Scopus in the years 1960-2024 and popping up when the *mechanochemistry* keyword is entered) or if the contribution of articles in the given journal in any of the analysed five-year ranges was at least 2.0%. However, for better readability and overview, for the column graphs in Fig. 3b, d, f and h, only the journals publishing more than the following threshold number of publications are presented: (1975-1994: more than 1, 1995-1999: 3, 2000-2009: 5, 2010-2014: 9, 2015-2019: 23, 2020-2024: 30). However, in some cases, also journals not respecting this criterion are presented, namely when their contribution in at least one five-year period is significant. This allows better tracking of the trend's evolution. These plots show the percentage contribution (from the overall articles found when entering the *mechanochemistry* keyword) of the articles published in the given journals in the particular five-year span. Fig. 3a, c, e and g show the number of published articles in the selected journals in the given five-year span. Here, the number of presented journals had to be further reduced to keep the figures legible. In this case, ten journals that published the most papers in the five-year frame are presented, and their contribution is then shown also in a neighbouring five-year range (although if they do not fall within the top 10 journals for that span). In some cases (for articles published in the range 2005-2009 and those published earlier than 1999), the number of journals is significantly lower than 10, because only some managed to publish more than one or two articles on *mechanochemistry* in the given timeframe.

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Methods Enzymology. Data until the year 2024 available in the Scopus database on February 3, 2025, was used.

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Until 1980, aside from biological journals, more papers on polymer mechanochemistry were published in the *Journal of Applied Polymer Science*. This journal has occasionally published research in the field to date (e.g., between 2000 and 2004, 5 contributions were identified). Another essential journal at that time was *Chemical Pharmaceutical Bulletin*, which published at least two papers on mechanochemistry across three consecutive five-year periods between 1975 and 1989. During the years 1985-1989, three contributions from the chemical journal *Kinetics and Catalysis* were published. In the following five years, five contributions appeared in *Holzforschung*. More importantly, the journal *Solid State Ionics* became a small platform for mechanochemists, publishing 25 articles between 1990 and 2019, a significant number, mainly in the first half of this period. Between 1995 and 1999, the percentage of papers published in biological journals decreased to about 8%. It remained similar until recently (Fig. 2). Mechanochemical research was almost exclusively published in materials science-oriented journals, with 28 contributions in *Materials Science Forum*. The contribution to this journal decayed in the following 10 years. Another vital journal that began publishing on mechanochemistry during this period is the *Journal of Alloys and Compounds*, which has remained a solid platform for inorganic mechanochemists to this day. Since 2000, chemical journals have begun to appear. Already in the years 2000-2005, the first five and four contributions in the journals *Angewandte Chemie International Edition (ANIE)* and *Chemistry- A European Journal (CEJ)*, respectively, were published. These two journals are excellent, widely used platforms for high-quality mechanochemical research. Nevertheless, during the years 2000-2004, the journal *Journal of Materials Synthesis and Processing* cannot be omitted, as it published 19 articles, 17 of which appeared in special issues devoted to the 3rd INCOME conference organised in 2000⁹. Unfortunately, this was the only contribution to mechanochemistry, and the journal ceased to exist in 2002. The year range 2005-2009 is characterised by publishing in diverse journals across the materials science and chemistry fields, with the latter starting to prevail. Since 2010, there has been a clear dominance of chemical journals, with *ANIE* as the journal with the most papers (more than 20) in the field, followed by *Chemical Communications*. In 2012 and 2013, a set of review articles was published within a themed issue entitled "Mechanochemistry" of a prestigious journal, *Chemical Society Reviews*, thus bringing mechanochemistry into the mainstream of chemical science¹⁰. The decade between 2015 and 2024 completes the transformation in the field, further underlining the dominance of *mechanochemistry* contributions in chemical journals. The journal *ACS Sustainable Chemistry Engineering & Technology (ACS SCE)* appears on the scene, becoming the leading journal with the most contributions in the field (namely, 111 articles were published between 2020 and 2024). Among them, there is also a virtual special issue initially planned to be devoted to the 10th INCOME conference¹¹. However, *ANIE* and *CEJ* are excellent players, having published 99 and 53 articles, respectively, in the given timespan. They are followed by an MDPI journal *Molecules* and *ChemSusChem*. This ranking has been the same for 10 years. For materials scientists, the good news is that a journal, *ACS Applied Materials & Interfaces*, keeps pace with solely chemical journals and remains among the top 10 journals in the field for 15 years. Apart from the INCOME conference-related special issues and those published in *Chem. Soc. Rev.*, as well as other journals such as *CEJ*, *Beilstein Journal of Organic Chemistry*, *ChemSusChem*, *ChemComm*, *Faraday Discussions*, and *Molecules*, have published special issues on mechanochemistry. To conclude this journal's analysis, the number of articles published in 2025 should be mentioned. As RSC Mechanochemistry, a new flagship journal for mechanochemists, was established in 2023 and indexed in Scopus since 2024, it is logical that it dominates the field, with 38 contributions in 2025. It is followed by 26, 20, 19 and 19 contributions published by *ANIE*, *CEJ*, *ACS SCE* and *ChemSusChem*. Thus, the dominance of chemical



journals is complete, albeit materials science-oriented articles can, of course, also be found in these journals. There is strong hope that, in the future, these once solely chemical journals will remain open to mechanochemical contributions that also feature results from sometimes already forgotten raw materials- and materials science-based beginnings.

