



Polymer extrusion processes in tire manufacturing: a systematic review and bibliometric analysis

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Abstract

Tire extrusion is a thermo-mechanical process in advanced tire manufacturing in which compound rheology, die/tooling design, and operating history jointly govern dimensional accuracy, stability, scrap, and downstream performance. This study provides a systematic review and bibliometric analysis of tire-extrusion research published between 2000 and early 2025 using an integrated Scopus–Web of Science corpus enriched with OpenAlex, CrossRef, and OpenCitations, complemented by automated keyword completion (YAKE) and cited-reference completion. We map production and collaboration patterns and reveal conceptual and intellectual structures using co-word/thematic analysis, thematic evolution, co-citation networks, and Reference Publication Year Spectroscopy (RPYS). To mitigate terminology-driven topic drift and enable engineering-centred interpretation, we introduce a technology-depth sensitivity (scope-control) layer that separates a broad tire-related corpus from nested, technology-explicit extrusion cores and organizes evidence through non-exclusive tagging by engineering degrees of freedom (rheology/constitutive behaviour; tooling/flow/die engineering; extrusion hardware/process window; simulation/CAE; monitoring/control). Results show that the broad corpus is dominated by materials/circular-economy themes, whereas the technology-explicit cores reveal a distinct process-engineering and CAE stream centred on die design, flow balancing, constitutive modelling, and simulation-supported optimisation. Finally, we translate these findings into actionable industrial levers and KPI-level implications for tire-profile extrusion/co-extrusion, including gauge stability, interface integrity, thermal hotspots/scorch risk, and reduced die-qualification time.

Keywords Tire extrusion · Co-extrusion · Bibliometric · Scope control · Rheology · Computer-aided Engineering (CAE)

1 Introduction

Tire extrusion is one of the most demanding elements of tire manufacturing, in which rubber compounds are shaped into profiles such as treads, sidewalls, and inner liners. Before the assembly and curing stages, extrusion contributes to component dimensional accuracy and influences key tire performance metrics (rolling resistance, traction, wear life, fuel economy) [1]. The viscoelastic behavior of rubber, along with high temperature and shear conditions used in extruders, presents extreme challenges in flow control, die swell mitigation and compound homogeneity [2]. Furthermore, modern tire design requires multi-layered and functionally graded profiles, thereby further complicating the impacts that upstream formulation science, process engineering, and materials modeling have on the extruding process [3].

Over the last few decades, the global tire manufacturing industry has seen two competing sets of demands. On the

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one hand, developments in electrification and the advent of intelligent tire systems are placing ever more stringent and complex needs on mechanical precision, thermal performance, and integrated sensors [4]. On the other, growing demands for more sustainable solutions to carbon reduction and circular economy policies are driving alternatives to oil-based rubber compounds and more energy-efficient production pathways [5, 6]. The quest for such alternative and sustainable systems has been diverse and fragmented: new polymer-filler systems [7], bio-based elastomers, smart extrusion dies, process optimization using new numerical simulation [8–10], and quality assurance using data-driven quality control systems. Even with this high level of research activity, there is still no unified body of knowledge on tire extrusion; instead, relevant results are dispersed across different disciplines (polymer chemistry, physics and rheology, mechanics, and manufacturing systems). Specifically, tire extrusion research has evolved across diverse thematic directions, spanning materials/fillers, processing, sustainability, vulcanization chemistry, and integration of new technologies. However, these studies remain topic-specific and even not synthesised into an integrated extrusion-technology perspective.

Extruded tire components rely on the interactions between the filler and polymer. Carbon black and silica are the primary reinforcements; dispersion and morphology play a significant role in both viscoelastic behavior and, ultimately, all downstream properties of tires (e.g., rolling resistance and wear), manufacturing stability (e.g., extrusion or calendaring), and vehicle performance (e.g., rolling resistance and behavior under load). Robertson et al. [11] provided a detailed overview of the fundamental reinforcement mechanisms of carbon black in elastomers, highlighting debates around polymer–particle adsorption and the role of surface chemistry in filler–rubber interactions. Studies on silica have emphasized its central role in enabling “green tire” technology by reducing rolling resistance and improving traction, while also addressing environmental and economic aspects of silica production from renewable sources [12]. Recently, novel nanofillers such as graphene oxide, layered double hydroxides (LDH), and functional bio-based proteins have been investigated for their mechanical, thermal, and sustainability benefits in elastomer compounds. Notable reviews include Xian et al. [13], who connect filler dispersion to smart elastomeric performance, and Basu et al. [14], who discuss advances in LDH-based composites. In addition, investigations into filler dispersion methods [15] and early studies of powder compound systems using twin-screw extrusion [16] have provided valuable insights into achieving uniform filler distribution and optimizing rubber mixing technologies.

From the process engineering perspective, both extrusion modeling and die/tooling design are central. Wilczyński et al. [17] introduced global modeling approaches for polymer extrusion, while Marschik et al. [18] refined single-screw melt conveying models. Tire-specific advances include co-extrusion studies for tread and sidewall flow balancing [19]. Tooling has also been reviewed extensively: Pittman [20] analysed computer-aided die design, and more recently, Wagner et al. [21] applied optimisation algorithms to automatically balance die flow. Related FE-based “virtual tryout” approaches show how die modifications can be screened computationally to reduce trial-and-error and improve flow uniformity in complex-profile extrusion [22].

Sustainability has emerged as the next areas of research. Ramarad et al. [23] and Markl et al. [24] reviewed waste tire devulcanisation and recycling technologies. Recent surveys have addressed dynamic devulcanisation and re-vulcanization pathways, highlighting chemical, ultrasonic, and greener alternatives [25]. Pyrolytic carbon black has been investigated as a sustainable secondary filler for new tire manufacturing [26]. Meanwhile, agricultural and animal protein-based fillers are gaining attention as multi-functional, renewable reinforcements [27]. These studies demonstrate a clear shift toward circular economy concepts, yet they remain largely disconnected from process-level extrusion research.

Rubber compounding for extrusion must also consider vulcanization chemistry. Zinc-based activators remain critical for sulfur curing, but their environmental impact has driven research on reduction and alternatives [28]. Advances have been reviewed in relation to activator mechanisms in accelerated vulcanization systems, highlighting the complex role of ZnO and the potential of multifunctional additives [29]. Further studies have addressed strategies to improve heat and reversion resistance in rubber compounding, balancing thermal stability with dynamic performance [30]. Such insights are essential to ensure that extruded profiles achieve the required mechanical and dynamic performance in the final cured tire.

Digitalization and advanced process monitoring are interestingly central to tire extrusion research. Laser-based sensor systems for monitoring tread deformation and dimensional control offer high-precision, real-time insights into extrusion profiles [31]. In-line near-infrared (NIR) spectroscopy has been a viable candidate for continuous process monitoring which provides real-time tracking of polymer composition, flow characteristics, and blend uniformity under extrusion conditions [32]. In addition, broader process analytical technologies (PAT) such as Raman spectroscopy and NIR spectroscopy are being adopted in polymer extrusion to ensure product quality through predictive, data-driven

control [33]. These technologies have the ability to enhance modeling and material complexity in polymer processes, relative to stabilizing the process, and moving forward with smart extrusion lines.

These efforts align with the wider shift toward advanced manufacturing, where Recent manufacturing research increasingly frames complex forming processes as cyber-physical systems in which physics-based models are coupled to data streams for in-line quality assurance, adaptive control, and faster process development. Digital twins are a central concept in this shift, enabling closed-loop links between sensing, simulation, and decision-making across design and production stages [34]. In parallel, extrusion-based processes (notably material-extrusion additive manufacturing) have become a testbed for advanced monitoring and control: state-of-the-art reviews emphasise sensor-driven process monitoring and closed-loop strategies to stabilise quality under strongly process-dependent conditions [35]. Representative implementations include real-time machine-condition diagnosis using acoustic-emission signatures [36] and high-resolution, layerwise geometric monitoring using optical profilometry [37]. These advances motivate similar scope for tire-profile extrusion and co-extrusion, where integrating thermo-rheological modelling with in-line metrology and control could strengthen robustness, reduce scrap, and support “smart” extrusion lines.

Taken together, the literature demonstrates progress across fillers, processing, sustainability, and vulcanization. However, most reviews remain topic-specific—focusing either on recycling, fillers, or extrusion die design—without offering a unifying perspective. What is missing is a systematic, bibliometric synthesis that integrates research across these fragmented streams. A dual-database bibliometric study can provide this perspective by mapping the thematic evolution, intellectual structure, and collaboration networks that shape tire extrusion research. Recent developments in methodology now enable systematic analysis of publications concerning tire extrusion using bibliometrics. Particularly, if one uses co-citation, co-word, and multiple correspondence methods, bibliometrics solidly enables researchers to map the structure and evolution of research fields in a transparent and reproducible way [38, 39]. Specifically, it allows researchers to investigate growth trajectories, influential authors and institutions, cluster fundamental themes of research, and identify emerging or declining areas of research over time [40, 41].

Almost all studies in materials and process engineering are limited to a single database (usually Scopus or Web of Science). Even though both databases provide high-quality indexing and citation data, they differ in coverage policies,

journal inclusion, and document types, which can significantly affect outcomes [42]. Comparative analyses confirm that while WoS remains strong in basic sciences and legacy publications, Scopus has broader coverage of engineering and conference proceedings, making database choice a critical methodological decision [43]. More recently, dual-database studies have shown how integrating WoS and Scopus can minimize bias and improve completeness, though such integration requires extensive data wrangling [44]. To the best of our knowledge, no bibliometric analysis has integrated Scopus and WoS specifically for tire extrusion.

This study fills this gap by constructing an integrated, dual-database corpus of peer-reviewed research on tire extrusion published between 2000 and 2025. Records were extracted from Scopus and Web of Science using search strings, then harmonized and enriched via CrossRef [45], OpenAlex [46], and OpenCitations [47]. Additional processing was performed in Python, including DOI retrieval, cited-reference completion, corresponding-author identification, and NLP-based keyword extraction using YAKE [48]. The workflow is guided by a set of research questions (RQs). In addition to the full-corpus bibliometric analyses, we introduce a technology-depth sensitivity (scope-control) layer to mitigate terminology-driven drift and to isolate an engineering-centred extrusion-technology core. Specifically, we define a broad tire-extrusion subset using tire-context and extrusion/process terminology, then apply strong technology markers to form two nested technology-explicit subsets (strict: ≥ 1 marker; technology-dense: ≥ 2 markers). Records are also tagged non-exclusively by engineering category (tooling/flow/die; rheology/constitutive modelling; extrusion hardware/process-window design; simulation/CAE; monitoring/control/digitalisation) to support a manufacturing-oriented technical synthesis. The analysis proceeds along three complementary avenues. First, it quantifies the evolution of the field through publication output, citation impact, and authorship patterns. Second, it characterizes research-front themes using co-word analysis, thematic mapping, and multiple correspondence analysis (MCA). Third, it examines the intellectual and social structure of the domain by identifying influential authors, institutions, countries, and sources, and by mapping their relationships via co-authorship and co-citation networks. The technology-depth sensitivity layer is then used to validate thematic robustness under stricter technology definitions and to ground the discussion in extrusion-engineering subdomains. In interpreting these structures, we briefly contextualize the contributions of the most influential works and author communities identified by local-citation and co-citation analyses.

This study makes the following contributions:

- **Dual-database mapping with enriched metadata.** We construct and analyse a harmonized Scopus+WoS corpus of tire–extrusion research (2000–2025), enriched through structured metadata augmentation to improve coverage and reliability for downstream bibliometric analyses.
- **Terminology-driven scope control (technology–depth sensitivity).** We introduce a deterministic scope-control layer that reduces terminology-driven drift by defining a broad tire–extrusion subset and two nested technology-explicit subsets (strict: ≥ 1 marker; technology-dense: ≥ 2 markers), enabling robustness checks under stricter technology definitions.
- **Technology-oriented synthesis via engineering-category tagging.** We connect bibliometric structures to manufacturing practice using non-exclusive engineering-category tagging (rheology/constitutive; tooling/flow/die; extrusion hardware/process-window; CAE/simulation; monitoring/control), supporting an extrusion-engineering interpretation rather than topic-only reporting.
- **Actionable industrial translation.** We translate the dominant technology themes into plant-relevant levers and implications, summarized systematically in Table 20 (industrial levers \rightarrow typical failure modes \rightarrow KPI impacts).

The remainder of this study is organized as follows. Section 2 presents the research design and scope. Section 3 describes the methodology. Section 4 reports the results. Section 5 discusses the findings. Section 6 provides answers to the research questions. Finally, Section 7 concludes the study.

2 Research design and scope

This research uses a multi-source bibliometric design to study the development of scientific research on tire extrusion over a 25-year period, from 2000 to 2025. Combining two major citation databases—Scopus and Web of Science (WoS)—the analysis considers different fields and reduces indexing bias. This dual-database approach improves data completeness, reliability, and reproducibility, offering a strong foundation for mapping the scientific landscape compared with single-source analyses.

To improve metadata quality, bibliographic records were enriched using CrossRef, OpenAlex, and OpenCitations. This enrichment pipeline allowed for accurate extraction of Digital Object Identifiers (DOIs), completion of cited references, identification of corresponding authors and affiliations, and extraction of author-provided and NLP-generated

keywords using the YAKE algorithm. The resulting dataset was analysed using both Python and R-based tools, including Bibliometrix and Biblioshiny, to generate descriptive statistics, co-authorship and co-citation networks, conceptual structure maps, and thematic evolution diagrams.

To assess the sensitivity of the results to terminology and to minimise scope drift, we complemented the main bibliometric workflow with a rule-based sensitivity analysis. A broad tire–extrusion subset was defined using tire- and extrusion-related terms, after which strong technology markers were used to form a strict subset (≥ 1 marker) and a technology-dense subset (≥ 2 markers). Records were also assigned non-exclusive tags (tooling/flow/die, rheology/constitutive modelling, CAE/simulation, monitoring/control) to structure the subsequent engineering discussion. Full rules and code are reported in the Appendix/Supplementary.

2.1 Research objectives

The main objectives of this study are:

- **Publication Trends** – Analyse the temporal growth and distribution of scholarly output on tire extrusion between 2000 and 2025.
- **Influence and Impact** – Identify the most cited publications, influential authors, key journals, and leading research institutions.
- **Thematic Structure and Evolution** – Identify the dominant research themes, map their conceptual relationships (co-word and thematic clustering), and examine how these themes evolve over time to reveal emerging and declining topics.
- **Collaboration Networks** – Map institutional and international research collaborations based on co-authorship and country-level networks.
- **Subject-matter depth in extrusion technology** – Test the robustness of conceptual structures under technology-focused restrictions and synthesise the engineering core of tire extrusion via marker-based filtering.

2.2 Research questions

To address these objectives, the following research questions (RQs) are raised:

- **RQ1:** How has the research output on tire extrusion evolved from 2000 to 2025?
- **RQ2:** Who are the most influential authors, institutions, and journals contributing to this domain?
- **RQ3:** What are the dominant research themes in tire extrusion, and how has the thematic focus evolved over time?

- **RQ4:** What patterns of collaboration exist across countries, institutions, and authors?
- **RQ5:** Which publications and intellectual foundations have had the greatest impact on tire extrusion research?
- **RQ6:** Within technology-explicit tire-extrusion studies, what engineering subdomains dominate, and which remain sparse?

These questions provide a structured foundation for analysing the scientific knowledge structure and dynamics within the field of tire extrusion, while the additional technology-focused layer enables a depth-oriented interpretation anchored in manufacturing-relevant extrusion challenges.

2.3 Scope of the analysis

- **Timeframe:** The analysis spans the period from 2000 to 2025.
- **Document Types:** The study includes peer-reviewed journal articles, review articles, and conference proceedings. Publications from non-scholarly sources were excluded to promote consistency and analytical thoroughness.
- **Language:** Only English-language publications were included.
- **Thematic focus and query design:** This study targets extrusion-related research in tire manufacturing, spanning compound formulation/processing and process-engineering aspects of rubber/profile extrusion and co-extrusion. The database queries combined tire-context terms (e.g., tire/tyre and key components) with extrusion/process terms (e.g., extrusion, extruder, die, cross-head, co-extrusion) to maximise recall while retaining tire relevance; technology-focused scope-control filters were then applied to improve specificity. The complete Scopus/WoS search strings and screening rules are reported in Appendix 8.
- **Technology-depth sensitivity scope:** In addition to the full corpus, we use a nested, rule-based subset strategy (broad tire-extrusion; strict ≥ 1 marker; technology-dense ≥ 2 markers) to isolate technology-explicit extrusion studies. These subsets validate thematic robustness under increased specificity and support a non-exclusive, category-based technical synthesis aligned with extrusion engineering practice.

This research design provides a transparent framework for exploring the intellectual, thematic, collaborative, and technology-depth dimensions of tire extrusion research.

3 Methodology

This study employs a multi-phase methodology to systematically analyze the evolution of tire extrusion research from 2000 to 2025. The approach integrates bibliographic data from Scopus and Web of Science (WoS), followed by semantic enrichment using external APIs and keyword extraction via natural language processing (NLP). The objective is to construct a unified, high-quality dataset for comprehensive bibliometric analysis.

3.1 Workflow overview

The methodological pipeline adopted in this study is summarized in Fig. 1. It includes seven key stages:

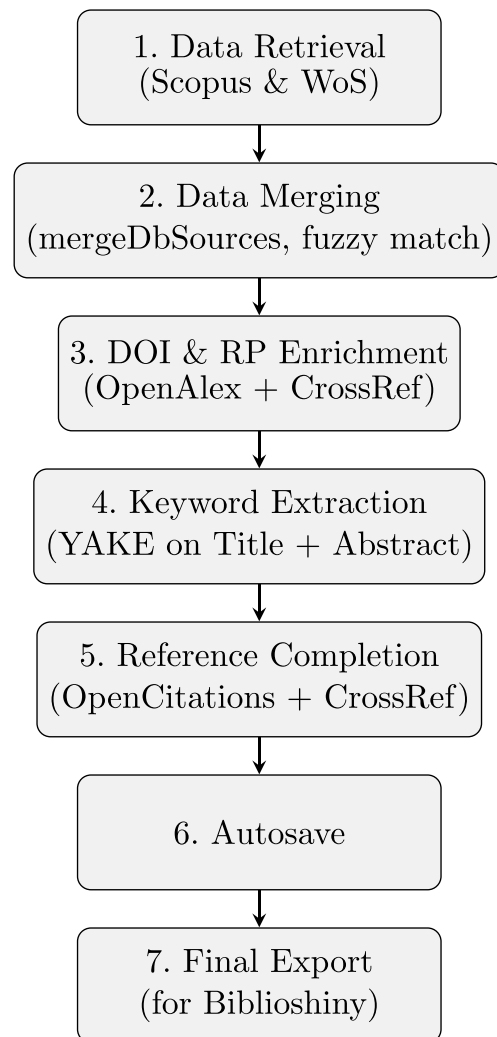


Fig. 1 Workflow Overview of Bibliometric Data Collection and Enrichment

- **Data Retrieval** - Collection of bibliographic records from Scopus and Web of Science using targeted Boolean queries.
- **Merging and Deduplication** - Harmonization of metadata using fuzzy matching and title normalization.
- **DOI and Author Enrichment** - Use of OpenAlex and CrossRef APIs to fill missing DOI and corresponding author fields.
- **Keyword Extraction** - Automatic enhancement of keywords using YAKE based on titles and abstracts.
- **Citation Reconstruction** - Citation enrichment and formatting using OpenCitations and CrossRef metadata.
- **Autosaving** - Periodic autosaves to ensure data integrity during enrichment.
- **Export for Analysis** - Final export to an Excel file compatible with Biblioshiny for visual and quantitative bibliometric analysis.

3.2 Data sources and search strategy

Bibliographic records were obtained from Scopus and WoS using Boolean queries focused on rubber and polymer extrusion in tire manufacturing. Searches were limited to English-language peer-reviewed journal articles, reviews, and conference proceedings published between 2000 and 2025. The Appendix A contains full search strings for full disclosure and better reproducibility of the search process.