2.2 Other keywords important for the mechanochemical community

Let's now have a look at a few keywords that are usually associated with the field of mechanochemistry. The same five-year intervals used for journal analysis were applied here. Apart from *mechanochemistry*, the following were also selected: high-energy ball milling, mechanical activation, mechanosynthesis, mechanical milling, mechanochemical ball milling, and mechanical alloying. Fig. 4a shows the total number of publications in which the given keyword appears. The highest number of results (almost 40,000) was obtained when searching for the keyword *ball milling*. In the second place, the term *mechanical alloying* yielded slightly more than 22,000 results. This is striking since, as will be presented later, this field is no longer present at the flagship event of the INCOME conference series. On the other hand, it underlines the importance of this field in the past. The third most prominent keyword is *mechanochemical*, which is almost 4 times as abundant as *mechanochemistry*. The adjective provides a more straightforward connection to our field than the noun. The number of papers detected by Scopus for *high-energy ball milling*, *mechanical milling*, and *mechanical activation* ranged from 6100 to 7900. These terms are a little old-fashioned and are more commonly used in subject areas that were part of the main research line in mechanochemistry in the previous decades. Some researchers prefer to use the keyword *mechanochemistry*, but this represents only a minor contribution. These statistics are also provided as percentages in a pie chart in Fig. 4b. Fig. 5 shows a year-wise breakdown of the number of publications containing these eight keywords. On the one hand, it shows a recent saturation of keywords: high-energy ball milling, mechanical milling, mechanical activation, and *mechanical alloying*. On the other hand, it shows a dramatic recent increase for keywords *ball milling*, *mechanochemical* and *mechanochemistry*.



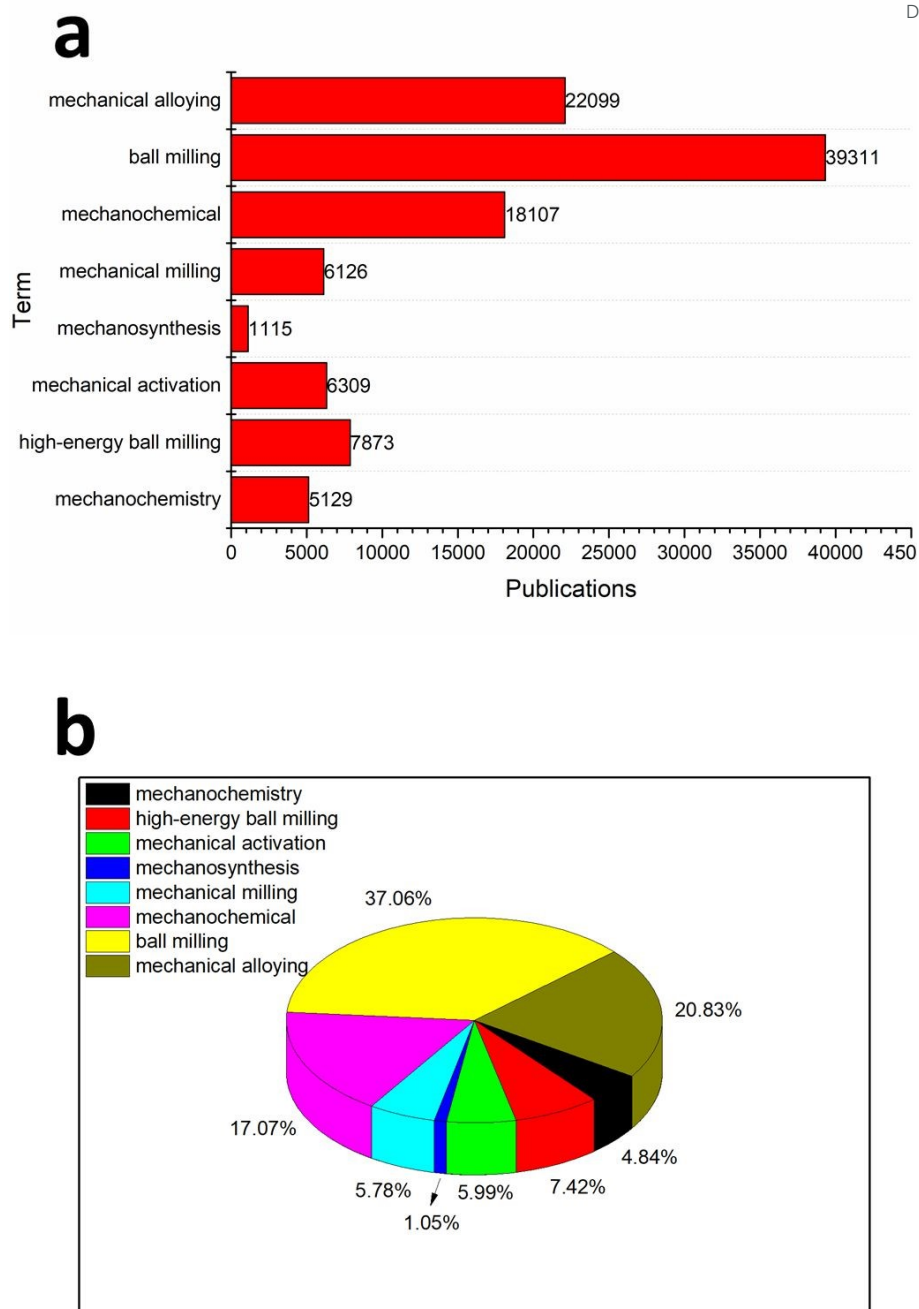


Fig. 4: Results popping up when typing eight selected keywords into the Scopus database: (a) overall number of publications up to year 2024, (b) pie chart showing the proportional contribution of each keyword. Data available in the Scopus database on February 4, 2026, was used.



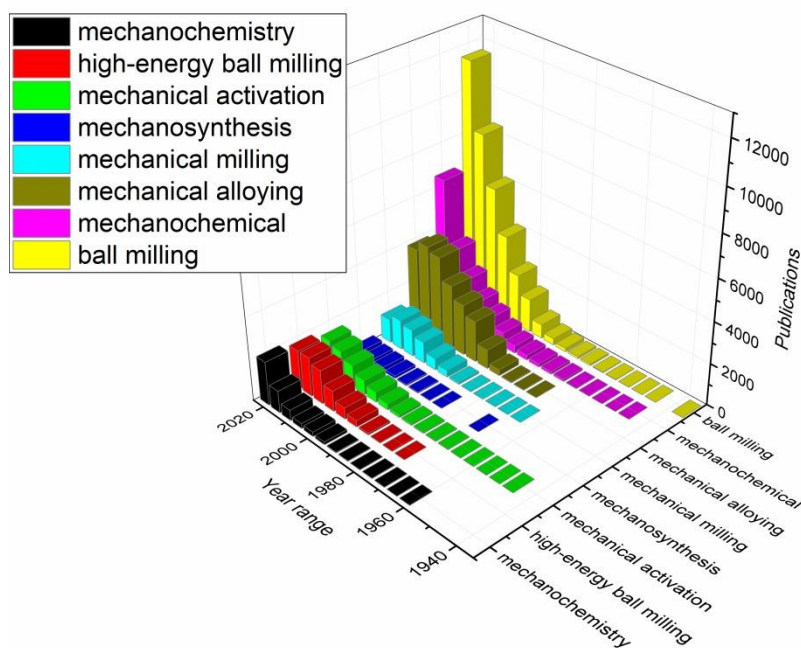


Fig. 5: Number of publications found for eight selected keywords in the Scopus database provided for five-year terms (2024 - 2020, 2019 – 2015, etc.). Data until the year 2024 available in Scopus database in September 2025 was used.

Additional information can be obtained via a closer look on the contribution of each of eight selected keywords into the given subject area throughout the years (in parts a, c, e and g of Fig. 6 and Fig. 7). Also, overall number of papers detected for the given keyword right to the column plots (as b, d, f and h parts) is listed on top of each column to assess relevance of the data. The results presented in the first one or two columns on the left should be taken as approximate, since only a limited number of papers were published. If the number of papers is too small, the contribution to the trend it provides might not be substantial, as just one or two papers can heavily influence results. The contributions of each subject area are presented as percentages. For the keyword *mechanochemistry*, the trend described earlier (Fig. 2) is also confirmed here (Fig. 6a). Clearly, the contributions of chemistry, energy and environmental sciences are increasing, while those of materials science, engineering, and physics and astronomy are decreasing. The same is true for the adjective *mechanochemical*, though in this case, the materials science seems slightly better preserved. The contribution of chemical engineering is also increasing somewhat throughout the years (Fig. 6b). The statistics regarding the most frequent keyword *ball milling* (Fig. 6c) show a less rapid increase in the number of contributions to the fields of chemistry and chemical engineering in comparison with the previous two keywords. In this case, contributions classified under engineering and physics are substituted by publications related to energy, environmental sciences, and chemical engineering. The number of papers shows an exponential trend for these three keywords (Fig. 6b, d, f). As for subject areas, a similar trend to the first three keywords can also be observed for mechanosynthesis (Fig. 6d); however, the contribution to the chemistry subject area is much more pronounced here. The increase in the overall number of publications for this keyword is less rapid than that shown in Fig. 6.