3.3 Metadata harmonization

Raw records from Scopus and WoS were merged using the `mergeDbSources()` function in the `bibliometrix` R package. Further cleaning was performed using `pandas` in Python to resolve duplicates and unify field structures. Figure 2 illustrates the merging process. The raw datasets from Scopus (499 records) and WoS (162 records) were combined using fuzzy matching and deduplication. After eliminating 119 duplicates, the final merged dataset contained 542 unique records.

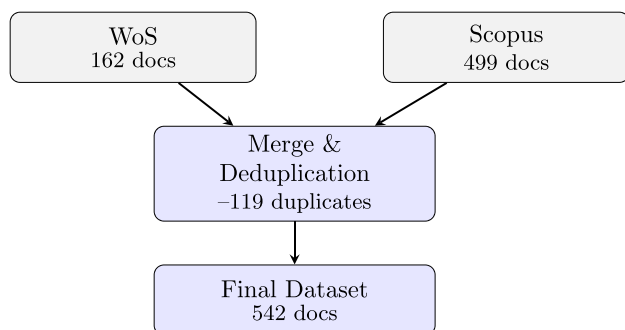


Fig. 2 Merging of Scopus and WoS records with deduplication step

3.4 DOI and author enrichment

To fill missing DOIs and retrieve corresponding author details, a dual-query enrichment pipeline was implemented in Python:

- The OpenAlex API was queried using article titles and author names. If unsuccessful, the CrossRef API was used as fallback.
- Fuzzy title similarity was calculated using the Sequence-Matcher from Python's `diffib` library, with acceptance thresholds of 0.8 (direct match) or 0.6 with author overlap.
- When available, corresponding author names were extracted from OpenAlex authorship metadata.
- Intermediate progress was saved every 50 records to ensure recoverability during batch processing.

3.5 Keyword extraction with YAKE

To complete the DE (author keywords) field, we used the YAKE (Yet Another Keyword Extractor) algorithm on titles and abstracts. YAKE was implemented using the `yake` Python package (v0.4.8) with language set to English (`lan="en"`), unigram extraction (`n=1`), and a maximum of five candidate keywords per record (`top=5`). No custom stopword list was provided; therefore, YAKE's built-in English stopword list was used. Keywords were extracted from the concatenated title and abstract and merged into the DE field only when author keywords were missing, preserving author-provided descriptors whenever present. Extracted keywords were exported using semicolon separators to ensure full compatibility with `bibliometrix`/`Biblioshiny` parsing.

3.6 Citation reference enrichment

Cited references (CR) were enriched in two stages:

- OpenCitations was used to retrieve reference DOIs for records missing citation data.
- Each reference DOI was then passed to the CrossRef API to reconstruct a complete, formatted reference string including author, year, journal title, volume, and page.

All CR entries were formatted for compatibility with `bibliometrix` and `Biblioshiny` tools.

3.7 Software and tools used

- **Python:** `pandas`, `requests`, `yake`, `diffib`, `html`, `openpyxl`
- **R:** `bibliometrix`, `biblioshiny`, `openxlsx`

- **APIs:** OpenAlex, CrossRef, OpenCitations
- **Databases:** Scopus, Web of Science

3.8 Metadata completeness evaluation

To assess the effectiveness of the enrichment process, we compared the completeness of key metadata fields before and after applying the pipeline. Table 1 presents a comparison of missing data across four critical fields. Notably, all missing keyword entries were resolved, and substantial improvements were achieved for DOI, corresponding author, and cited reference fields.

3.9 Technology-depth sensitivity (scope-control) layer

To assess sensitivity to terminology-driven scope and to isolate an engineering-centred extrusion-technology core, we complemented the main bibliometric workflow with a deterministic rule-based filtering layer. For each record, the available title (TI), abstract (AB), keywords (DE), and Keywords Plus (ID) fields were concatenated and case-insensitive regex match counts were computed for (i) tire-context terms, (ii) extrusion/process terms, and (iii) category-specific strong-technology markers. Records with ≥ 1 tire hit and ≥ 1 extrusion hit formed the broad tire–extrusion subset. A total strong-technology score then defined two nested, technology-explicit subsets: a strict subset (strong-tech score ≥ 1) and a technology-dense subset (strong-tech score ≥ 2). In parallel, records were tagged non-exclusively by engineering category (tooling/flow/die; rheology/constitutive modelling; extrusion hardware/process-window design; simulation/CAE; monitoring/control/digitalisation) to structure the subsequent technical synthesis. Full term lists, filtering rules, and scripts are reported in Appendix B and Supplementary.

These categories operationalize the dominant engineering degrees of freedom in extrusion/co-extrusion: material response (rheology/constitutive), flow shaping (tooling/die), thermo-mechanical operating history (hardware/process window), predictive design support (CAE/simulation), and quality stabilization (monitoring/control). [49–52]

Table 1 Completeness of key metadata fields before and after enrichment

Field (Description)	Before Enrichment	After Enrichment
CR (Cited References)	100% missing (542)	3.51% missing (19)
DI (DOI)	18.45% missing (100)	13.10% missing (71)
RP (Corresponding Author)	21.40% missing (116)	17.53% missing (95)
DE (Keywords)	26.57% missing (144)	0.00% missing (0)

Figure 3 summarises the scope-control pipeline and category coverage: panel (a) operationalises progressively stricter technology definitions via the marker-count threshold, enabling robustness checks under technology-focused restrictions; panel (b) reports non-exclusive category coverage within the broad subset, where rheology/constitutive markers are most prevalent and monitoring/control markers are sparse.

3.10 Dataset representativeness check

To assess whether the retrieved corpus captures the expected intellectual backbone of the field, we performed a representativeness check by cross-referencing influential items identified using complementary indicators within the dataset: (i) the most globally cited documents (Table 5), (ii) the most locally cited documents (Table 6), (iii) the most locally cited references (Table 7), and (iv) centrality-ranked co-cited references derived from the co-citation network (Table 11). We further verified that these influential references align with the major RPYS peaks (Fig. 23), supporting that the dataset contains core works shaping the domain and is suitable for mapping thematic and intellectual structures.

4 Results

4.1 Descriptive overview of the dataset

This bibliometric dataset was constructed from Scopus and Web of Science (WoS), two major academic databases. It contains 542 publications on tire-extrusion research (2000–2025), which were subsequently tagged and sub-setted using technology-focused markers to support an engineering-centred interpretation. These works consist of peer-reviewed journal articles, conference papers and proceedings, and a small number of book chapters indexed in either Scopus or WoS.

Table 2 presents the essential descriptive statistics of the final dataset. Furthermore, the annual growth rate of scientific productivity over the 25 years was 2.81%, indicating a slow, but constant increase in research within this field. Documents, on average, received an average of 19.54 citations, and cited 27.2 sources, contributing 14,788 references.

The dataset includes 1,395 unique authors, with an average of 3.95 co-authors per publication, reflecting a relatively collaborative research environment. Notably, 5.35% of the publications involved international co-authorship, suggesting limited but measurable global collaboration. In terms of content, 3,344 Keywords Plus and 1,415 author keywords were extracted, which provided a robust basis for subsequent thematic and conceptual analyses.

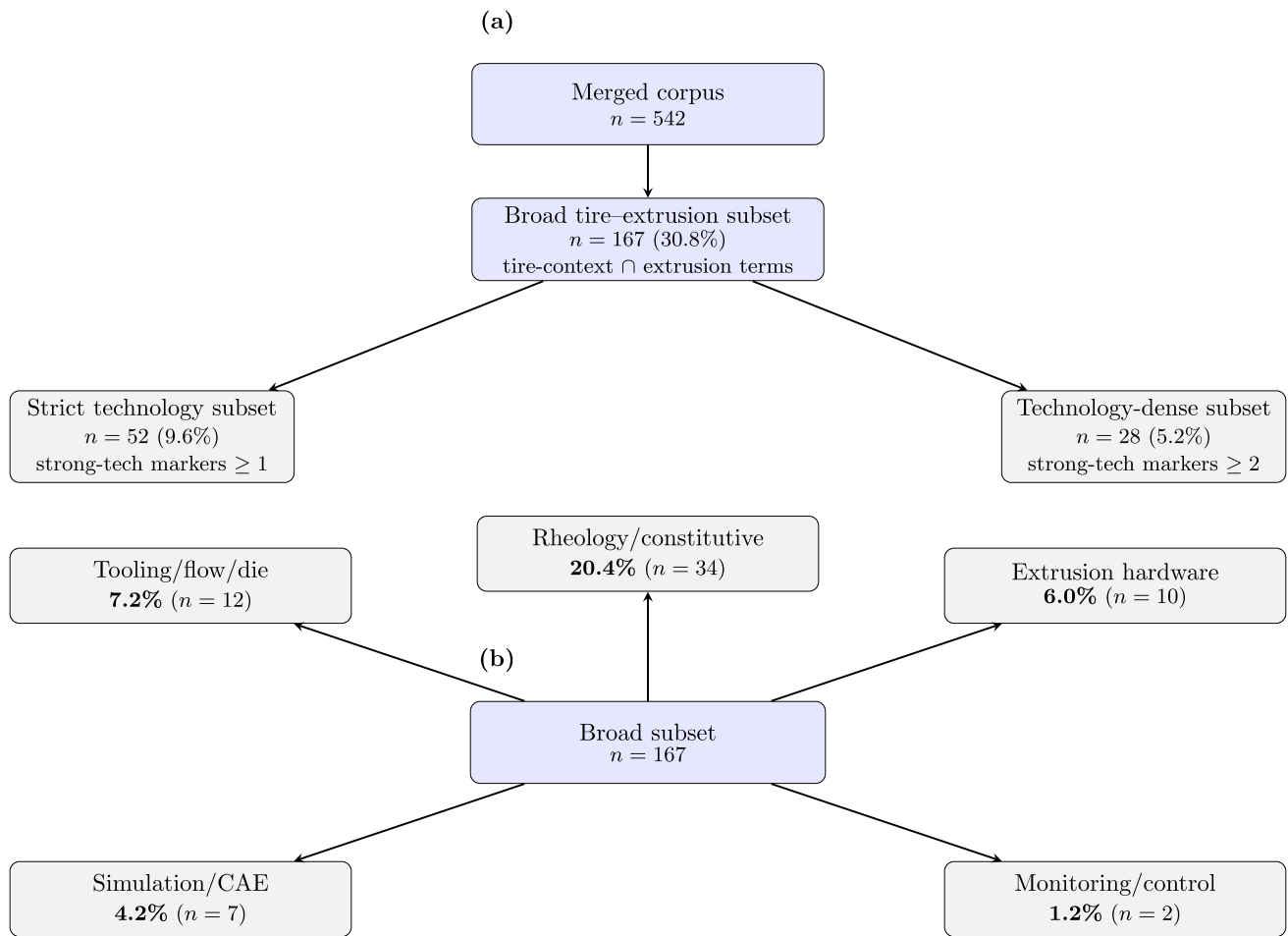


Fig. 3 Technology-depth sensitivity layer used for scope control and engineering interpretation. **(a)** Deterministic filtering from the merged corpus to a broad tire-extrusion subset and two nested technology-

explicit subsets. **(b)** Non-exclusive strong-technology tagging within the broad subset ($n = 167$)

4.2 Scientific production trends

The evolution of annual scientific production in tire extrusion research is illustrated in Fig. 4. The dataset shows a relatively modest number of publications in the early 2000s, indicating a foundational phase for this research field. There was an acceleration in scholarly output after 2010 and the output peaked around 2020. Although some fluctuations are observed in subsequent years, the overall trajectory demonstrates a steady upward trend, consistent with the annual growth rate of 2.81% as noted in Table 2. The observed pattern suggests that tire extrusion is a growing yet still specialized research area with evolving industrial relevance.

Figure 5 presents the average number of citations per document by publication year. The trend indicates increasing citation impact from 2000 to 2020, with significant peaks in 2015 and 2020. These peaks may reflect the publication of influential studies or the emergence of thematic clusters that gained attention from the research community.

A decline in citation averages after 2021 is likely due to citation lag, as recently published articles have had limited time to accumulate citations. This temporal variation highlights the importance of interpreting citation metrics in context and underscores the growing influence of the field over the last two decades.

4.3 Source analysis

This section explores the most influential publication sources in the field of tire extrusion using multiple indicators. Figure 6 presents the top 10 most prolific sources based on the number of documents published. The Journal of Applied Polymer Science leads with 48 documents, followed by Rubber Chemistry and Technology and Rubber World. These journals play a central role in publishing tire extrusion research, especially within polymer and rubber science communities.

Figure 7 ranks the top 10 sources based on local citation counts, determined through fuzzy-matching to ensure

Table 2 Descriptive statistics of the dataset (2000–2025)

Description	Results
Timespan	2000–2025
Sources (Journals, Books, etc.)	217
Documents	542
Annual Growth Rate (%)	2.81
Document Average Age	11.5
Average Citations per Document	19.54
References	14,788
Keywords Plus (ID)	3,344
Author's Keywords (DE)	1,415
Authors	1,395
Authors of Single-Authored Documents	31
Single-Authored Documents	37
Co-Authors per Document	3.95
International Co-Authorships (%)	5.35
Document Types	
Article	423
Article; Book Chapter	1
Article; Early Access	4
Article; Proceedings Paper	3
Conference Paper	73
Proceedings Paper	16
Review	21
Review; Book Chapter	1

accurate aggregation of similar source names. Consistently, the Journal of Applied Polymer Science leads with over 800 local citations, demonstrating its importance in both volume and influence. Rubber Chemistry and Technology, Polymer Degradation and Stability, and Polymer Testing also show substantial local impact, indicating that their articles are widely cited within this research domain.

To identify the field's core publication venues, Bradford's Law was applied (Figure 8). This law states that scientific literature on a topic is distributed in concentric zones: a small core of journals (Zone 1) accounts for the majority of publications, while additional zones include more journals with fewer contributions [53, 54]. The Zone 1 sources—Journal of Applied Polymer Science, Rubber Chemistry and Technology, and Rubber World—emerge as the most productive journals, confirming their central role in disseminating tire extrusion research.

In addition, Table 3 presents bibliometric indicators including the *h*-index, *g*-index, and *m*-index. The Journal of Applied Polymer Science again ranks highest across all impact measures, reflecting both its longevity (since 2000)

Fig. 4 Annual scientific production on tire extrusion technologies (2000–2025)

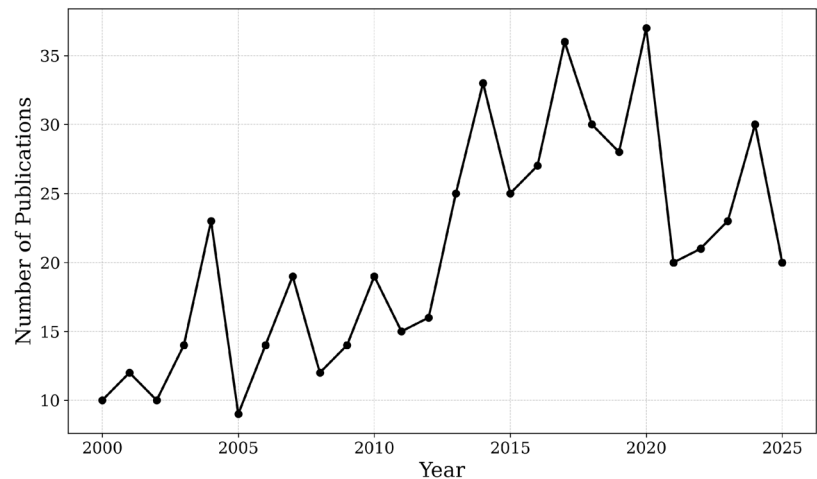


Fig. 5 Average citations per document by publication year (2000–2025). Citation peaks in 2015 and 2020 suggest influential research outputs during these years, while recent declines are attributable to citation delays

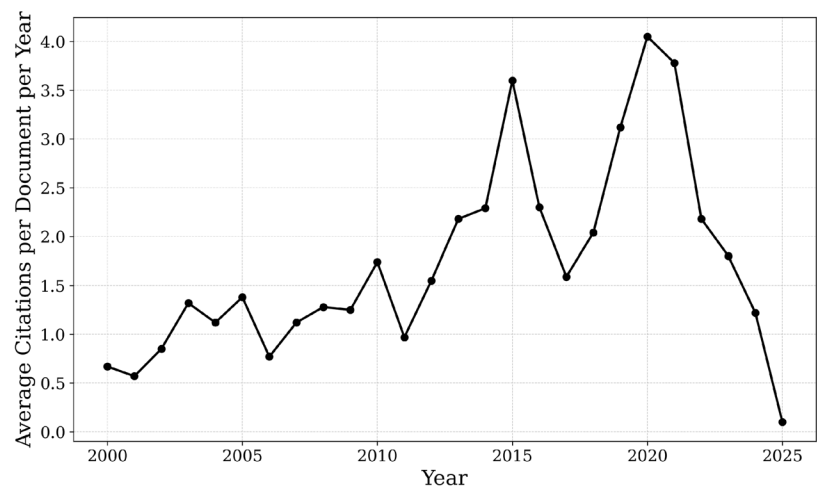


Fig. 6 Top 10 most relevant sources in the tire extrusion literature based on publication frequency

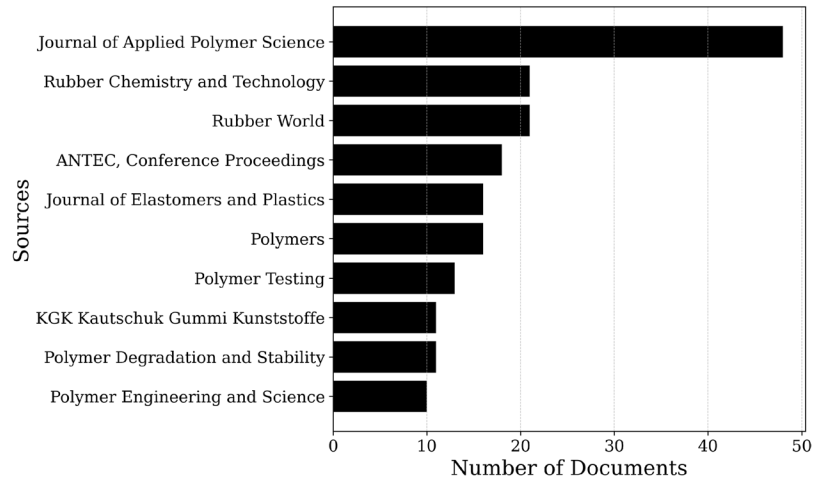


Fig. 7 Top 10 most locally cited sources in the tire extrusion literature

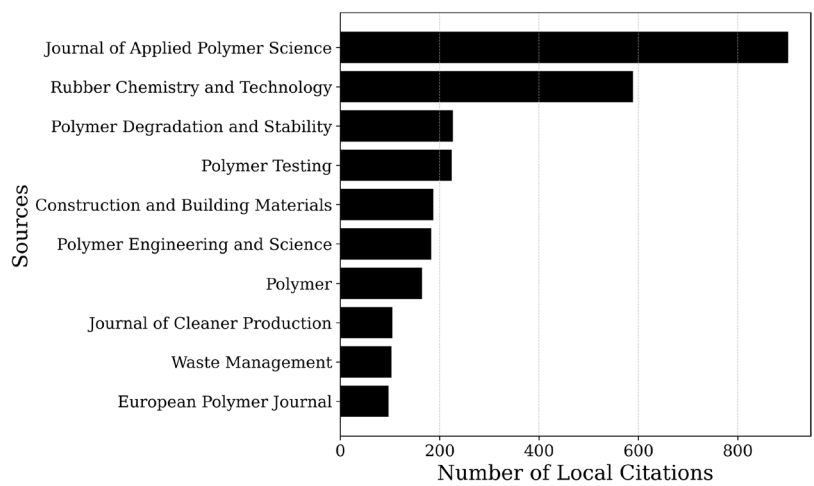
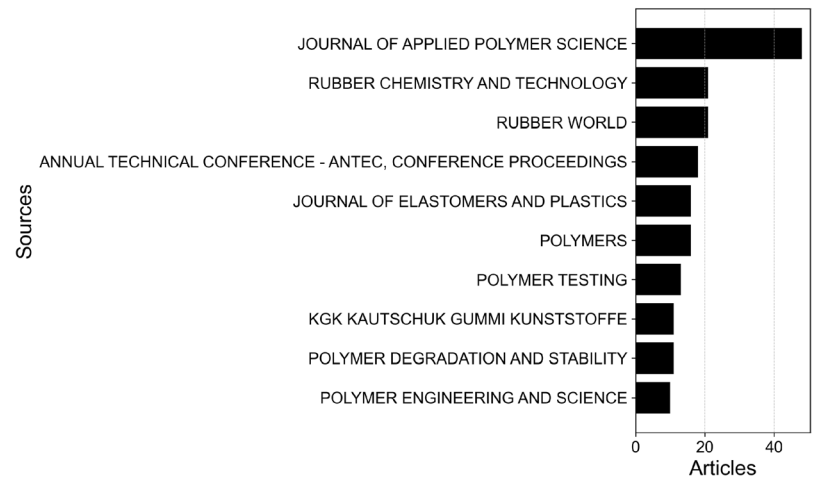


Fig. 8 Core sources identified using Bradford’s Law



and sustained influence. Other strong performers include Polymer Testing and Polymer Degradation and Stability, which show consistent citation performance relative to their publication counts and age.