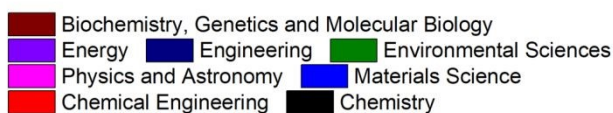
Regarding the other four terms (Fig. 7), the increase in the contributions to the field of chemistry is almost negligible. Nevertheless, the decrease in contributions to physics and engineering over time is



marked. The materials science-related content is on a steady level here; thus, these keywords are still actively used in the field. Therefore, for these four terms, the physics and engineering articles are substituted by those falling within chemical engineering, energy and environmental sciences. For these four keywords, the contribution to biochemistry, genetics and molecular biology is negligible. The overlap for this subject area is more closely related to keywords that include the word root “mechano”. As for the number of publications, those related to *mechanical activation* seem to be getting close to the saturation state (Fig. 7d). In the case of *high-energy ball milling*, it is already saturated (Fig. 7b) and mentioning *mechanical alloying* and *mechanical milling* (Fig. 7f and h) seems to be already decreasing.

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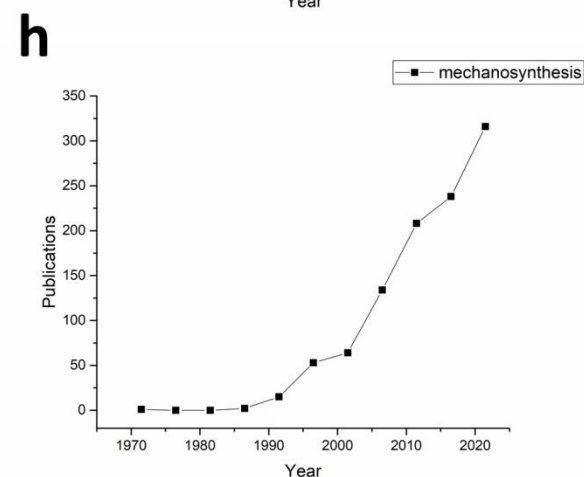
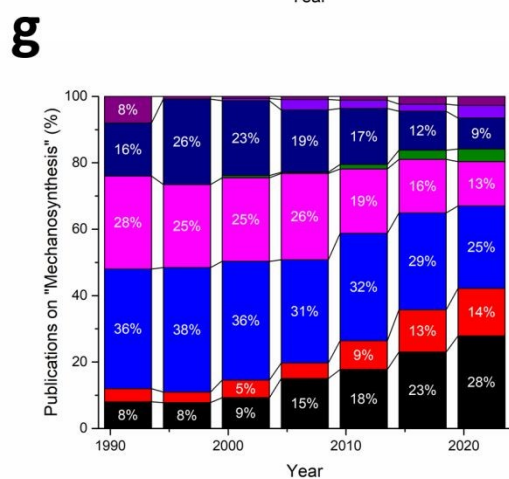
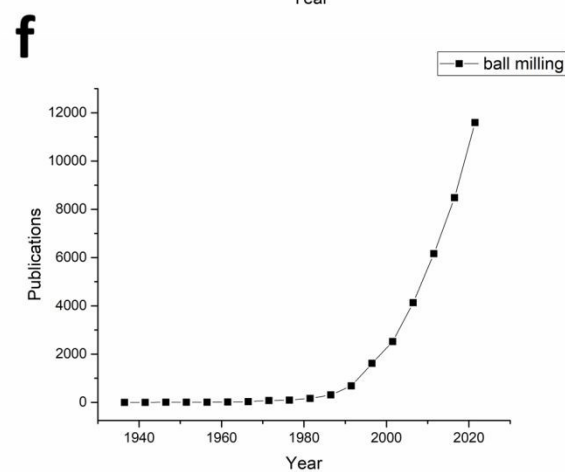
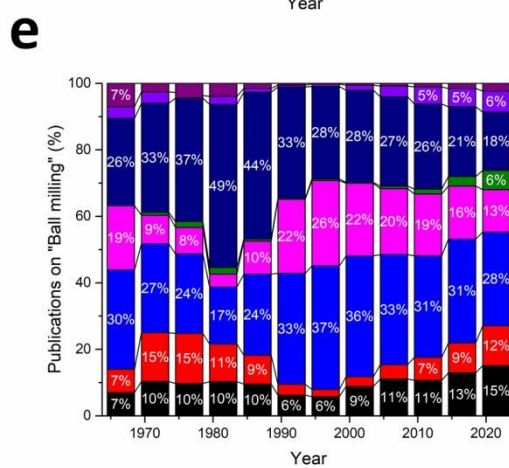
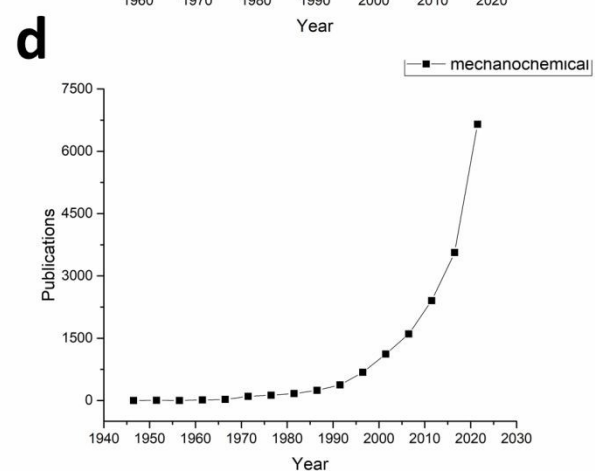
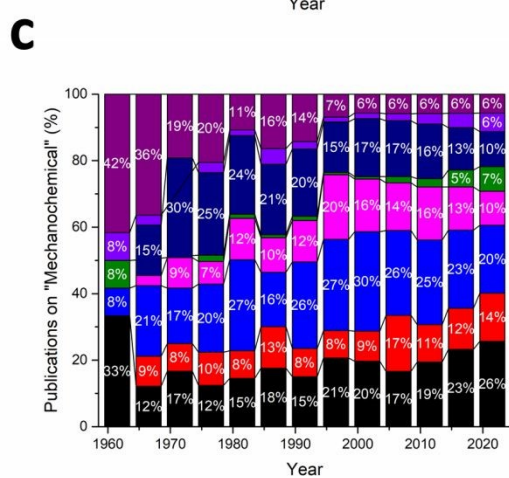
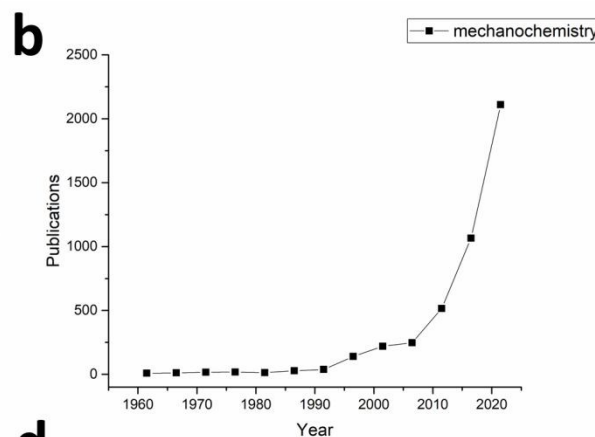
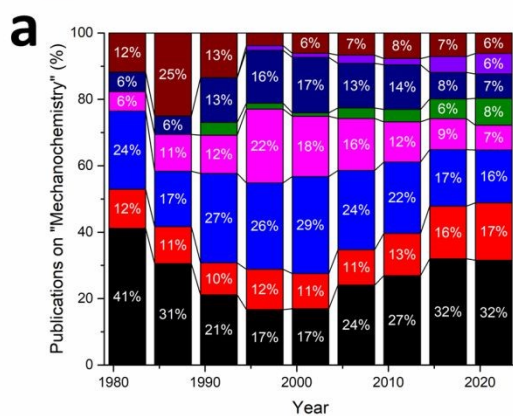
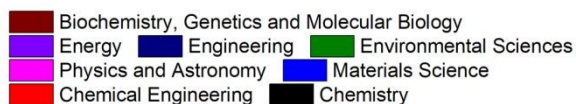


Fig. 6: Contribution of a given keyword to the eight most important subject areas during the years until 2024 (the results are presented for five-year terms (2024 - 2020, 2019 – 2015, etc.)) for selected keywords: (a, b) mechanochemistry, (c, d) mechanochemical, (e, f) ball milling, (g, h) mechanosynthesis. Left- contribution to the overall number of papers when neglecting those not falling into any of the eight subject areas (referred to as “Others” in Fig. 2a), right- number of publications found for the given keyword. Eight selected keywords in the Scopus database were provided for five-year terms (2024 - 2020, 2019 – 2015, etc.). Data until the year 2024 available in Scopus database in September 2025 was used.

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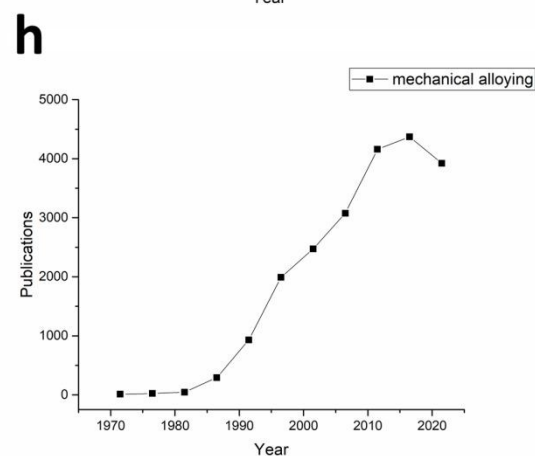
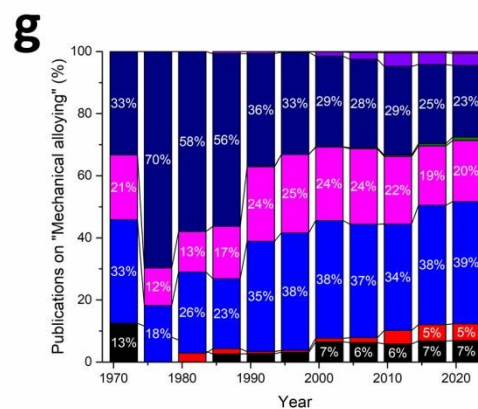
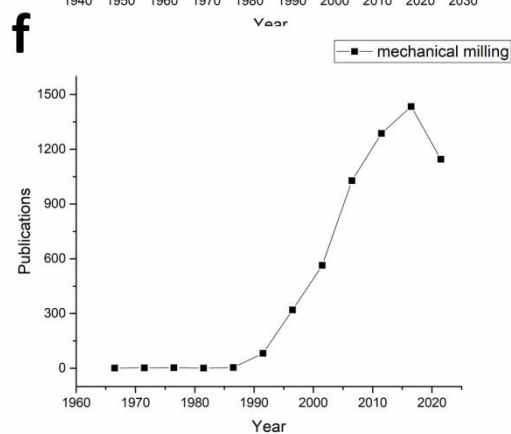
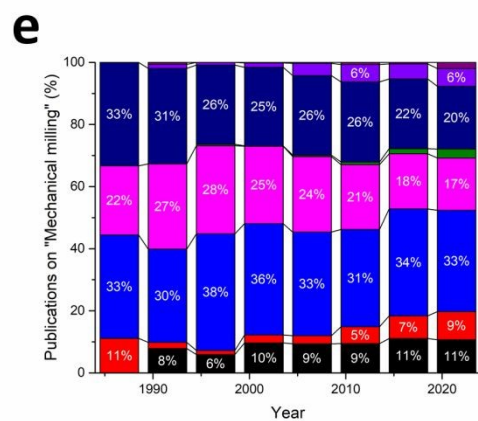
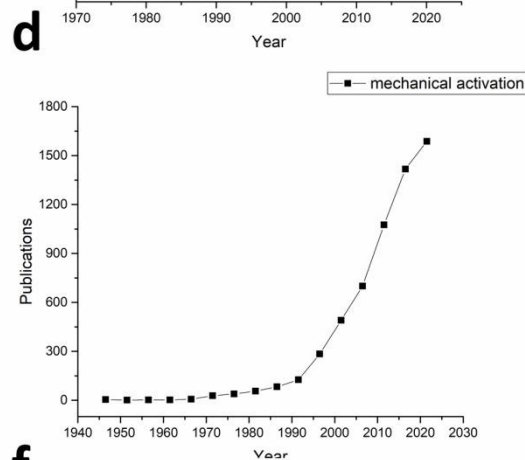
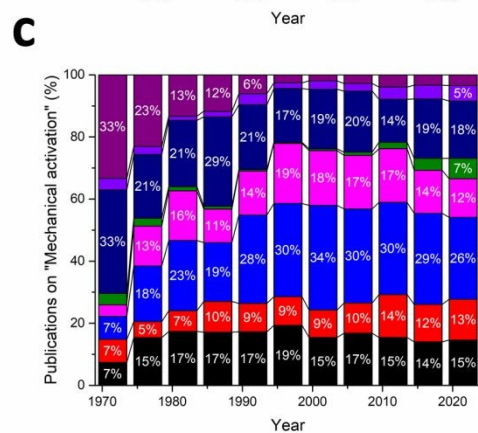
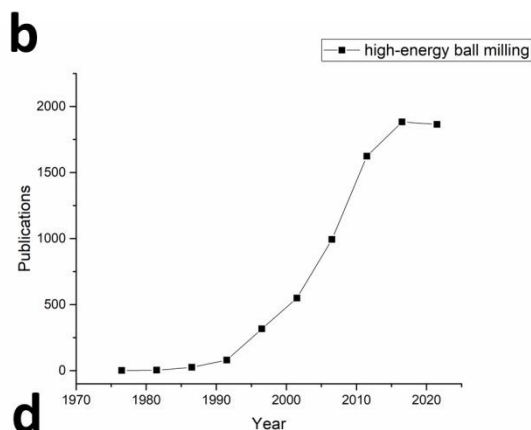
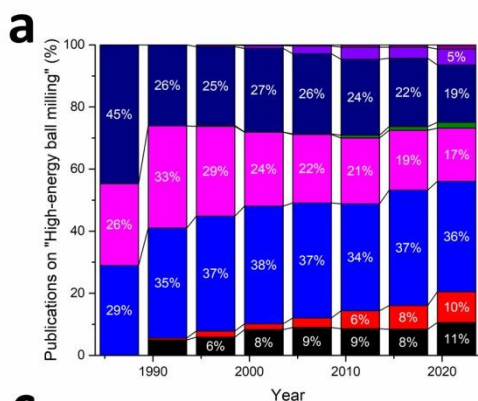