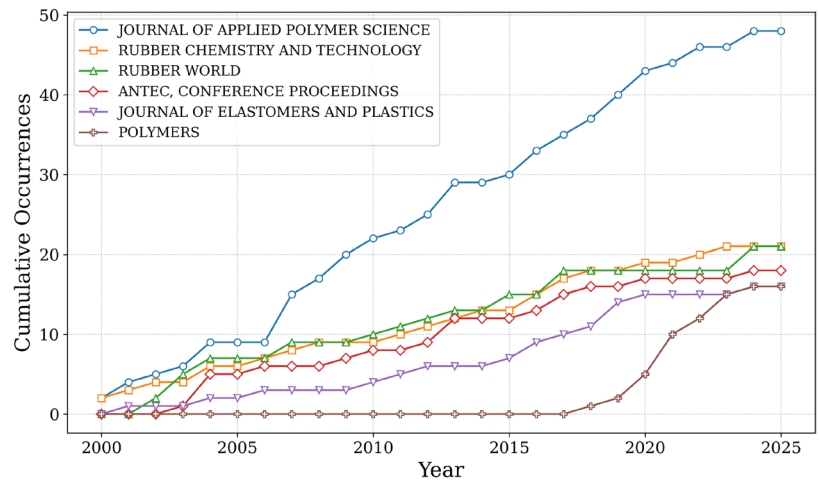
Finally, Fig. 9 illustrates the cumulative scientific output of key journals between 2000 and 2025. The Journal

of Applied Polymer Science demonstrates steady and dominant growth throughout the period, confirming itself as the primary outlet for tire extrusion research. Other journals, including Rubber World and Polymers, also show notable upward trends, reflecting their increasing role in publishing contributions to this domain.

Table 3 Local impact of key sources based on *h*-index, *g*-index, and *m*-index values

Source	<i>h</i> -index	<i>g</i> -index	<i>m</i> -index	TC	NP	\mathbb{R}_{start}
Journal of Applied Polymer Science	19	30	0.731	1019	48	2000
Polymer Testing	11	13	0.423	530	13	2000
Polymer Degradation and Stability	10	11	0.417	592	16	2002
Polymers	10	13	1.250	196	16	2018
Rubber Chemistry and Technology	10	21	0.385	625	21	2001
Journal of Elastomers and Plastics	7	15	0.280	245	10	2001
KGK Kautschuk Gummi Kunststoffe	6	11	0.273	176	11	2004
Polymer Engineering and Science	6	10	0.250	129	6	2002
Composites Science and Technology	5	6	0.217	453	6	2003
Construction and Building Materials	5	5	0.500	242	5	2016

Fig. 9 Cumulative scientific output of key journals from 2000 to 2025



4.4 Author analysis

This part explores the productivity and influence of authors in the field of tire extrusion. Figure 10 presents the most prolific contributors based on the number of documents published. Formela K., Zhang L., and Zhang Y. emerge as leading authors, reflecting sustained engagement and leadership in the domain.

Fig. 10 Most relevant authors based on the number of published documents

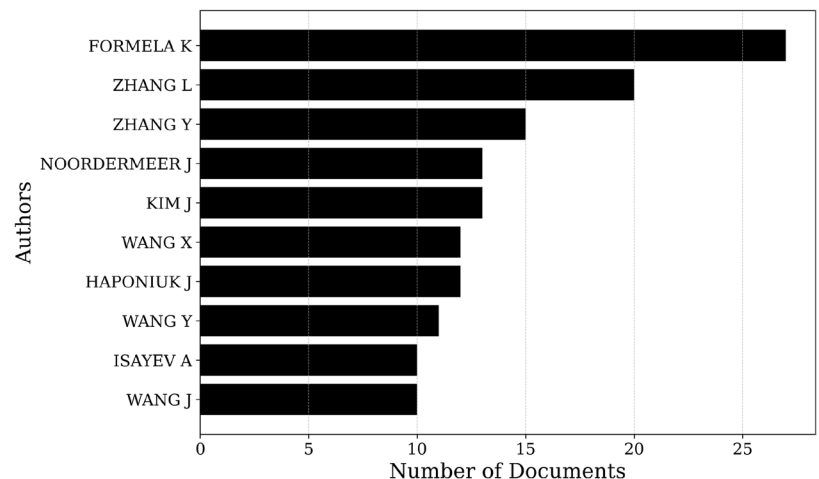
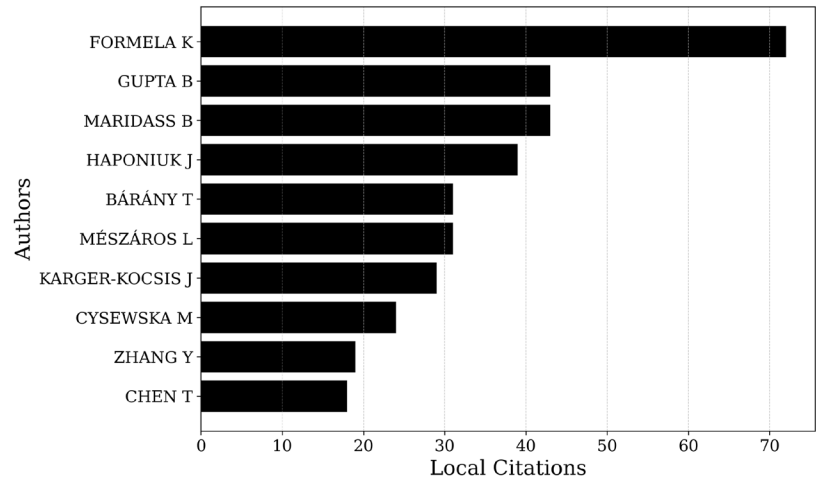


Figure 11 shows the most locally cited authors. Formela K. again stands out with 72 local citations, indicating both high productivity and central influence in the dataset. Other frequently cited authors include Gupta B. and Maridass B., suggesting their work has played a foundational role within the specific research community.

To visualize the interconnection between intellectual foundations, active researchers, and thematic focus, the

Fig. 11 Most locally cited authors in the dataset



Three-Field Plot (Figure 12) maps the relationships among the most cited references (CR), most prolific authors (AU), and most frequent author keywords (DE). This Sankey-style diagram illustrates how seminal works, such as those by Isayev A. and Formela K., influence recurring keywords like recycling, rubber, and devulcanization.

Temporal publication trends are shown in Figs. 13, 14, and 15. These visualizations reveal not only publication frequency over time but also citation performance. Key contributors such as Formela K. and Zhang L. demonstrate consistent scholarly activity with high citation impact across multiple years.

Table 4 summarizes the local impact metrics of the most influential authors. Metrics such as *h*-index, *g*-index, and *m*-index are used to capture both long-term consistency and recent productivity. Formela K., Zhang L., and Kim J. rank highest, underscoring their prominent and sustained contributions.

Lotka’s Law [54, 55] describes the expected inverse-square relationship between the number of authors and the number of publications they produce (see Eq. (1)). Formally, the number of authors A_n contributing n publications is given by:

$$A_n = \frac{A_1}{n^2} \tag{1}$$

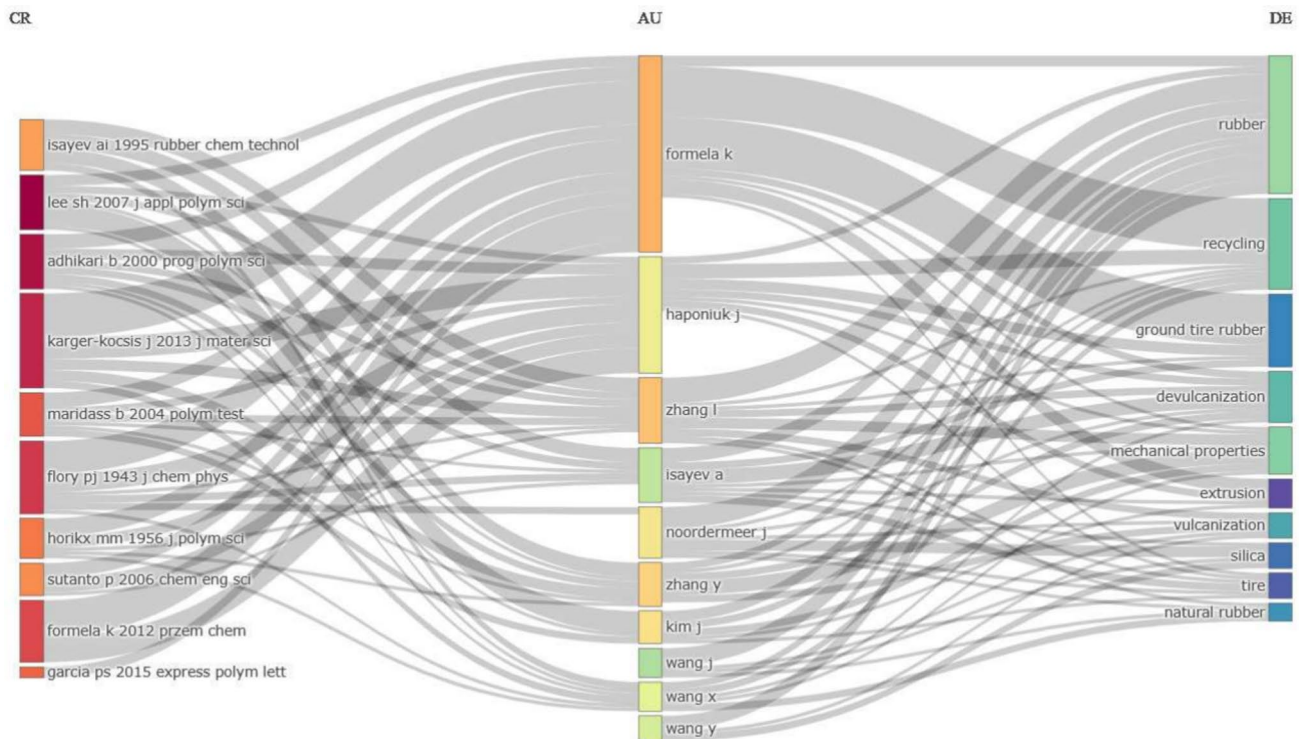


Fig. 12 Three-field plot linking cited references (CR), top contributing authors (AU), and dominant keywords (DE)

Fig. 13 Temporal distribution of publications by the most productive authors

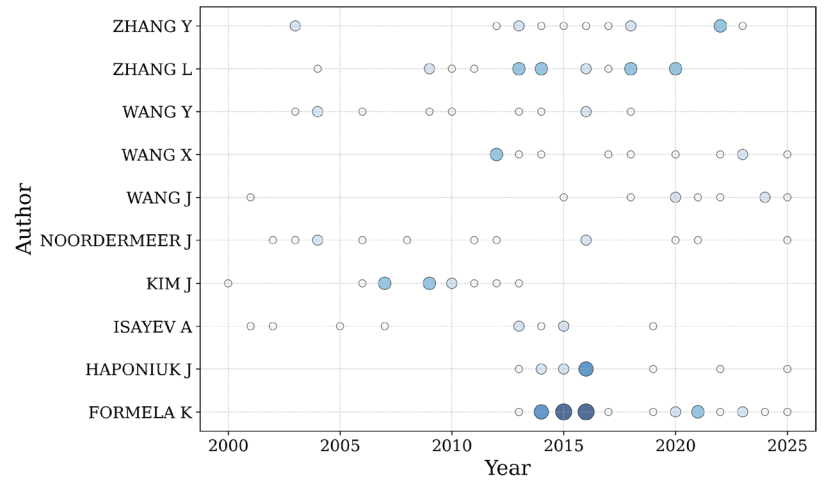


Fig. 14 Author productivity over time, weighted by average citations per year (TCpY)

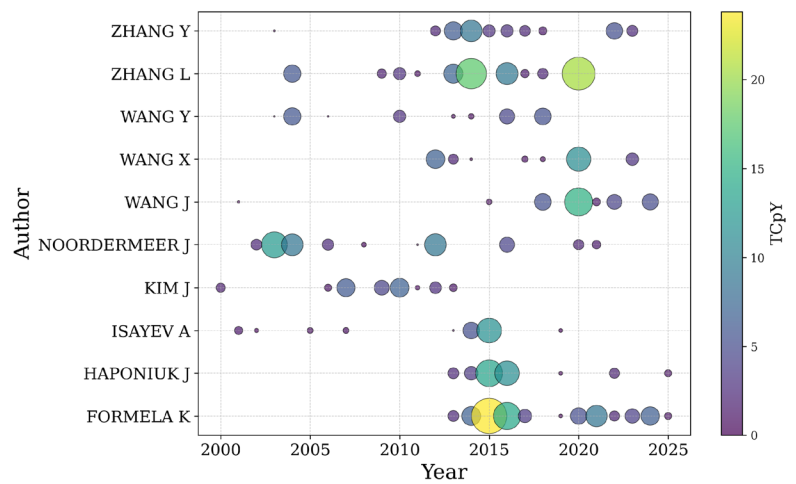


Fig. 15 Total citation performance of authors across time. Bubble size indicates cumulative citations

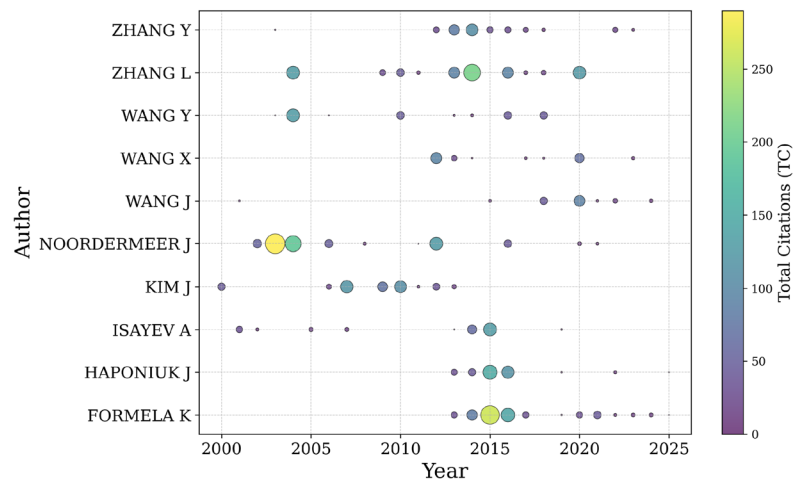


Table 4 Local impact of the most productive authors in the dataset

Author	h-index	g-index	m-index	TC	NP	PY_start
FORMELA K	15	25	1.154	657	27	2013
ZHANG L	14	20	0.636	757	20	2004
KIM J	12	13	0.462	418	13	2000
NOORDERMEER J	9	13	0.375	783	13	2002
ZHANG Y	9	15	0.391	337	15	2003
HAPONIUK J	8	12	0.615	348	12	2013
LEE S	8	8	0.308	248	8	2000
HEJNA A	8	8	0.636	184	10	2015
ISAYEV A	7	10	0.280	261	10	2001
WANG S	7	10	0.700	252	10	2016

where A_1 represents the number of authors with a single publication. Figure 16 compares the observed author productivity distribution in the dataset with the theoretical curve. The strong alignment indicates that the majority of authors have published only one document, while a smaller number have contributed multiple publications—a pattern consistent with established bibliometric regularities. This conformity reinforces the representativeness of the dataset and validates the reliability of the author-level analysis.

Fig. 16 Author productivity distribution in the dataset, compared with Lotka’s Law. The observed proportion of authors (solid line) closely follows Lotka’s inverse-square law (dashed line), confirming that the dataset conforms to expected bibliometric patterns

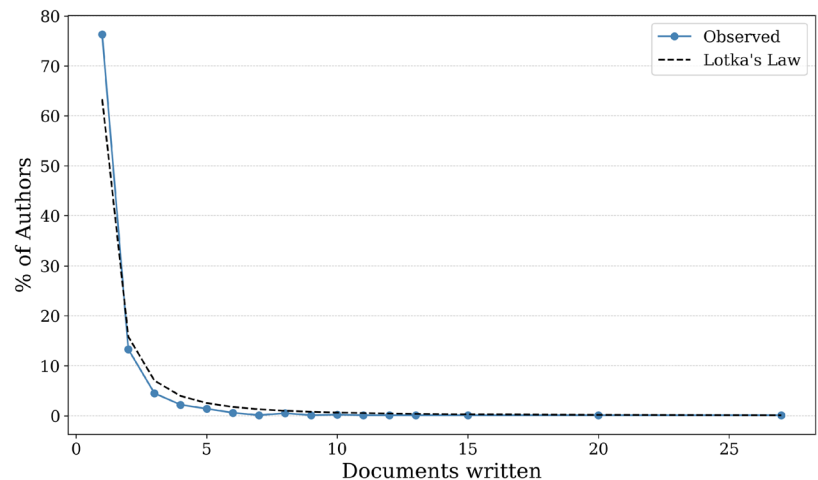
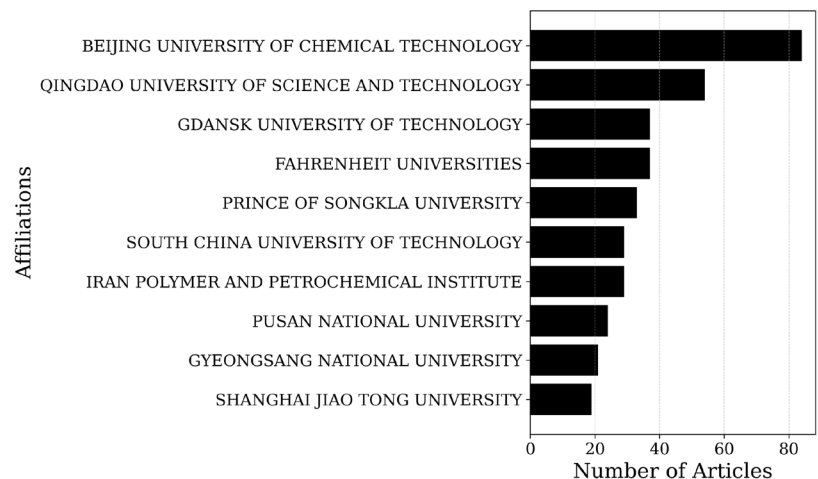


Fig. 17 Most relevant affiliations based on publication volume



4.5 Affiliation and country analysis

This section evaluates institutional contributions to tire extrusion research. Figure 17 shows that the Beijing University of Chemical Technology is the leading contributor, followed by Qingdao University of Science and Technology and Gdansk University of Technology. These institutions represent the primary hubs of knowledge production, reflecting strong research capacity in both China and Europe.

Figure 18 illustrates annual scientific output of the top five institutions from 2000 to 2025. The Beijing University of Chemical Technology exhibits the most consistent growth, especially after 2010, whereas others like the Gdańsk University of Technology show steady but less pronounced trends.