Fig. 7: Contribution of a given keyword to the eight most important subject areas during the years until 2024 (the results are presented for five-year terms (2024 - 2020, 2019 – 2015, etc.)) for selected keywords: (a, b) high-energy ball milling, (c, d) mechanical activation, (e, f) mechanical milling, (g, h) mechanical alloying. Left- Contribution to the overall number of papers when neglecting those not falling into any of the eight subject areas (referred to as “Others” in Fig. 2a), right- number of publications found for the given keyword. Eight selected keywords in the Scopus database were provided for five-year terms (2024 - 2020, 2019 – 2015, etc.). Data until the year 2024 available in Scopus database in September 2025 was used.

The publication date of the very first papers related to the given keyword is also worth mentioning. The oldest contribution comes from *ball milling*, which was published as early as 1935¹². This is followed by the keyword *mechanochemical* with the first paper published in 1943¹³. A little later, the articles that mention *mechanical activation* start from 1947¹⁴. This is followed by articles mentioning the term *mechanochemistry*, as discussed above. The first reports for the other four keywords are younger.

2.3. Analysis based on the Books of Abstracts of the International Conference on Mechanochemistry and Mechanical Alloying (INCOME)

To investigate whether similar trends identified in the analysis of the Scopus database are also evident in the dissemination of mechanochemical results at scientific meetings, within the framework of this study, the contribution titles presented at the INCOME conference series were analysed. Namely, the Books of Abstracts from the INCOME conference were checked after approximately every 10 years (namely, the first INCOME conference in 1993¹⁵, the ones organised in 2003¹⁶, 2014¹⁷ and a recently finished one in 2025³). Regarding the number of contributions, the highest number was presented at the conference in 2003 (almost 280). Interestingly, the number of contributions on the very first INCOME conference and the one that has just finished is nearly the same (130 and 127, respectively). The lowest amount of contributions (101) was presented in 2014. Thus, the growth of the community, as reflected in the number of publications, does not correspond to the increase in the number of participants at the INCOME conference series.

In addition to the statistics above, the titles of all contributions presented at these four conferences were assessed, and the eight keywords analysed in the Scopus database described in the previous section were specifically sought (Fig. 8).

It is clearly shown that the change of contributions from the “classical raw materials-based ones” into “synthetic chemical ones” is even more pronounced for the INCOME meetings than in the case of the Scopus database. This can be well exemplified by the keyword mechanical activation, which was present in more than 20% of the titles of the 1st conference in 1993 (it was the second-most-used keyword after mechanochemical), but was not used in any of the abstract titles at the 11th INCOME in 2025. A similar situation holds for mechanical alloying, which was the second-most-used keyword in 2003 but was completely absent in 2025. In 2025, only the terms *mechanochemistry*, *mechanochemical* and *ball milling* were used in the contribution titles, while the other five were not mentioned at all. This shows that the contributions presented at the INCOME became more focused on a narrower field mainly related to chemistry, although according to the Scopus database, the publications mentioning also the other keywords are being published (Fig. 5). Thus it seems that the mechanical alloying and raw materials’ community is not too interested in the INCOME conference



series anymore. In addition to the eight keywords, the number of contributions with titles clearly related to organic chemistry was specifically checked. Surprisingly, by 1993, more than 13% of contributions had some connection to organics. This number was lower in 2003 and 2014, then shot up to 50 of 127 in 2025. This clearly shows that organic mechanochemistry is now the dominant field and a driving force within the field. Also, the titles of the contributions in 2025 mention modern technologies such as *twin screw extrusion* or *resonant acoustic mixing*, which was not the case before.