Figure 19 compares single-country publications (SCP) and multi-country publications (MCP) for the top contributing countries. China leads in total output, driven primarily by domestic collaborations (SCP), reflecting a strong internal research base. In contrast, countries like the Korea and Poland show a higher proportion of internationally co-authored publications (MCP), indicating greater global integration in tire extrusion research.

The choropleth map in Fig. 20 shows the geographic distribution of scientific output in tire extrusion research. China leads as the most active contributor, shown in bright yellow, followed by countries like the United States, India, and Poland in darker shades. The color scale represents publication volume, with yellow indicating the highest and dark blue or purple indicating lower levels of activity.

Fig. 18 Yearly scientific output of the productive affiliations

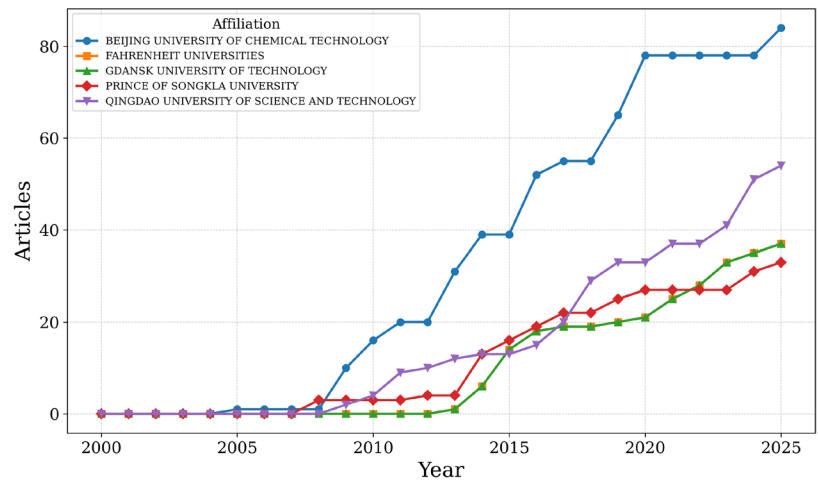
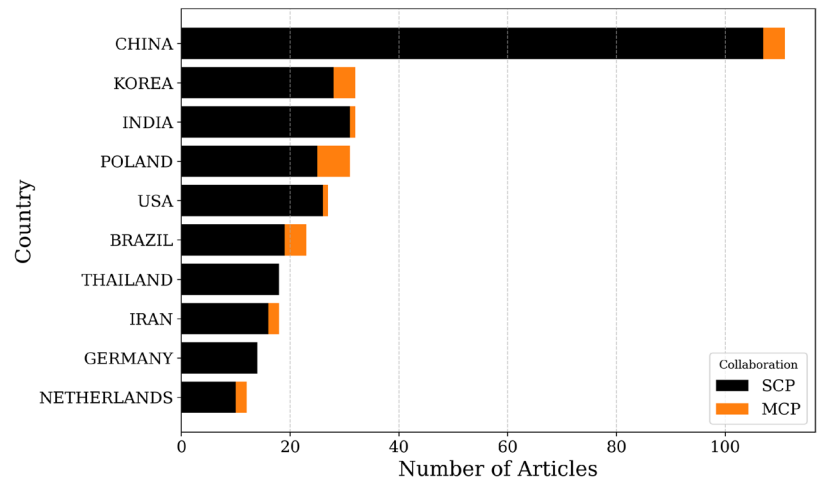


Fig. 19 SCP and MCP breakdown by country based on corresponding author affiliation



Temporal publication trends by country are illustrated in Fig. 21. China shows a sharp and sustained rise in publication output, particularly after 2010, strengthening its position in tire extrusion research. In contrast, countries such as Poland, South Korea, and India demonstrate more gradual but steady growth, while the United States shows consistent contributions with moderate increases over time.

In terms of scholarly influence, Fig. 22 presents total citation counts by country. China leads with over 2200 citations, followed by the Netherlands, South Korea, and Poland. This reflects both high research activity and impact.

4.6 Citation analysis

Citation analysis provides insight into the intellectual impact and recognition of publications within the field of tire extrusion. Table 5 presents the ten most globally cited documents in the dataset. The most influential work is by Ramarad et al. [23], published in Progress in Materials Science, which provides a comprehensive review on waste tire recycling and devulcanization technologies. Other key

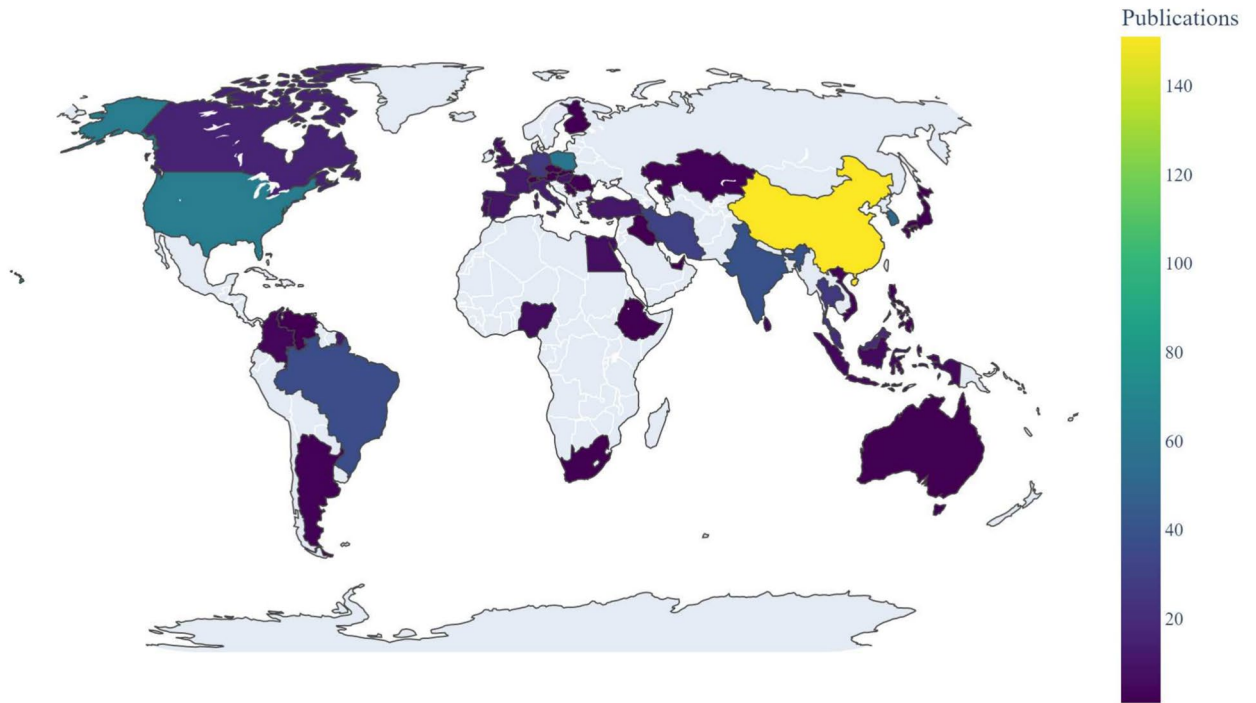


Fig. 20 Choropleth map of global scientific output in tire extrusion

Fig. 21 Publication trends by country

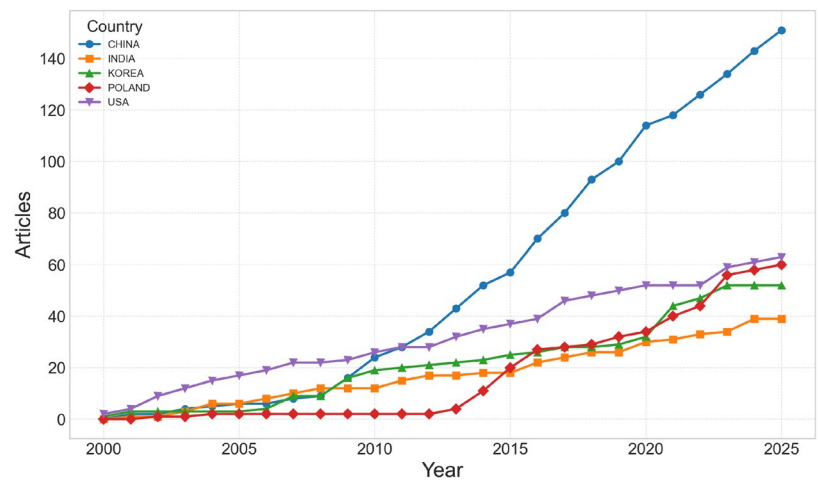


Fig. 22 Total citations by country

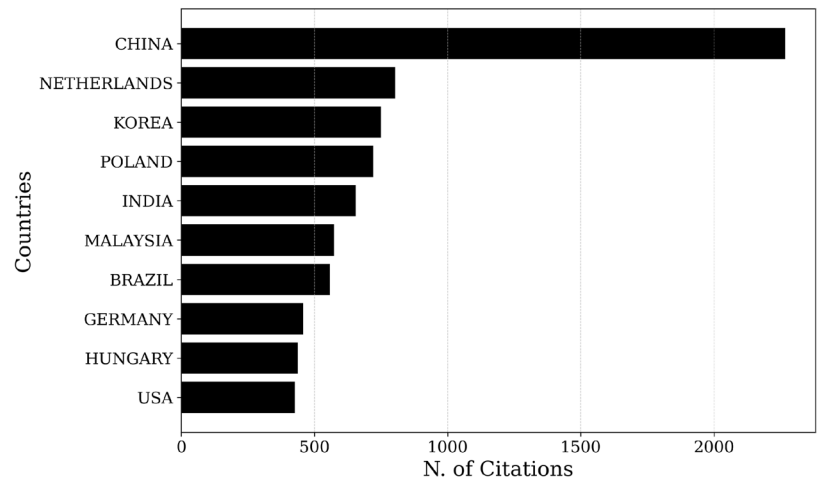


Table 5 Top 10 most globally cited documents in the dataset

Author (Year)	Journal	DOI	TC	TC/Year	Norm. TC
Ramarad S. (2015)	<i>Progress in Materials Science</i>	10.1016/j.pmatsci.2015.02.004	388	35.67	9.80
Karger-Kocsis J. (2013)	<i>Journal of Materials Science</i>	10.1007/s10853-012-6564-2	291	22.38	10.25
Ten B. J. (2003)	<i>Composites Science and Technology</i>	10.1016/S0266-3538(03)00077-0	290	12.61	9.55
Basu D. (2014)	<i>Progress in Polymer Science</i>	10.1016/j.progpolymsci.2013.03.001	225	18.75	9.00
Stöckelhuber K. (2010)	<i>Polymer</i>	10.1016/j.polymer.2010.03.013	171	13.15	9.00
Martínez J. (2019)	<i>Waste Management</i>	10.1016/j.wasman.2019.01.016	153	21.86	7.00
Heideman G. (2004)	<i>Rubber Chemistry and Technology</i>	10.5254/1.3547844	150	6.82	6.11
Dominic M. (2020)	<i>Carbohydrate Polymers</i>	10.1016/j.carbpol.2019.115620	147	24.50	6.05
De S. F. (2017)	<i>Polymer Degradation and Stability</i>	10.1016/j.polyimdegradstab.2017.03.008	134	14.89	5.97
Wu Y. (2004)	<i>Macromolecular Materials and Engineering</i>	10.1002/mame.200400085	127	5.77	5.17

Table 6 Top 10 most locally cited documents in the dataset

Author(Year)	Journal	DOI	Local Citations	Global Citations	LC/GC Ratio (%)	Normalized LC
Karger-Kocsis J. (2013)	<i>Journal of Materials Science</i>	10.1007/s10853-012-6564-2	29	291	9.97	15.43
Maridass B. (2004)	<i>Polymer Testing</i>	10.1016/j.polymertesting.2003.10.005	22	56	39.29	15.33
Shi H. (2013)	<i>Journal of Applied Polymer Science</i>	10.1002/app.38170	18	58	31.03	9.57
Seghar S. (2019)	<i>Resources, Conservation & Recycling</i>	10.1016/j.resconrec.2019.01.047	15	122	12.30	19.09
Ramarad S. (2015)	<i>Progress in Materials Science</i>	10.1016/j.pmatsci.2015.02.004	13	388	3.35	6.91
Gagol M. (2016)	<i>Polymer Degradation and Stability</i>	10.1016/j.polyimdegradstab.2015.05.007	13	88	14.77	6.91
Formela K. (2016)	<i>Journal of Vinyl and Additive Technology</i>	10.1002/vnl.21426	13	87	14.94	6.91
Tantayanan S. (2004)	<i>Journal of Applied Polymer Science</i>	10.1002/app.13182	11	74	14.86	7.24
Maridass B. (2008)	<i>Polymer Composites</i>	10.1002/pc.20379	10	26	38.46	6.61
Mangili I. (2015)	<i>Chemometrics and Intelligent Laboratory Systems</i>	10.1016/j.chemoable.2015.03.003	10	66	15.15	5.32

contributions include Karger-Kocsis [56] in the Journal of Materials Science and Ten Brinke et al. [57] in Composites Science and Technology. Collectively, these highly cited studies highlight research priorities around rubber recycling, polymer degradation, and composite reinforcement, underlining their enduring relevance to both academic and industrial research.

While global citations reflect broad scholarly recognition, local citations capture documents that have had a more immediate impact within the tire extrusion research domain. As shown in Table 6, Karger-Kocsis [56] leads with more local citations, reinforcing its centrality in the field. Maridass [58] and Shi [59] also stand out with high local-to-global citation ratios (LC/GC), indicating that although their global visibility is comparatively lower, their contributions are particularly influential within this specialized community.

Table 7 highlights the most locally cited references within the dataset, reflecting the conceptual core of tire extrusion research. The most frequently cited works include Adhikari

B. [60], Karger-Kocsis J. [56], and Maridass B. [58], which confirm their foundational role in defining the field. These references are co-cited in studies addressing rubber processing, devulcanization, and polymer performance.

To identify key historical contributions, Fig. 23 presents the Reference Publication Year Spectroscopy (RPYS) of the dataset. The black dashed line represents the total number of cited references per publication year, while the blue line illustrates deviations from a five-year median, emphasizing citation peaks. RPYS deviations were computed relative to a five-year rolling median (diffMedian5) as a compromise between reducing year-to-year noise and preserving temporal resolution of citation peaks. In addition, RPYS was evaluated from 1950 onward to avoid distortion from sparse early-year reference counts.

4.7 Thematic and conceptual structure

This part provides insights into the dominant topics, their maturity, and how research themes have developed.

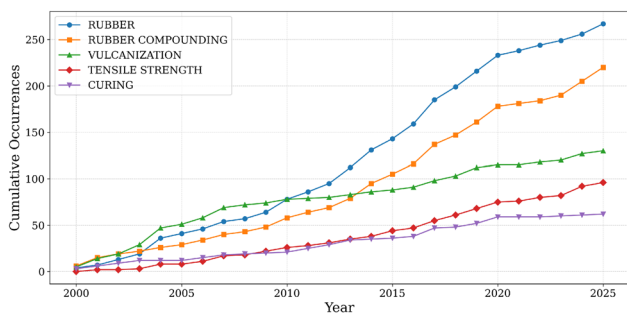


Fig. 25 Temporal evolution of selected Keywords Plus. The trends highlight shifting thematic focus over time

Table 9 Top 25 trending terms in the field based on frequency and temporal distribution. Columns indicate the first quartile (Q1), median, and third quartile (Q3) publication years for each term

Term	Freq.	Q1	Median	Q3
rubber	267	2004	2006	2009
rubber compounding	220	2004	2006	2009
vulcanization	130	2002	2004	2007
tensile strength	96	2003	2004	2016
curing	62	2003	2004	2006
mechanical properties	61	2003	2004	2016
tires	57	2003	2004	2006
crosslinking	52	2004	2006	2012
mechanical-properties	48	2004	2005	2009
silica	48	2004	2005	2009
fillers	47	2003	2004	2006
extrusion	45	2003	2004	2015
morphology	42	2003	2004	2006
carbon black	39	2003	2004	2007
rubber industry	39	2003	2004	2006
elastomers	38	2003	2004	2007
styrene	38	2003	2004	2006
thermoplastic elastomers	38	2003	2004	2007
mixing	37	2003	2004	2006
nanocomposites	36	2003	2004	2007
reinforcement	36	2003	2004	2006
twin-screw extruder	36	2003	2004	2006
rubber applications	34	2003	2004	2007
polymer blends	33	2003	2004	2006
butadiene	33	2003	2004	2007

within 2002–2009) and continue to be well represented, highlighting their foundational role. On the other hand, terms including tensile strength (Q3 = 2016), mechanical properties (Q3 = 2016), and extrusion (Q3 = 2015) show later concentration, indicating continued focus in more recent years; crosslinking peaks around 2012. In contrast, nanocomposites (Q3 = 2007), twin-screw extruder (Q3 = 2006), and silica (Q3 = 2009) cluster in the mid-2000s rather than being recent emergent topics.

The keyword co-occurrence (co-word) network was generated in Biblioshiny using Keywords Plus as the field,

association normalization, and Louvain community detection. For this figure, the visualization was restricted to the top 30 nodes; isolated nodes were removed and edges were retained only when at least two links were present (minimum number of edges = 2). The layout was computed using the automatic layout option with repulsion force set to 0.1, and label-overlap avoidance was enabled. Figure 26 displays the resulting co-occurrence network of Keywords Plus and the corresponding clusters.

The network reveals three major thematic clusters:

- **Red cluster:** Dominated by terms such as rubber, rubber compounding, vulcanization, and tensile strength, this group centers on material formulation and processing.
- **Blue cluster:** Includes thermoplastic elastomers, extrusion, devulcanization, and recycling, indicating a focus on processing technologies and sustainability.
- **Green cluster:** Composed of fillers, carbon black, reinforcement, and rubber industry, this cluster reflects the use of additives and industrial aspects.

Figure 27 presents the thematic map of the field based on Keywords Plus. The motor-theme quadrant is dominated by a large cluster centred on rubber, rubber compounding, curing, and mechanical properties, indicating that formulation and property-driven studies constitute the most central and strongly connected knowledge base in the retrieved corpus. A second specialised theme combines vulcanization, crosslinking, tensile strength, and extrusion, reflecting a cohesive but narrower process–structure focus that is relatively well developed but less central than the main compounding/property theme. In contrast, themes such as thermoplastic elastomers and twin-screw extruder appear with lower centrality and density, suggesting emerging or peripheral research streams under the applied parameter thresholds.

Figure 28 shows the thematic evolution of the field based on Keywords Plus across four time slices (2000–2009, 2010–2016, 2017–2020, and 2021–2025), using Louvain clustering and the inclusion index weighted by word occurrences (top 100 terms; minimum cluster frequency = 30 per 1000 documents; minimum weight index = 0.1; label-overlap avoidance enabled). The map indicates a field-wide backbone centred on rubber from 2010 onward, with early prominence of vulcanization in 2000–2009. Subsequent slices emphasize a formulation–performance orientation through mechanical properties and tensile strength, while the most recent period shows increased salience of formulation themes such as rubber compounding and rubber composite. Process- and equipment-specific strands (e.g., extrusion and twin-screw extruder) appear as smaller, more time-local clusters, connected to the central backbone via weaker continuity links.

Fig. 26 Keyword co-occurrence network using Louvain clustering. Node size indicates term frequency, and edge thickness reflects co-occurrence strength

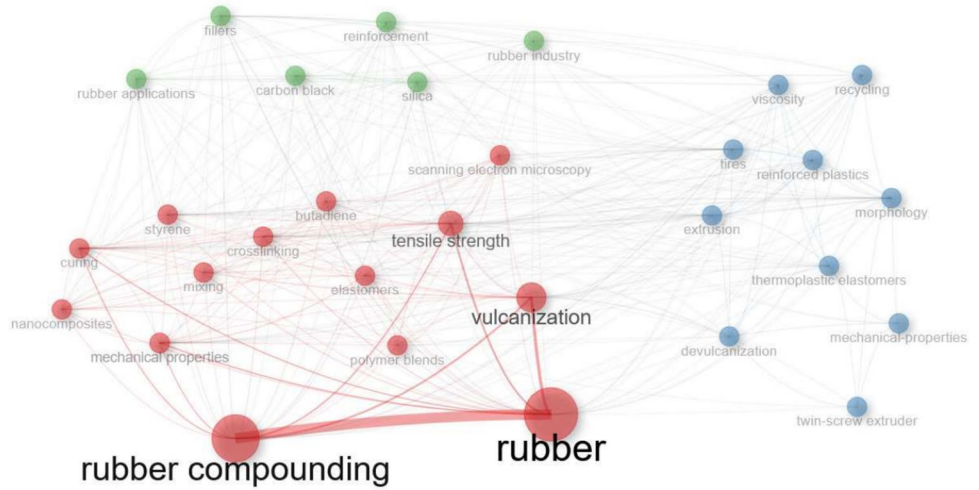


Fig. 27 Thematic map based on Keywords Plus (Louvain clustering). Parameters: top 100 terms; minimum cluster frequency = 30; community repulsion = 0.5; labels per cluster = 4. Bubble size indicates theme frequency

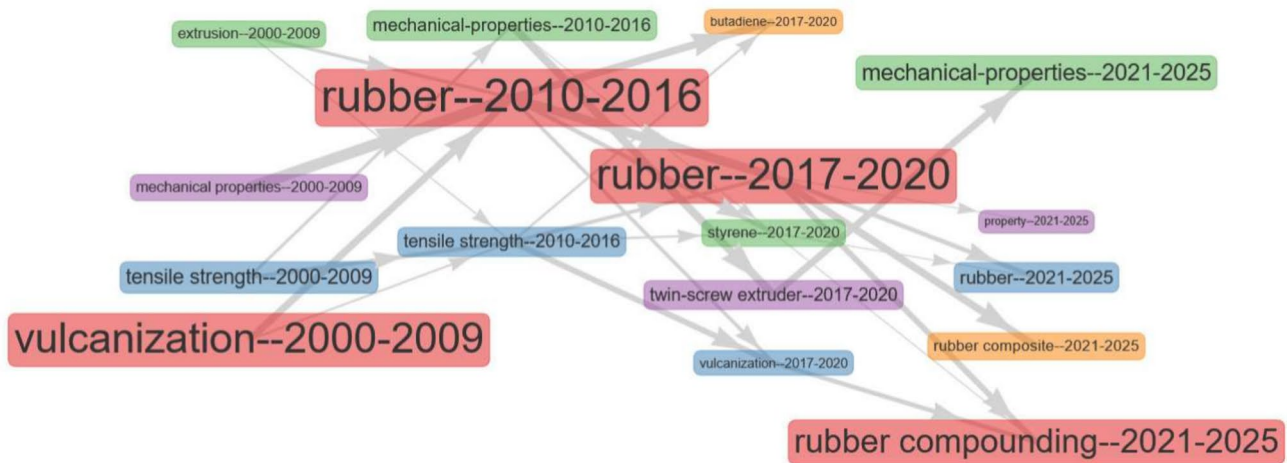
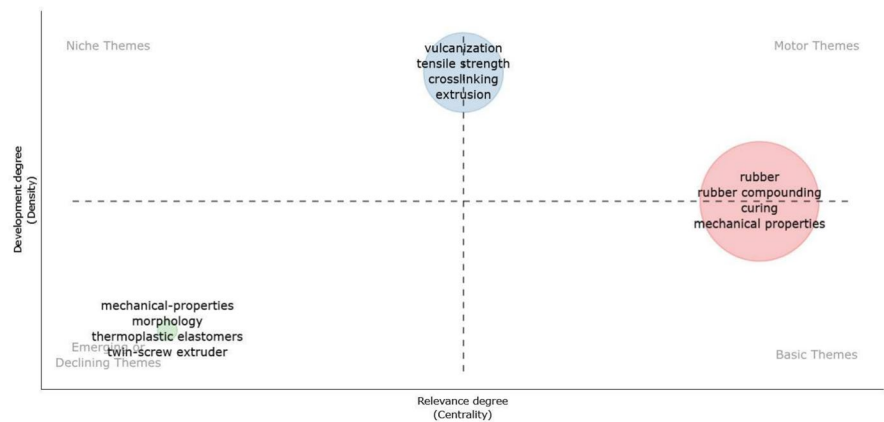


Fig. 28 Thematic evolution map (Keywords Plus) across four time slices (2000–2009, 2010–2016, 2017–2020, 2021–2025). Parameters: Louvain clustering; top 100 terms; minimum cluster frequency = 30 per 1000 documents; inclusion index weighted by word occurrences;

minimum weight index = 0.1; label overlap avoidance enabled; labels per cluster = 4; label size = 0.5. Arrow thickness indicates the strength of thematic continuity between periods

Figure 29 presents the thematic map slice for 2000–2009. A highly central basic-theme cluster is anchored in vulcanization, rubber, rubber compounding, and crosslinking, indicating that crosslinking chemistry and formulation dominate the early conceptual backbone. A distinct motor-theme cluster links tensile strength with thermoplastic elastomers and polymer blends, suggesting a well-developed stream focused on elastomer modification and mechanical response. Niche themes include mechanical properties, synthetic rubber, and butadiene. Process-oriented terms such as extrusion, rheology, viscosity, and extruders appear in the emerging/declining quadrant, reflecting extrusion-relevant studies that remain peripheral in this period.

Figure 30 shows that the conceptual structure consolidates around a dominant motor theme centred on rubber, rubber compounding, and mechanical properties. The appearance of nanocomposites as a prominent descriptor in this slice indicates increased attention to filler-reinforced formulations and structure–property optimisation. Compared with the previous period, the map is more concentrated, suggesting that formulation-driven performance research becomes more central in the literature.

Fig. 29 Thematic map slice for 2000–2009 (Keywords Plus; Louvain clustering; same parameter settings as Fig. 28)

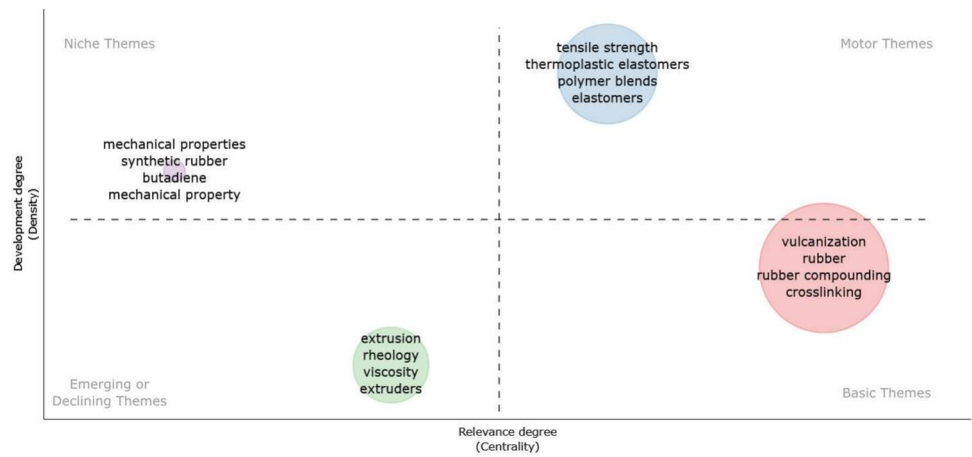
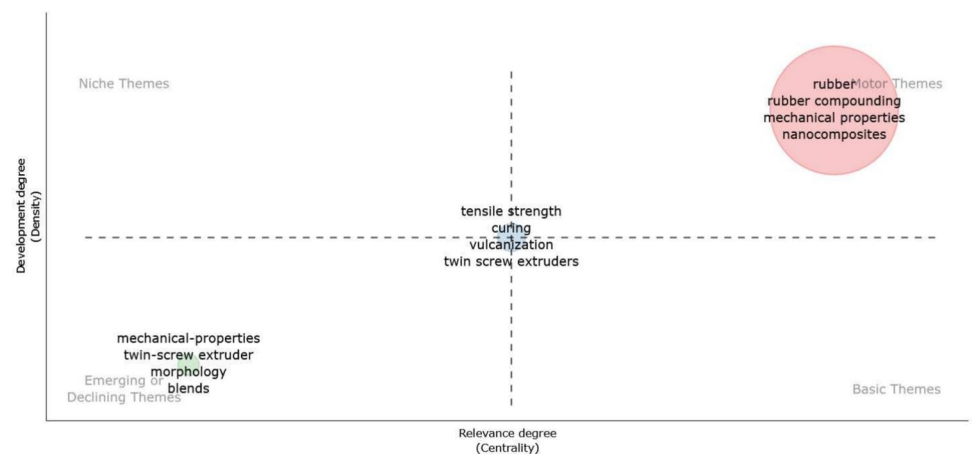


Fig. 30 Thematic map slice for 2010–2016 (Keywords Plus; Louvain clustering; same parameter settings as Fig. 28)



In 2017–2020 (Fig. 31), emphrubber, rubber compounding and performance-related terms such as tensile strength and mechanical properties remain central as a basic theme, while a separate developed theme emerges linking styrene, tires, and reinforced plastics, showing a shift toward specific materials and reinforcement methods. In parallel, a specialised theme associated with twin-screw extruder persists, indicating a continuing but narrower process-oriented trajectory that remains less central than the dominant formulation/property axis.

Figure 32 shows that rubber compounding remains the main basic theme in 2021–2025, alongside performance terms such as tensile strength and industry-related terms (e.g., rubber industry, vulcanisation). A motor-theme cluster highlights carbon black and particle size (with rubber and tires), pointing to ongoing work on fillers and microstructure to improve performance. Devulcanization also appears in a central cluster (with natural rubber and mechanical properties), suggesting growing interest in recycling and end-of-life processing.

Figure 33 presents the factorial map derived from multiple correspondence analysis (MCA). The analysis was conducted on Keywords Plus terms. No custom removal list and no

Fig. 31 Thematic map slice for 2017–2020 (Keywords Plus; Louvain clustering; same parameter settings as Fig. 28)

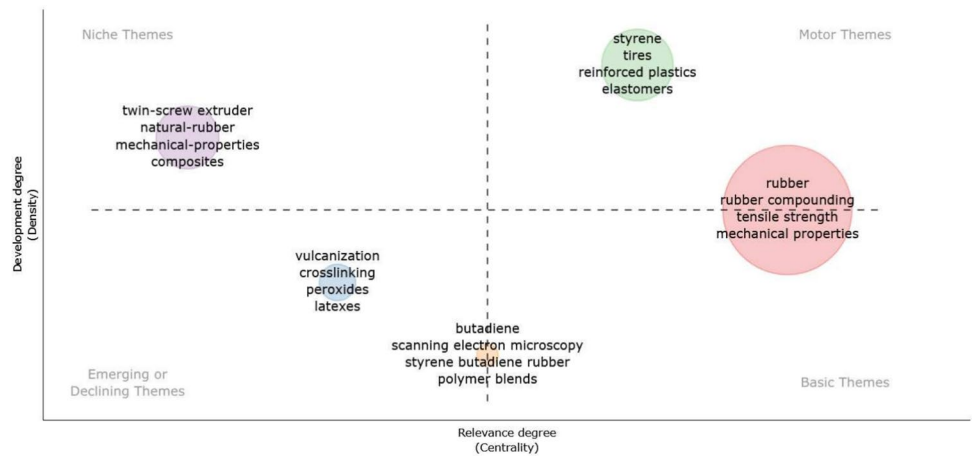


Fig. 32 Thematic map slice for 2021–2025 (Keywords Plus; Louvain clustering; same parameter settings as Fig. 28)

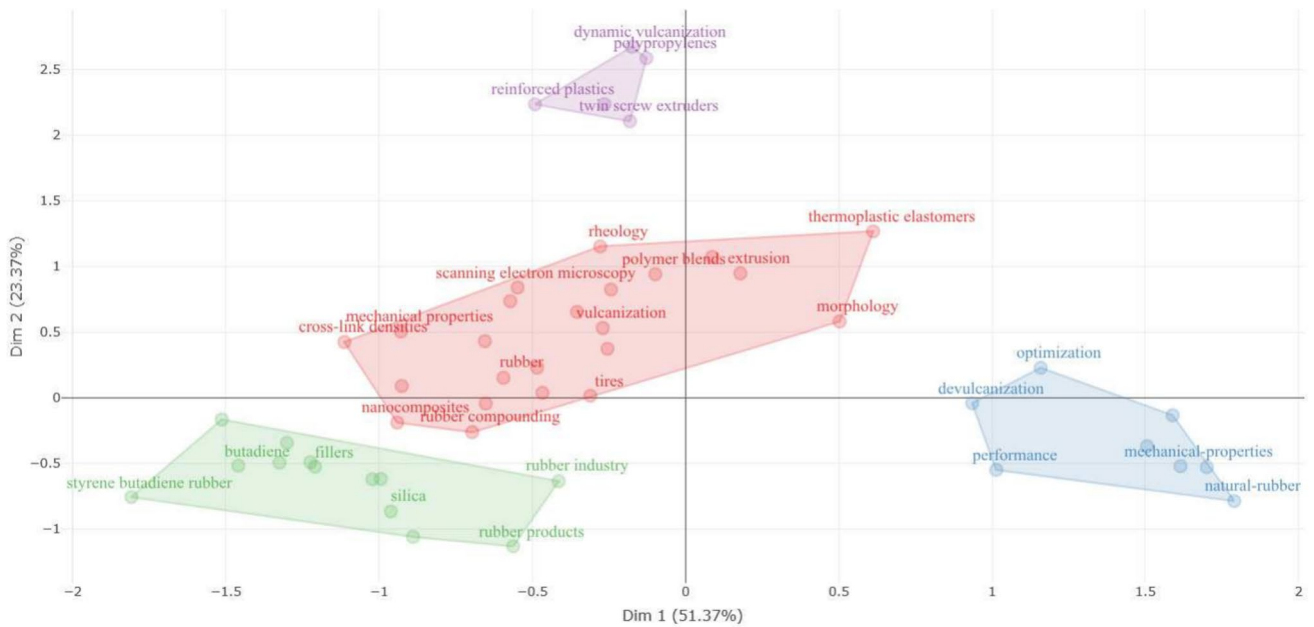
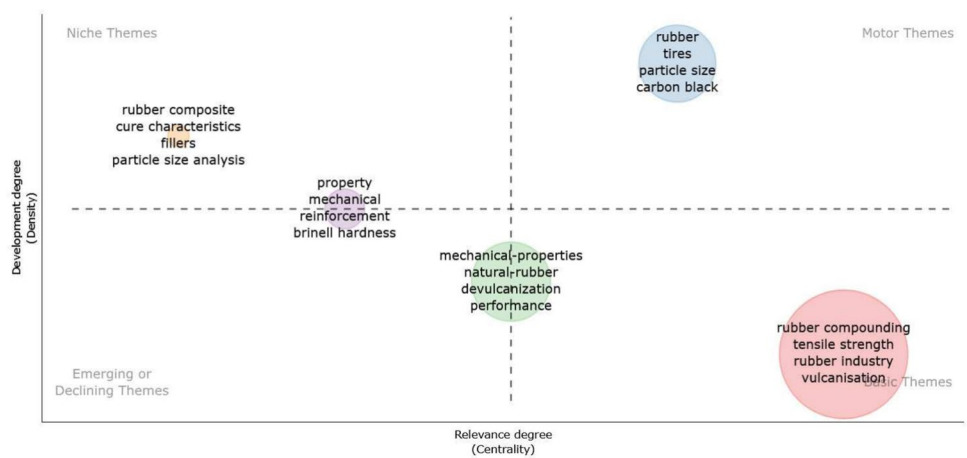


Fig. 33 Factorial map from co-word analysis

Table 10 Conceptual clusters in tire extrusion literature (2000–2025) via bibliographic coupling

Group	Label (Keywords with Confidence)	Freq	Centrality	Impact
1	mechanical-properties (conf 38.5%), twin-screw extruder (conf 39.4%), powder (conf 69.2%), natural-rubber (conf 36.4%)	43	0.954	3.649
2	twin-screw extruder (conf 27.3%), mechanical-properties (conf 20.5%), composites (conf 46.2%), high-density polyethylene (conf 66.7%)	18	1.215	3.504
3	devulcanization (conf 57.9%), mechanical-properties (conf 28.2%), natural-rubber (conf 50%), blends (conf 35.3%)	29	1.043	2.099
4	twin-screw extruder (conf 21.2%), blends (conf 35.3%), dynamic reaction (conf 62.5%), mechanical-properties (conf 12.8%)	10	0.688	1.000

synonym thesaurus were applied. The MCA was computed using the top 50 terms and the resulting conceptual space was partitioned into 4 clusters. For visualization, label size was set to 10 and the most representative documents were displayed (top 5). Four distinct conceptual clusters emerge:

- **Red:** Core processing and material characterization, centered on rubber, tires, rubber compounding, vulcanization, and morphology.
- **Green:** Traditional formulation topics such as fillers, silica, butadiene, and rubber products.
- **Blue:** Sustainability and performance-oriented terms, including devulcanization, natural rubber, mechanical properties, and optimization.
- **Purple:** Emerging polymer technologies, with emphasis on twin-screw extruders, dynamic vulcanization, and advanced composites like polypropylenes and reinforced plastics.

To uncover conceptual groupings within the tire extrusion literature, bibliographic coupling was applied. Conceptual clusters were identified in Biblioshiny using documents as the unit of analysis and coupling measured by shared references. Document impact was weighted by the Local Citation Score, and cluster labels were derived from Keywords Plus. We retained the top 100 coupled documents, required a minimum cluster frequency of 10, and detected communities using the Louvain algorithm (community repulsion = 0.5; four labels per cluster; label size = 0.5). Four major clusters were identified (Table 10, Figure 34). Cluster 1 and Cluster 2 are both centered on extrusion and composite formulation,

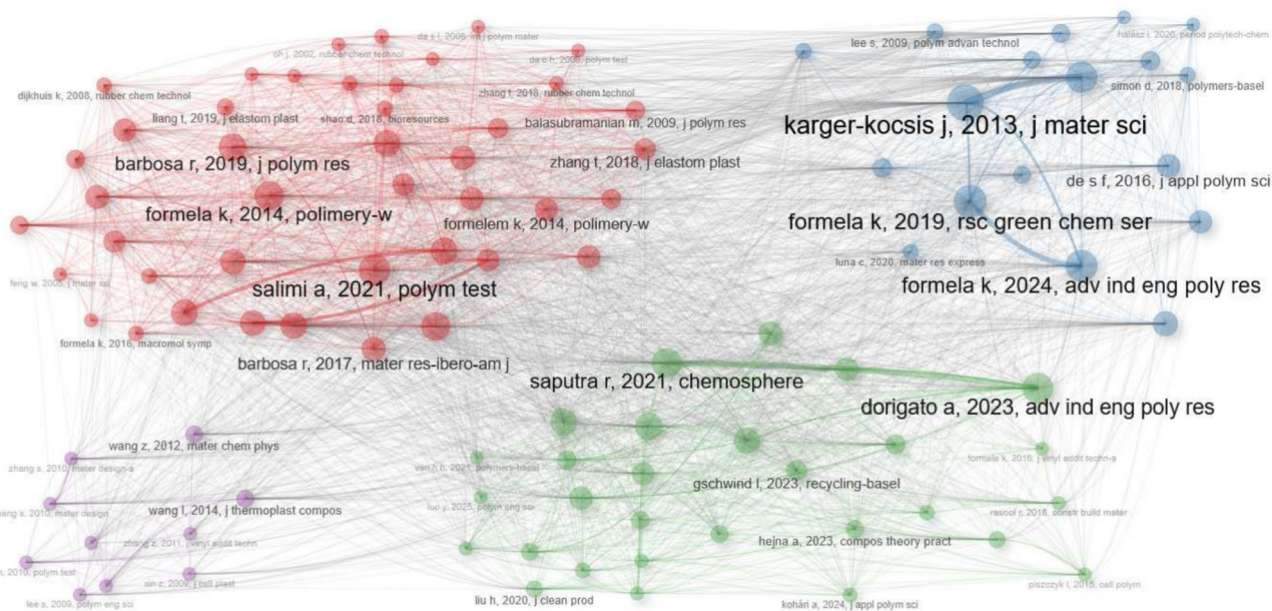


Fig. 34 Conceptual clusters based on bibliographic coupling. Bubble size indicates number of documents; axes represent centrality and impact

showing the highest impact and document frequency. Cluster 3 emphasizes sustainability and devulcanization themes. Cluster 4, while smaller, includes niche and emerging topics such as dynamic systems and blend optimization.