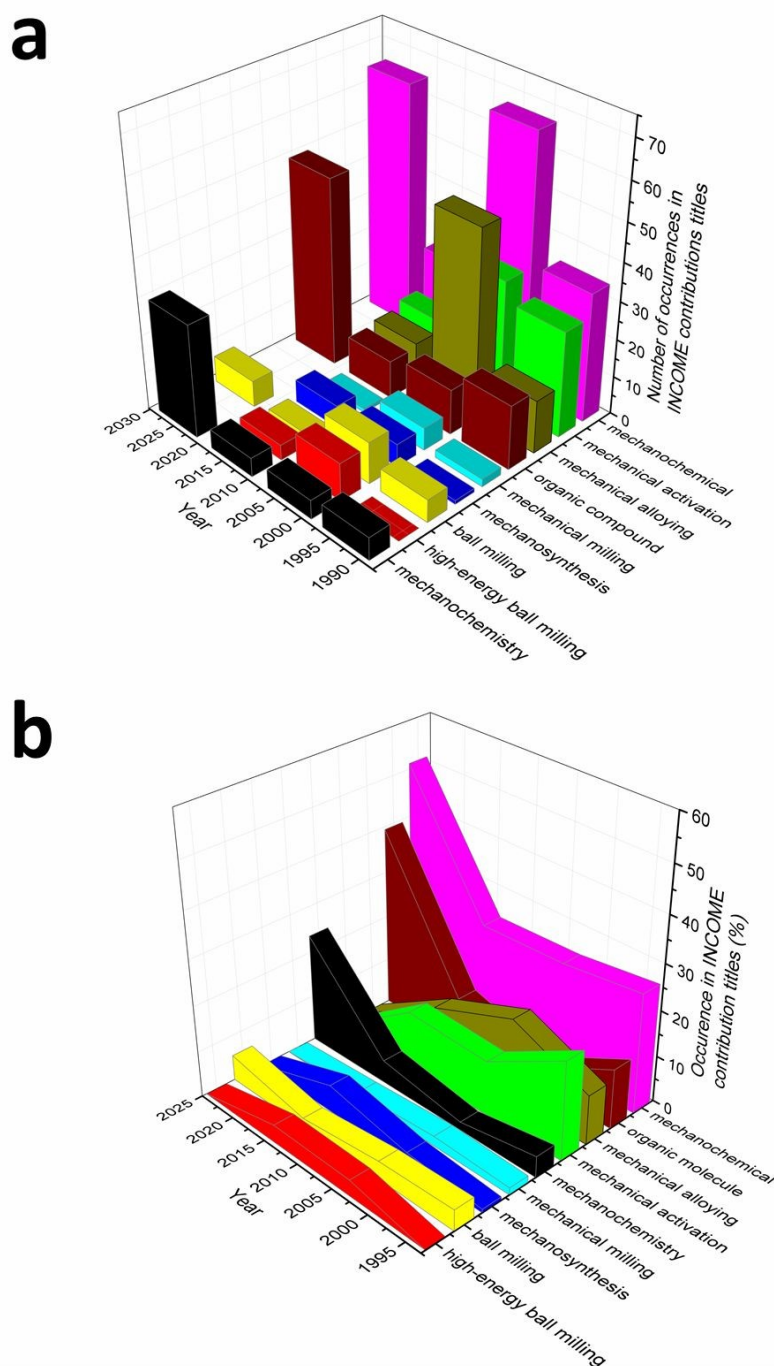


Fig. 8: Occurrence of eight selected keywords in the contribution titles to the four INCOME conferences held in 1993, 2003, 2014 and 2025 bearing the mentioned keyword in the title (the



occurrence of organic compound name is also shown): (a) overall number of contributions, (b) percentual content from all the contributions presented.

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3. Summary

This perspective shows that the transformation the mechanochemical field has undergone, particularly over the last 15 years, is evident. It has transformed from a methodology for processing raw materials and examining fundamental effects of milling on natural resources in terms of physico-chemical properties into a modern synthetic tool capable of yielding products that chemists using a solution-based approach only dream about. The mechanochemical field, while initially focused on processes of mechanical activation and mechanical alloying, has now shifted to a greater focus on the chemical transformations mechanochemistry can enable.

Of course, this perspective documents only a bibliometric perspective, and there are plenty of other issues that deserve a separate perspective, such as terminology and symbols¹⁸ or the evolution of milling tools. In contrast to mainly planetary ball mills used in the past, the mixer/oscillation ball mills, twin screw extruders or resonant acoustic mixers currently enable the time-resolved *in situ* monitoring techniques¹⁹ (mainly X-ray diffraction and Raman spectroscopy), well-documenting the events taking place directly during milling, mainly for softer organic mechanochemistry for now.

This contribution clearly shows that mechanochemistry is not just evolving, but is actively being shaped by the scientists who have driven it forward. As the diversity of contributors increases, so does the language and culture of mechanochemistry, making it even more dynamic and exciting. The field's future direction is uncertain, but this growing diversity ensures a vibrant and expanding discipline. It would be a pure guess and a check of the crystal ball to predict where our exciting branch will be in another 30 years²⁰, but the growing diversity of mechanochemists ensures a vibrant and expanding discipline.

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Data availability statement

This study was carried out using publicly available data from the Scopus database (www.scopus.com) and by analysing the INCOME conference proceedings cited in the paper.

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