4.8 Intellectual structure

To uncover the intellectual structure underlying tire extrusion research, a co-citation network analysis was conducted. We built the co-citation network from cited references and mapped the 50 most-cited items, removing isolated nodes and keeping only links with at least two co-citations (edge weight ≥ 2). We applied Louvain clustering and Biblioshiny's automatic layout. Figure 35 displays the resulting network. Three major intellectual clusters are evident:

- **Cluster 1 (Red):** Focused on polymer composites and elastomer modification, represented by influential works such as Karger-Kocsis [56], Scaffaro [61], Lee SH [62], and Grigoryeva [63].
- **Cluster 2 (Blue):** Reflects the foundational literature on polymer theory and vulcanization, including landmark studies by Flory [64], Adhikari [60], Maridass [58], and Scuracchio [65].
- **Cluster 3 (Green):** Highlights developments in rubber recycling, devulcanization, and sustainability, represented by seminal contributions such as Horikx [66], Formela [67], Shi [68], and Garcia [69].

The top 10 most influential co-cited references are presented in Table 11, ranked by PageRank and Betweenness

Table 11 Top 10 influential references based on co-citation network analysis (PageRank)

Reference	PageRank	Betweenness	Cluster
Adhikari B. (2000) [60]	0.033	170.037	2
Horikx M. (1956) [66]	0.033	50.130	3
Flory P. (1943) [64]	0.031	41.196	2
Maridass B. (2004) [58]	0.030	37.603	2
Shi J. (2013) [68]	0.027	30.116	3
Lee S. (2007) [62]	0.027	5.233	1
Garcia P. (2015) [69]	0.027	27.304	3
Formela K. (2014) [67]	0.026	42.083	3
Seghar S. (2019) [70]	0.026	4.585	3
Yazdani H. (2011) [71]	0.025	32.204	2

centrality. These metrics highlight both citation strength and bridging role within the network.

Figure 36 (historiograph) maps how influential local references connect over time. Early studies (e.g., Bilgili [72] and Tantayanon [73]) lead into a major cluster in 2013–2016 (Formela [67, 74]), and later work (e.g., Seghar [70]) continues the chain, highlighting an increasing focus on recycling and sustainability.

4.9 Social structure

The collaboration network analysis, shown in Fig. 37, illustrates the structure of co-authorships among researchers in the field of tire extrusion. Distinguished nodes such as Formela K. and Zhang L. occupy central positions, reflecting their high connectivity and crucial roles within the research network. The Louvain clustering algorithm reveals several distinct collaborative communities, indicated by the

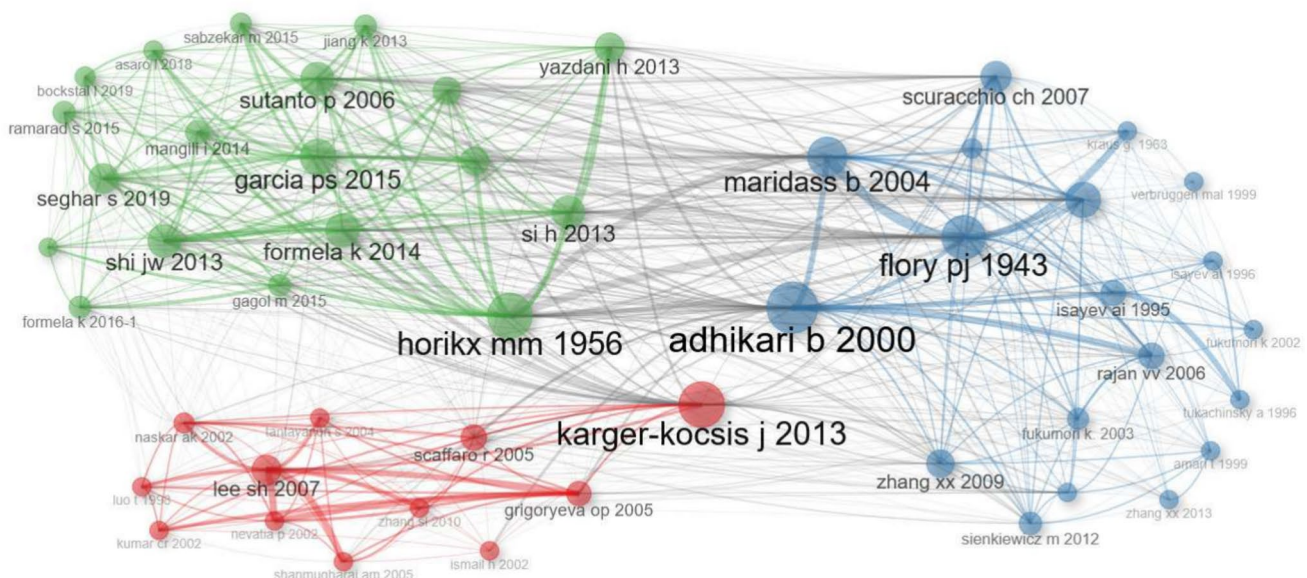


Fig. 35 Co-citation network of influential references in tire extrusion literature. Node size reflects citation frequency; colors denote thematic clusters

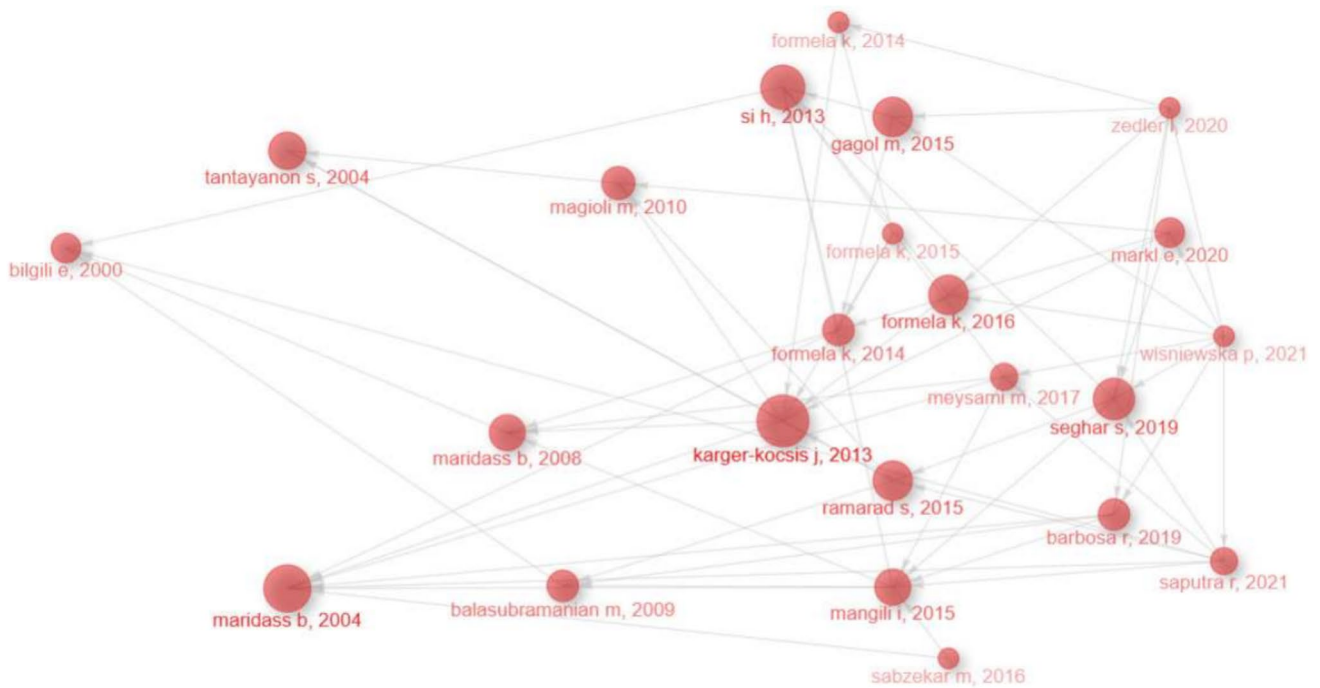


Fig. 36 Historiograph of the most locally cited publications. Arrows indicate citation relationships and knowledge evolution

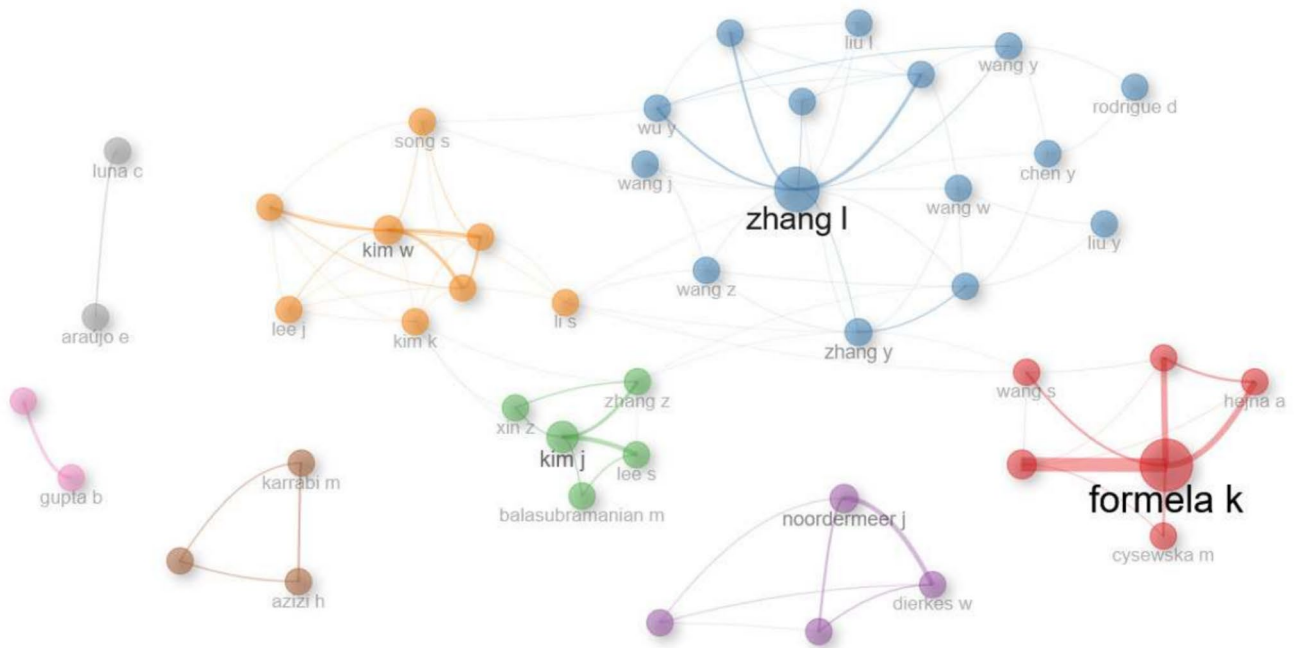


Fig. 37 Author collaboration network in the field of tire extrusion. Node size reflects author centrality (PageRank), and colors denote distinct collaborative clusters identified via the Louvain algorithm

color-coded clusters. The network demonstrates moderate fragmentation, with key bridging authors facilitating inter-group collaboration and the dissemination of knowledge across clusters.

Table 12 presents the top five most influential authors within the collaboration network, based on PageRank centrality. Zhang L. and Formela K. lead in terms of influence and connectivity. High Betweenness values for

Table 12 Top 5 most influential authors in the collaboration network, based on PageRank

Rank	Author	PageRank	Betweenness	Cluster
1	Zhang L.	0.066	150.675	2
2	Formela K.	0.048	49.928	1
3	Kim W.	0.037	27.031	5
4	Kim .	0.036	31.510	3
5	Zhang Y.	0.026	143.636	2

authors such as Zhang Y. highlight their roles as bridges between distinct research communities, supporting cross-cluster knowledge exchange.

Figure 38 depicts the institutional collaboration network derived from co-authorship data. Node size represents publication volume, while edge thickness indicates co-authorship strength. Several prominent clusters emerge: the Gdansk University of Technology–Fahrenheit Universities axis dominates in publication activity; Chinese institutions such as the Beijing University of Chemical Technology and Qingdao University of Science and Technology form a dense regional cluster; and additional collaborative groups are visible. This structure highlights both regional concentration and international bridges in tire extrusion research.

Table 13 presents the five most influential institutions in the collaboration network, as measured by PageRank centrality. Qingdao University of Science and Technology emerges as the primary center, with Beijing University of Chemical Technology and China University of Petroleum, which together dominate Cluster 1. University of Massachusetts represents a key North American presence, while the Warsaw University of Technology highlights European

Table 13 Top 5 most influential institutions in the collaboration network based on PageRank centrality

Rank	Institution	PageRank	Betweenness	Cluster
1	Qingdao University of Science and Technology	0.072	2.50	1
2	Beijing University of Chemical Technology	0.067	0.00	1
3	China University of Petroleum	0.062	0.00	1
4	University of Massachusetts	0.060	0.00	3
5	Warsaw University of Technology	0.057	5.00	2

contributions. This ranking underscores the strong influence of Chinese institutions, complemented by international partners in the United States and Europe.

Figure 39 presents the country-level collaboration network. Node size corresponds to the number of publications per country, and edge thickness represents collaboration intensity. Colors distinguish regional clusters. China is the most central and productive nation, followed by Poland and the USA. France and Brazil also demonstrate significant collaborative activity, especially within their respective clusters.

Table 14 shows the five most influential countries in the collaboration network, ranked by PageRank centrality. China leads with the highest PageRank value (0.141), demonstrating its dominant role in tire extrusion research. Poland follows with a strong position (0.099), supported by the highest betweenness score (63.556), indicating its role as a key bridge connecting different international research communities. The USA (0.069) and France (0.065)

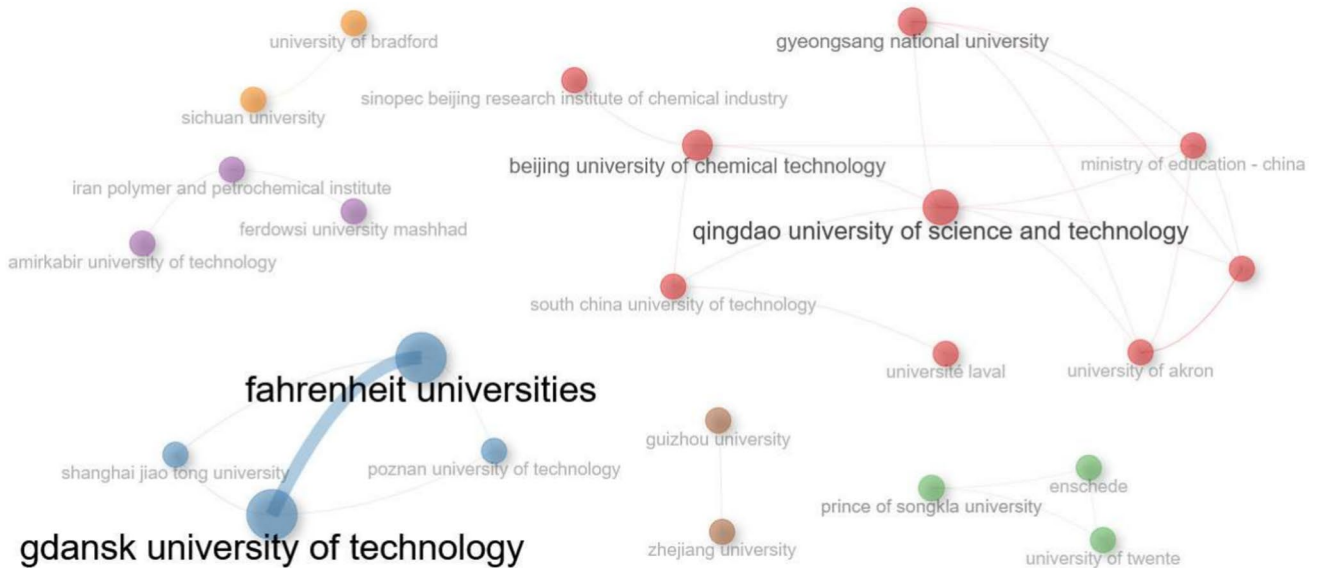


Fig. 38 Institutional collaboration network in tire extrusion research. Node size denotes the number of affiliated publications, and edge thickness indicates co-authorship strength. Colors reflect collaborative clusters

Fig. 39 Country-level collaboration network in tire extrusion research. Node size reflects publication output, and edge thickness denotes the strength of international collaboration. Cluster membership is color-coded

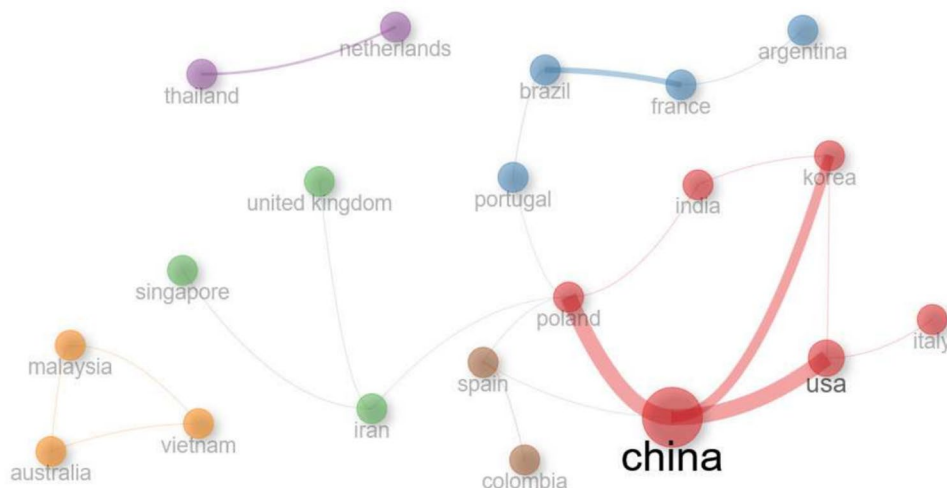


Table 14 Top 5 most influential countries in the collaboration network based on PageRank centrality

Rank	Country	PageRank	Betweenness	Cluster
1	China	0.141	29.619	1
2	Poland	0.099	63.556	1
3	USA	0.069	13.000	1
4	France	0.065	13.000	2
5	Brazil	0.061	24.000	2

also emerge as influential contributors, reflecting their established presence in the field. Brazil (0.061) completes the top five, underlining the growing importance of South America in the global research landscape.

4.10 Subject-matter depth in tire extrusion technology

To address potential scope drift, we complemented the main bibliometric workflow with a technology-focused sensitivity analysis. Starting from the merged corpus ($n = 542$), we first defined a broad tire–extrusion subset by requiring (i) tire-context terminology (e.g., tire/tyre and tire components such as tread, sidewall, inner liner, carcass, bead, belt) and (ii) extrusion-related terminology (e.g., extrusion/extrude, extruder, co-extrusion, crosshead, extrusion head, die). This filter yielded $n = 167$ records (30.8% of the full corpus).

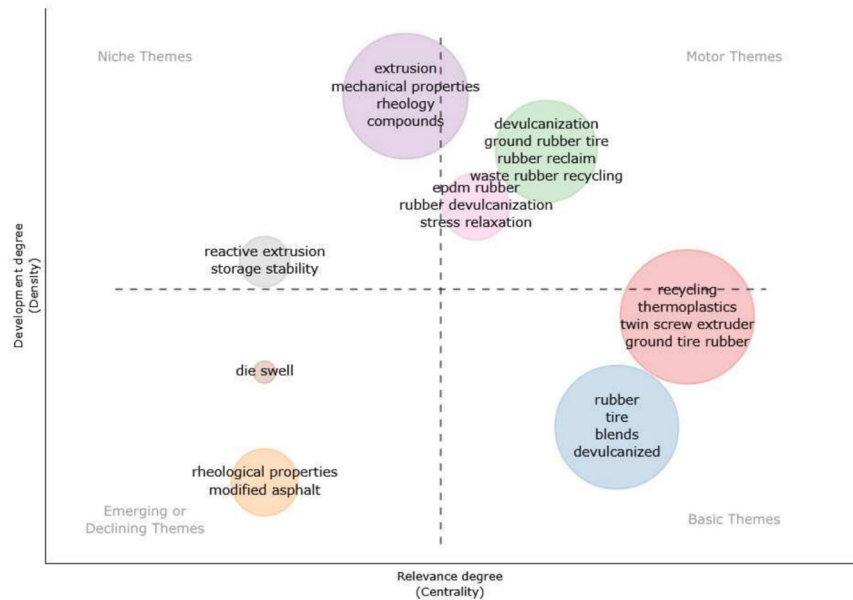
Next, to isolate literature explicitly focused on technology, we applied a second layer of rule-based filtering using strong technology markers grouped into: (i) tooling/flow/die (e.g., die design, manifold, pressure drop, die swell); (ii) rheology/viscoelastic/constitutive modelling (e.g., rheology, viscoelastic, constitutive, and representative models such as Giesekus/FENE-P/Oldroyd/PTT); (iii) extrusion hardware and operating-history descriptors (e.g.,

screw design, compression ratio, L/D, residence time); (iv) CAE-based simulation (e.g., FEM, CFD, numerical/flow simulation, and common platforms such as ANSYS Polyflow, OpenFOAM, COMSOL); and (v) monitoring/control/digitalisation (e.g., process monitoring, in-line/on-line sensing, sensors, digital twin, model predictive control). Using the same rule set with different marker-count thresholds, we defined (i) a strict technology subset requiring ≥ 1 marker ($n = 52$, 9.6% of the full corpus) and (ii) a technology-dense subset requiring ≥ 2 markers ($n = 28$, 5.2%). The complete term lists and filtering rules are provided in Appendix 9, and the corresponding reproducible Python script is provided as Supplementary.

To test whether the conceptual structures are robust under technology-focused restrictions, we repeated thematic mapping for both subsets using Author Keywords (DE) and Keywords Plus (ID), which capture author-intended topics and indexed descriptors, respectively.

Strict technology subset ($n = 52$) Figure 40 shows several clear themes in the strict subset based on Author Keywords (DE). A main motor theme (top-right) focuses on devulcanization, waste-rubber recycling, ground rubber tire, rubber reclaim, and related terms. In the basic-themes quadrant (bottom-right), two complementary clusters appear: one linking rubber, tire, blends, and devulcanized, and another connecting recycling, twin-screw extruder, thermoplastics, and ground tire rubber. A dense but less central niche cluster (top-left) combining extrusion, rheology, mechanical properties, and compounds reflects the process–material coupling core relevant to extrusion design and performance. Tooling-specific terms (e.g., die swell) appear only as small, low-frequency nodes in DE, motivating complementary reference-level synthesis using the core-paper lists.

Fig. 40 Sensitivity thematic map based on Author Keywords (DE) for the strict technology subset ($n = 52$). Plot settings: 100 words, minimum cluster frequency = 30 per thousand documents, 4 labels per cluster, label size = 0.45, community repulsion = 0.5, Louvain clustering, and label-overlap avoidance enabled



As a complementary check, the Keywords Plus (ID) thematic map for the strict subset (Fig. 41) places greater weight on broadly indexed descriptors, yielding a dominant basic-theme cluster centred on rubber, tires, recycling, and devulcanization. At the same time, extrusion-related terminology remains visible across multiple clusters, including a central cluster containing extrusion together with mechanical-property descriptors (e.g., tensile strength) and ground tyre rubber, as well as a niche cluster containing extrusion molding and extruders. This contrast reflects the different nature of DE and ID: Keywords Plus (ID) tends to emphasise broadly indexed, cross-domain descriptors (e.g., rubber/tires, mechanical properties, recycling/devulcanization) and may introduce indexing terms such as extrusion molding or polyethylenes,

whereas Author Keywords (DE) more often capture author-selected, process-specific descriptors (e.g., die swell, stress relaxation, rubber reclaim).

The most frequent Keywords Plus terms in the strict subset (Table 15) include rubber and tires (11 occurrences each) and extrusion (7 occurrences). Property- and process-coupling descriptors are also prominent, including mechanical-properties, rheological properties, and viscosity, together with circular-economy terms such as recycling and devulcanization.

Technology-dense subset ($n = 28$) Under the technology-dense criterion (requiring ≥ 2 strong technology markers; $n = 28$), DE-based thematic mapping becomes sparse due

Fig. 41 Sensitivity thematic map based on Keywords Plus (ID) for the strict technology subset ($n = 52$)

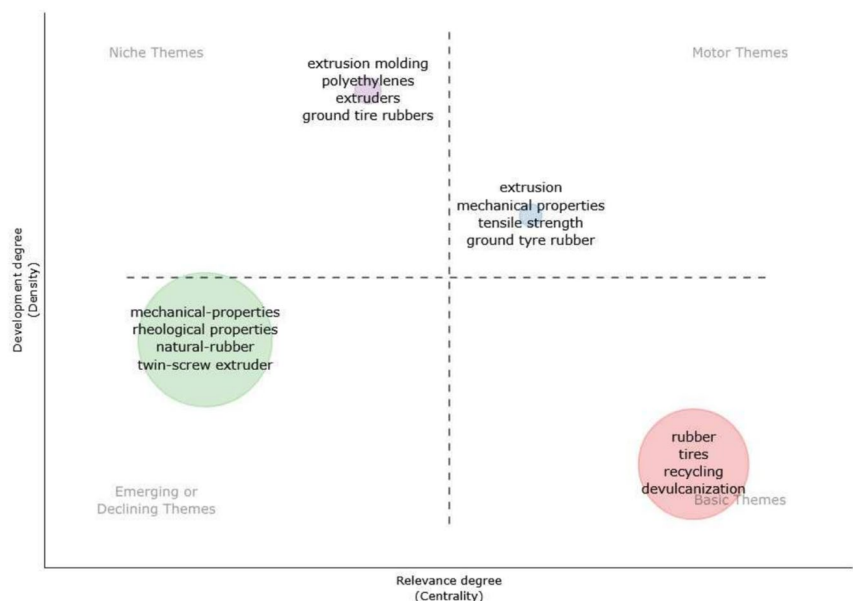


Table 15 Most frequent keywords plus terms in the strict technology subset ($n = 52$)

Keyword	Occurrences
rubber	11
tires	11
extrusion	7
mechanical-properties	7
recycling	6
rheological properties	6
devulcanization	5
natural-rubber	5
viscosity	5
extrusion molding	4

to the small subset size and variability of author-supplied keywords; the corresponding DE map is therefore reported in the Supplementary for completeness. We therefore use the Keywords Plus (ID) thematic map as the primary sensitivity check at this restriction level (Fig. 42). The central cluster includes extrusion dies and finite element method, together with tires, rubber, and extrusion, indicating that the restricted corpus retains a distinct core of tooling- and simulation-oriented extrusion studies. This supports the scope-control objective by showing that process-engineering and CAE-related terminology remains structurally central under the technology-dense restriction.

The most frequent Keywords Plus terms (Table 16) are led by tires (9 occurrences), rubber (8), and extrusion (5). Rheology-related descriptors remain prominent (e.g., rheological properties, rheology, viscosity), alongside recycling and process/material descriptors such as extrusion molding and

Table 16 Most frequent Keywords Plus (ID) terms in the technology-dense subset ($n = 28$)

Keyword	Occurrences
tires	9
rubber	8
extrusion	5
rheological properties	5
recycling	4
rheology	4
viscosity	4
composites	3
extrusion molding	3
mechanical-properties	3

composites. These frequencies support the interpretation that the technology-dense subset retains a process–material coupling core while maintaining visibility of extrusion-enabled recycling/formulation themes.

Reference prominence and core-paper prioritization To anchor the subsequent qualitative synthesis, we report the top 10 most globally cited documents within the strict and technology-dense subsets (Tables 17 and 18).

To further increase technological specificity beyond citation prominence, we prioritized a compact set of core papers using a rule-based relevance score computed from the combined text fields. The score upweights extrusion signals and strong technology markers and downweights recycling-dominated records:

$$S = 2 \min(\text{score}_{\text{extr}}, 5) + 2 \min(\text{score}_{\text{strongtech}}, 10) - 0.5 \min(\text{score}_{\text{recycle}}, 5), \quad (2)$$

Fig. 42 Sensitivity thematic map based on Keywords Plus (ID) for the technology-dense subset ($n = 28$). ID surfaces process-engineering and CAE terminology (e.g., *extrusion dies*, *finite element method*) as structurally central themes within the restricted corpus

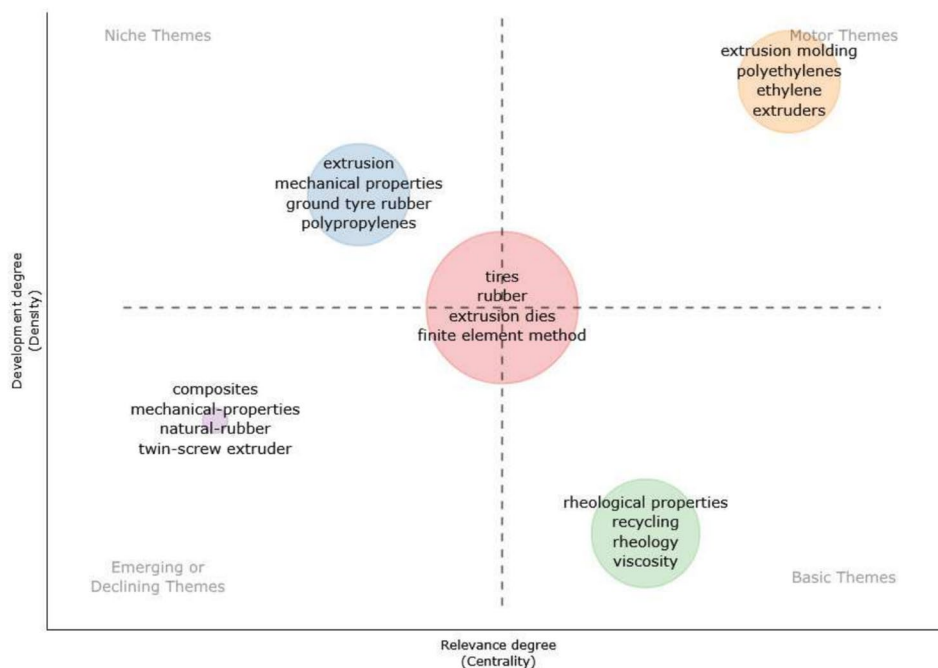


Table 17 Top 10 most globally cited documents in the strict technology subset ($n = 52$)

Author (Year)	Journal	DOI	TC	TC/Year	Norm. TC
Ramarad S. (2015)	Progress in Materials Science	10.1016/j.pmatsci.2015.02.004	388	32.33	1.00
Scaffaro R. (2005)	Polymer Degradation and Stability	10.1016/j.polymdegradstab.2005.03.022	100	4.55	2.56
Markl E. (2020)	Materials	10.3390/ma13051246	68	9.71	1.73
Rasool R. (2018)	Construction and Building Materials	10.1016/j.conbuildmat.2018.06.104	68	7.56	2.06
Isayev A. (2014)	Rubber Chemistry and Technology	10.5254/RCT.13.87926	63	4.85	1.91
Si H. (2013)	Journal of Applied Polymer Science	10.1002/app.38170	58	4.14	2.49
Wu X. (2016)	Construction and Building Materials	10.1016/j.conbuildmat.2016.02.208	55	5.00	1.90
Liang M. (2020)	Construction and Building Materials	10.1016/j.conbuildmat.2019.116966	46	6.57	1.17
Formela K. (2016)	Construction and Building Materials	10.1016/j.conbuildmat.2015.12.108	45	4.09	1.55
De S F. (2016)	Journal of Applied Polymer Science	10.1002/app.43503	34	3.09	1.17

Table 18 Top 10 most globally cited documents in the technology-dense subset ($n = 28$)

Author (Year)	Journal	DOI	TC	TC/Year	Norm. TC
Scaffaro R (2005)	Polymer Degradation and Stability	10.1016/j.polymdegradstab.2005.03.022	100	4.55	1.94
Rasool R (2018)	Construction and Building Materials	10.1016/j.conbuildmat.2018.06.104	68	7.56	2.06
Wu X (2016)	Construction and Building Materials	10.1016/j.conbuildmat.2016.02.208	55	5.00	1.40
Liang M (2020)	Construction and Building Materials	10.1016/j.conbuildmat.2019.116966	46	6.57	1.00
Formela K (2016)	Construction and Building Materials	10.1016/j.conbuildmat.2015.12.108	45	4.09	1.15
De S F (2016)	Journal of Applied Polymer Science	10.1002/app.43503	34	3.09	0.87
Hong C (2001)	Journal of Elastomers and Plastics	10.1106/5AMQ-XEAY-A05B-P1FY	32	1.23	2.00
Schaal S (2000)	Rubber Chemistry and Technology	10.5254/1.3547587	32	1.19	1.00
Da C H (2008)	Polymer Testing	10.1016/j.polymertesting.2007.08.001	25	1.32	1.00
Saiwari S (2016)	Materials	10.3390/ma9090724	23	2.09	0.59

Table 19 Top 10 core documents ranked by the technology-relevance score S . The list is identical under both the strict subset ($n = 52$) and the technology-dense subset ($n = 28$).

Author (Year)	Source	DOI	S
Kauzlarich (2005)	Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications	10.1243/146442005X10247	30.0
Wang (2023)	Materials	10.3390/ma16093301	30.0
Huang (2024)	Proceedings of the Thermal and Fluids Engineering Summer Conference	10.1615/TFEC2024.trm.050931	30.0
Silva (2021)	Journal of Manufacturing Processes	10.1016/j.jmapro.2021.03.022	24.0
Wießner (2012)	KGK Kautschuk Gummi Kunststoffe	— [75]	24.0
Moghaddamzadeh (2018)	Journal of Applied Polymer Science	10.1002/app.46563	23.5
Wu (2013)	Advanced Materials and Engineering Materials II	10.4028/www.scientific.net/AMR.683.548	20.0
Snow (2004)	Rubber World	— [76]	20.0
Limper (2001)	Rubber Chemistry and Technology	10.5254/1.3547660	18.0
Schaal (2000)	Rubber Chemistry and Technology	10.5254/1.3547587	16.0

where ties are broken by total citations (TC). Table 19 reports the shared top-10 core list (strict: $n = 52$, ≥ 1 marker; technology-dense: $n = 28$, ≥ 2 markers).

Category-based technical synthesis (non-exclusive tagging) To complement the sensitivity thematic maps with an engineering interpretation, we performed a category-based

technical synthesis using the strong-technology subsets generated by the rule-based script. This step links the technology-oriented records to practical extrusion challenges and strengthens the manufacturing relevance of the bibliometric structures. Within the broad tire-extrusion subset ($n = 167$), category coverage was highest for rheology/constitutive behaviour ($n = 34$; 20.4%), followed by tooling/flow/die engineering ($n = 12$; 7.2%), extrusion hardware and processing-window design ($n = 10$; 6.0%), simulation/CAE ($n = 7$; 4.2%), and monitoring/control/digitalisation ($n = 2$; 1.2%). Tags are non-exclusive; therefore, a record can belong to more than one category.

Rheology and constitutive behaviour (category subset: $n = 34$) In this category, the literature converges on a central materials-processing constraint: end-of-life tires are multi-material composites and, critically, contain vulcanized rubber that cannot be remelted. As a result, dominant end-of-life pathways (e.g., landfill, incineration/co-processing, and grinding to crumb rubber or powder) remain common but are increasingly framed as insufficient for circular-economy targets. Two broad value-recovery directions are repeatedly pursued [23, 24].

The first direction is materials recycling via devulcanization or controlled degradation to partially cleave sulfur crosslinks and recover processability. Reported approaches include chemical and thermo-mechanical routes as well as microwave- and ultrasonic-assisted processes, supercritical- CO_2 -assisted treatments, and high-shear (reactive) extrusion [24, 77, 78]. Across studies, operating conditions and particle size are repeatedly identified as key factors governing the balance between crosslink scission and main-chain scission, which in turn influences sol/gel fraction, crosslink density, viscosity (e.g., Mooney), revulcanization behaviour, and the strength-elongation trade-off in reprocessed rubbers [59, 79–81].

The second direction is incorporation of waste tire rubber (crumb/ground/devulcanized rubber) into polymer matrices and infrastructure binders, where performance is dominated by dispersion and interfacial compatibility. Accordingly, compatibilizers, coupling agents, crosslinkers, and dynamic revulcanization are frequently used to tailor morphology and interface strength [82–84]. In polymer blends, they consistently indicate that outcomes depend on rubber particle size, loading, modification route, and interfacial design [23, 61, 83, 85, 86]; thermoplastic-elastomer-type systems produced via reactive extrusion and/or dynamic revulcanization are often highlighted as promising routes to improve the balance between toughness, elasticity, and processability relative to non-compatibilized blends [77, 84, 87]. Several records further address asphalt/bitumen modification, where tire-derived rubber can improve rutting, fatigue,

cracking, and low-temperature response [88–90]; however, storage stability and phase separation are repeatedly noted as persistent challenges, motivating extrusion-based pretreatments and engineered additives to improve compatibility and dispersion [87, 91–94].

A recurring result across this category is that process variables enter tire-extrusion research primarily through their rheological consequences. Temperature, screw speed, shear severity, residence time, compatibilization route, and particle-size distribution are repeatedly studied because they modify the constitutive and processability response that ultimately controls extrusion stability, die swell, pressure demand, and downstream quality. Representative studies illustrate this clearly. Ultrasonic devulcanization work linked mesh size, ultrasonic amplitude, and temperature to frequency-dependent complex viscosity and die-pressure behavior, reporting a power-law index of 0.06 for devulcanized rubber and 0.02 for revulcanized rubber at an ultrasonic frequency of 40 kHz. In reclaimed EPDM systems, stress relaxation, DMTA, and frequency-sweep measurements showed that reclaiming conditions such as screw speed (40/80/120 rpm) and reclaiming-agent dosage (0/1.5/3 phr) significantly altered storage modulus and relaxation behavior, with the best reclaiming condition reported at 120 rpm and 3 phr. Other studies on DGTR, GTR/TPE, PP/GTR, and recycled tire-fiber blends similarly show that changes in shear history, compatibilization, and thermal route modify Mooney viscosity, gel fraction, melt rheology, and interfacial response, thereby shifting the feasible processing window. In tire-tread co-extrusion specifically, rheological characterization using tools such as the RPA 2000 and constitutive fitting via PTT-type models provides the material input required to simulate viscoelastic flow and swelling, with reported dimensional error below 6% in one validated case. Overall, this subset shows that rheology is not merely a material-characterization layer; it is the mechanism through which operating conditions are translated into extrusion-process behavior and therefore a central basis for defining stable operating windows in tire manufacturing. Selected representative rheology-oriented studies, variables, and quantitative indicators are summarized in Appendix Table 21.

Finally, a subset explicitly links rheological characterization and viscoelastic simulation (CFD/FEA with constitutive models) to tire-manufacturing process control, including extrusion/co-extrusion, die swell management, and defect prevention [19, 95]. Overall, this category underscores that rheology is not merely a material descriptor but a manufacturing-relevant lever for process-window design, quality stability, and scrap reduction [96–98], while also highlighting the need for more systematic structure-property-processing maps and long-term performance evaluation to support industrial transfer [23, 24].

Tooling, flow, and die engineering (category subset: $n = 12$) The tooling/flow/die subset concentrates on manufacturing-critical questions in tire-profile extrusion and co-extrusion: how die geometry and thermal management govern flow distribution, interface integrity, and dimensional accuracy of the final profile. A recurring objective is to achieve uniform throughput in complex channels while avoiding pressure-drop imbalance, local over-shear, and shape distortion. Several contributions frame die/profile design as an inverse problem, where geometry is iteratively modified to match a target extrudate shape, with numerical simulation used to screen candidate designs and operating windows prior to production trials [99, 100].

A technologically defining stream in this category is multi-compound tread co-extrusion. They report simulation-driven die and process design where viscoelasticity and die swell are treated as first-order determinants of final geometry. Constitutive descriptions fitted to rheological data are incorporated into three-dimensional simulations and validated against extrusion trials, allowing the internal development of velocity, pressure, and shear-rate fields to be linked to dimensional deviations and swelling mechanisms. These studies collectively indicate that parameters such as inflow-rate partitioning, traction speed, die convergence angles, channel thickness, and flow-balancing features can be tuned to improve shape accuracy and production efficiency [19, 99, 101].

Thermal management also appears as a practical manufacturing constraint. They addressing tire-related composite processing emphasize that poorly controlled temperature profiles can lead to premature vulcanization (scorch) or inadequate impregnation of reinforcement cords, with direct implications for durability, safety, and scrap generation. By combining flow/temperature modelling with experimental temperature mapping and rheological/vulcanization measurements, the studies propose temperature-control strategies intended to stabilize processing and reduce reject rates [98, 102].

Representative studies in this subset make the process dependence of tooling decisions more explicit. In tri-compound tread co-extrusion, inflow rate, traction speed, die convergence angle, and die thickness were identified as critical variables governing the internal velocity, pressure, and shear-rate fields, with reported simulation–experiment tread-size deviation below 6%. In studies of short-fiber radial orientation, die geometry and expansion characteristics were decisive, with preferred expansion ratios of 3–4 and average fiber-orientation angles of 70°–80°. Additional work on sidewall dies showed that face-relieved configurations improved thin-edge filling, reduced tearing, and avoided local velocity minima, while inverse die-design approaches used reference swell, material properties, and operating conditions to predict die profiles for target extrudate shapes with good

agreement against theory and experiments. Together, these studies indicate that tooling and die engineering in tire extrusion cannot be separated from process variables: geometry, temperature control, traction conditions, and flow balancing jointly define whether the final profile remains stable and manufacturable. Representative tooling and die-engineering studies together with their key process-sensitive variables are summarized in Appendix Table 22.

Overall, this category highlights die design, non-isothermal flow control, and simulation-assisted optimization as a technology backbone for tire extrusion, providing a direct link between material viscoelasticity and manufacturable profile accuracy [19, 99–101].

Extrusion hardware and processing-window engineering (category subset: $n = 10$) The extrusion-hardware subset focuses on continuous devulcanization and reactive compounding routes in which extruder configuration and operating conditions govern the thermal–mechanical history of tire-derived materials and, therefore, the reproducibility of reclaimed feedstocks. The overarching engineering aim is to achieve controlled network modification and consistent downstream processability by managing shear, temperature, and residence time through hardware- and process-window design [75, 103–105].

A dominant theme is the translation of batch devulcanization concepts into continuous processing using twin-screw extrusion (co-rotating and counter-rotating). They repeatedly treat screw design (including low-shear concepts), screw speed, feed rate/fill factor, residence time, and barrel temperature profiles as key degrees of freedom. Process performance is evaluated using selectivity concepts (random chain scission versus crosslink scission, including Horikx-type analyses in some records) together with rheological/thermal indicators, solvent extractables (e.g., acetone/toluene solubles), and mechanical testing after revulcanization; a DPDS-based devulcanization aid is explicitly discussed within this subset [104–106].

Representative studies within this subset make the role of operating windows more explicit. In continuous and reactive extrusion routes, process performance is repeatedly linked to screw design, screw speed, feed rate, shear severity, and residence-time control rather than to hardware choice alone. For example, passenger-car tire devulcanization studies report scale-up from 15 g/batch to 2 kg/h using co-rotating twin-screw extrusion, with feed particle sizes of 1–3.5 mm and deliberately low-shear screw concepts to limit excessive chain damage while preserving devulcanization efficiency. Other twin-screw studies show that devulcanization degree increases with higher screw speed and feed rate when the screw configuration is designed to generate sufficient shear,

whereas counter-rotating intermeshing designs indicate that screw geometry itself can shift performance, with one reported configuration using $L/D = 10$ and selected operating conditions around $170\text{ }^{\circ}\text{C}$ and 30 rpm. Additional records highlight that residence-time control can be more critical than nominal mean residence time alone: in dynamic revulcanized GTR/HDPE systems, good performance depended on matching rubber residence time to revulcanization kinetics, while in reactive compounding studies the width of the residence-time distribution was identified as a decisive engineering variable. Overall, these studies reinforce that extrusion hardware in tire-related recycling and compounding should be interpreted through a process-window framework in which screw configuration, thermal history, throughput, and residence-time distribution are jointly optimized for each material system. Representative operating-window variables and hardware-related examples from this subset are compiled in Appendix Table 23.

Several records further report extrusion-based incorporation of ground or (partially) devulcanized tire rubber into thermoplastic matrices (e.g., polyethylene or polypropylene) via reactive compounding and dynamic revulcanization, with processing parameters linked to morphology development and resulting performance [75, 77]. They highlight that the width of the residence-time distribution can be more influential than the mean residence time for continuously prepared elastomeric alloys [107]. Overall, this category reinforces that high-quality reuse of tire-derived rubber is fundamentally processing-controlled, and that extrusion hardware and operating-window design are critical enablers for reproducible compound quality and stable manufacturability.

Simulation and CAE for extrusion process and die design (category subset: $n = 7$) Tire manufacturing relies on rubber extrusion and co-extrusion to produce key components (e.g., profile elements and multi-material treads). Because rubber is viscoelastic and temperature-sensitive, inadequate control of flow and thermal conditions can lead to quality issues such as dimensional deviations associated with die swell and thermal instabilities (including premature vulcanization). The studies in this category show that combining experimental characterization with numerical simulation is repeatedly used to diagnose such mechanisms and to optimize process settings and die geometry [19, 95, 98, 101].

Finite-element/CFD models—often three-dimensional and non-isothermal—incorporate viscoelastic constitutive descriptions and temperature-dependent viscosity to predict velocity, pressure, and shear-rate fields together with extrudate swelling and geometry evolution. In this subset, Phan–Thien–Tanner-type formulations are explicitly used in some studies,

and numerical robustness is addressed through convergence aids such as parameter-evolution strategies and remeshing procedures. Model inputs and validation are supported by rheological testing and by process measurements (including thermographic temperature mapping and sensor-based data acquisition), with some studies reporting close agreement between simulation and extrusion trials (e.g., dimensional error below 6% in a co-extrusion case) [19, 98, 101].

Representative studies in this subset further show that CAE is not used only for geometric prediction, but also for process-window interpretation. In cap-ply extrusion, CFD-based analysis of rubber flow and temperature fields was combined with thermographic imaging and sensor-based measurements to compare alternative temperature-control strategies, showing that thermal management in the extrusion head is critical for avoiding premature vulcanization and insufficient cord impregnation. In viscoelastic tread co-extrusion, three-dimensional simulations implemented in ANSYS POLYFLOW with a PTT constitutive model linked inflow rate, traction speed, die convergence angle, and die thickness to internal velocity, pressure, and shear-rate fields, with reported tread-size deviation below 6% between simulation and experiment. Related non-isothermal co-extrusion studies using Polyflow together with Arrhenius-type viscosity descriptions likewise show that mold-channel geometry and material mass-flow distribution can be optimized numerically, with only minor local differences reported between simulation and experiment. Additional FEM-based studies on sidewall dies, inverse profile die design, and extrusion swell further indicate that die-face relief, operating conditions, and reference swell can be incorporated into computational design workflows to reduce trial-and-error and improve flow balance. Taken together, these records show that simulation-supported extrusion engineering already incorporates process variables such as temperature, flow rate, traction speed, and die geometry as explicit design inputs, and that CAE can serve as a practical route for compensating dimensional deviation, thermal imbalance, and flow instability when operating conditions change. Representative CAE studies, input variables, and quantitative validation outcomes are summarized in Appendix Table 24.

Beyond predictive analysis, simulation is also framed as a practical tool for rapid die development, including flow-balancing concepts for thin regions and inverse-design-type strategies to approach target extrudate shapes [99, 100].

Monitoring, sensing, and process control (category subset: $n = 2$) This category is small but directly aligned with advanced manufacturing priorities. One study reports that, in cap-ply production (cord impregnation with an extruded rubber compound), inadequate extrusion temperature control can promote premature vulcanization and/or insufficient

impregnation; the proposed response couples CFD-based analysis of flow/temperature fields with rheological/vulcanization characterisation and experimental temperature mapping (thermography and sensor-based acquisition), with reported reductions in scrap and electrical energy consumption [98]. A second study discusses non-contact PSD-based laser triangulation sensors for in-line measurement and quality monitoring; applications described include thickness measurement, extrusion profiling/guiding, splice/overlap detection, runout monitoring of green tires, and sidewall inspection [108].

Although small in volume, the monitoring/control subset is particularly relevant to operating-window robustness. The retrieved studies show two complementary monitoring roles. First, sensor-supported thermal supervision was used in cap-ply extrusion to compare alternative temperature-control strategies in the extrusion head, combining thermographic imaging, Arduino-based sensor acquisition, and CFD-supported interpretation of flow and temperature fields. This approach enabled the development of an improved control strategy and was reported to reduce scrap and electricity consumption. Second, non-contact PSD-based laser triangulation sensors were reported for in-line dimensional and surface monitoring in tire manufacturing, including thickness measurement, profile guidance, overlap or splice detection, radial and lateral runout inspection, and sidewall-surface assessment. Taken together, these studies indicate that monitoring methods can provide practical error-compensation support by detecting thermal drift, dimensional deviation, and profile instability early enough for corrective action. At the same time, the very small number of retrieved records confirms that explicit sensing, closed-loop control, and digitalized process stabilization remain underdeveloped relative to materials, tooling, and CAE-oriented research. The two representative monitoring and sensing records retrieved in this category are summarized in Appendix Table 25.

Cross-category synthesis and implications for advanced manufacturing Taken together, the category-based study synthesis confirms that the technology-focused tire-extrusion literature is organised around a process-material coupling backbone, where rheological/constitutive behaviour (including recycling-enabled formulations) is repeatedly used to interpret processability and quality stability. Tooling/flow/die engineering and CAE-based simulation then translate this material response into manufacturable profile accuracy, addressing non-isothermal flow control, co-extrusion balance, and die-swell-driven geometry deviations through simulation-assisted design and validation. Extrusion-hardware studies complement this by showing that screw/thermal design and residence-time management are decisive levers

for controlling the severity and selectivity of network modification and for achieving reproducible compound quality in continuous processing. In contrast, explicit monitoring/control and digitalization appear only sparsely in the retrieved corpus, suggesting a clear opportunity for advanced manufacturing research on integrated in-line sensing, closed-loop control, and digital-twin-enabled extrusion/co-extrusion to improve robustness, reduce development iterations, and further lower scrap and energy use in tire production. Notably, the scarcity of monitoring/control studies relative to materials and process-design work suggests that closed-loop extrusion control (linking in-line sensing with rheology-informed models and CAE-calibrated dies) remains underdeveloped in the retrieved literature and represents a clear opportunity for future tire-manufacturing research.

5 Discussion

5.1 Evolution of research output

Our analysis confirms that tire extrusion research has grown steadily between 2000 and 2025, with an annual growth rate of 2.8%. While modest compared to other areas of polymer science, this trajectory reflects the emergence of extrusion as a vital domain. The two citation peaks (2015 and 2020) coincide with the publication of reviews on waste tire recycling (Ramarad et al. [23]) and sustainable polymer-filler systems (Martínez et al. [109]). The decline in citation averages after 2021 is a common bibliometric effect of citation lag rather than evidence of reduced research activity.

5.2 Knowledge hubs and collaboration patterns

China emerges as the dominant contributor in both publication volume and overall influence, supported by a dense cluster of institutions such as Beijing University of Chemical Technology and Qingdao University of Science and Technology. Key authors including Formela K. and Zhang L. combine high productivity with strong citation impact.

At the country level, Poland stands out as a major connector in the international collaboration network, consistent with its high betweenness centrality, whereas several other countries contribute substantial impact through either publication output or citations. Despite these hubs, international co-authorship remains relatively limited (5.35%), suggesting that the field is still shaped largely by national or regional research ecosystems. Strengthening cross-border collaboration could facilitate faster diffusion of best practices and accelerate alignment with global sustainability and circular-economy agendas in tire manufacturing.

5.3 Thematic and conceptual structure of the field

Based on the thematic evolution, thematic maps, and factorial structure (MCA), the literature associated with tire extrusion is organized around a persistent materials-centric core while progressively incorporating sustainability-driven and technology-oriented directions. Over the four time periods, the most common and central themes remain focused on rubber, rubber compounding, and vulcanization, highlighting the key role of formulation and crosslinking chemistry in performance-critical tire components. In every period, compounding and property terms stay near the center of the thematic map, suggesting that the field is mainly shaped by materials design and structure–property relationships rather than process physics alone.

In addition, the thematic maps reveal gradual diversification: process-oriented and polymer-technology descriptors become more visible over time but remain comparatively less central when the full corpus is considered. In the early period (2000–2009), extrusion-related terms such as extrusion, rheology, and extruders appear in the emerging/declining region of the thematic map, indicating that extrusion-relevant studies were present but did not dominate the overarching conceptual structure. In subsequent slices, themes linked to reinforcement engineering and microstructure control (e.g., carbon black, particle size, and nanocomposites) gain prominence, consistent with the increasing emphasis on engineered fillers and performance tuning. In the most recent period (2021–2025), the visibility of devulcanization within developing clusters aligns with a growing sustainability agenda and circular-economy framing in tire-related polymer research.

The MCA map complements these observations by separating the literature into: (i) a central processing/material-characterization space dominated by compounding and vulcanization, (ii) a formulation and reinforcement region (fillers, silica, butadiene), (iii) a sustainability–performance region (devulcanization, optimization, mechanical properties), and (iv) a technology-oriented region associated with twin-screw extrusion, dynamic vulcanization, and advanced composite families. Overall, the maps indicate that “tire extrusion” functions as an intersectional domain: it spans classical rubber technology and reinforcement science while selectively incorporating process engineering and emerging manufacturing methods. This intersection helps explain why extrusion-related terms can be present in the corpus without becoming structurally central unless technology-focused restrictions are applied (see Section 5.5).

5.4 Intellectual structure and the knowledge base

The intellectual-structure analyses connect the field’s research front to its underlying knowledge base. Bibliographic coupling

highlights how recent studies cluster through shared reference foundations, whereas co-citation and historiographic mapping capture the canonical lineages and citation pathways that continue to shape current work.

The bibliographic coupling structure resolves four coherent clusters. Two clusters are clearly dominant: one concentrates the largest document count and the highest impact, while another exhibits the highest centrality together with comparably high impact. Both are organized around extrusion-enabled compound development and composite/formulation research, reflected by recurring descriptors such as twin-screw extruder, mechanical-properties, and composites. This concentration suggests that a substantial portion of the current research front builds on shared references related to mixing/compatibilization strategies and formulation-driven performance optimization. A third cluster is dominated by devulcanization and sustainability-related descriptors, consistent with the increasing prominence of recycling-oriented streams. The remaining cluster is comparatively niche and is characterized by dynamic reaction and blends, indicating a specialized frontier focused on reactive processing routes and targeted property tailoring.

Co-citation analysis complements this picture by revealing three major intellectual lineages that underpin the coupled research fronts: (i) polymer composites and elastomer modification, (ii) foundational polymer theory and vulcanization/crosslinking, and (iii) rubber recycling/devulcanization within a sustainability framing. This three-part core helps explain why full-corpus conceptual maps highlight compounding and recycling. The historiograph reinforces this interpretation by showing how early influential contributions on composite modification provide a citation pathway into later work increasingly oriented toward recycling and sustainability.

Taken together, the intellectual structure suggests that extrusion is frequently positioned as an enabling platform for compound development (mixing, compatibilization, dynamic vulcanization, and property optimization) rather than as a standalone process-physics problem. Consequently, topics such as tooling/die design and flow balancing become more visible when the analysis explicitly targets the technology-centered core via the technology-depth sensitivity layer (Section 5.5); however, in-line monitoring/control remains comparatively sparse in the retrieved corpus.

5.5 Subject-matter depth in tire extrusion technology

A central outcome of the technology-depth sensitivity layer is that a substantial share of the literature retrievable through tire+extrusion terminology remains dominated by broad rubber-processing, compounding, and recycling descriptors. Starting from the merged corpus (n=542), the

broad tire–extrusion subset ($n=167$) captures records that simultaneously contain tire-context terminology and extrusion/process terminology. When strong technology markers are additionally required—covering die/flow engineering, rheology/viscoelastic/constitutive modelling, simulation/CAE, and monitoring/control/digitalisation—the technology-explicit core contracts to the strict subset ($n=52$; ≥ 1 marker) and the technology-dense subset ($n=28$; ≥ 2 markers). This stepwise contraction quantifies the extent to which explicitly technology-oriented extrusion studies form a relatively small portion of the tire+extrusion discoverable literature, motivating a clear separation between “extrusion-enabled compound research” and “extrusion-technology research” when drawing engineering conclusions.

The sensitivity thematic maps clarify how conceptual emphasis shifts as the operational definition of “technology” is tightened. Within the strict subset, the Author Keywords (DE) map indicates a prominent motor theme centred on devulcanization and waste-rubber recycling, while complementary basic themes connect tire rubber, blends, and extrusion-enabled compounding routes. Importantly, an additional upper-quadrant cluster combines extrusion, rheology, mechanical properties, and compounds, capturing the process–material coupling core most relevant to extrusion design and performance. In contrast, the Keywords Plus (ID) map places greater weight on broadly indexed descriptors, yielding a more generic thematic framing even under strict filtering, while still retaining extrusion-related terminology across multiple clusters.

Under the technology-dense criterion, Keywords Plus further surfaces explicitly engineering and methodological descriptors as structurally central, notably extrusion dies and the finite element method. This shift directly addresses terminology-driven scope drift: strengthening the technology definition moves the conceptual structure toward tooling and CAE language that is comparatively peripheral in the full corpus. Taken together, the strict and dense sensitivity maps indicate two overlapping but distinguishable agendas: (i) extrusion-enabled materials and recycling research, and (ii) a smaller process-engineering/CAE core where die design, flow balancing, and constitutive modelling are explicit research objects. For engineering synthesis and industrial translation, the latter agenda provides the most direct bridge to controllable process degrees of freedom (die geometry, thermal history, residence time) and closed-loop stabilization.

5.6 Industrial impact: actionable levers and examples

Beyond describing thematic structure, the results translate into manufacturing levers for tire-profile extrusion and co-extrusion. The technology-depth sensitivity layer indicates

that the technology-explicit core is dominated by rheology/constitutive terminology and tooling/process-design themes, whereas monitoring/control/digitalisation remains sparse. This suggests strong capability for off-line understanding and optimisation (materials, dies, CAE), but a weaker footprint in on-line robustness mechanisms (in-line sensing and closed-loop control).

From an industrial perspective, the identified subdomains map directly to common plant KPIs and failure modes. Rheology/constitutive work underpins processing-window definition (viscosity/viscoelasticity versus temperature and shear), with direct implications for die swell, gauge stability, and profile accuracy. Tooling/flow/die studies translate those material responses into geometry control for multi-compound tread co-extrusion, where flow balance and swelling govern dimensional error and start-up scrap. Simulation/CAE studies reduce die-development iteration by enabling virtual screening of die concepts and non-isothermal settings prior to trials, shortening qualification cycles and reducing material waste. Extrusion-hardware/process-window studies emphasise residence-time and thermal–mechanical history control as decisive for reproducible compound quality, including recycling-enabled formulations.

Examples from the technology-focused subset are typical of tire manufacturing:

- **Cap-ply extrusion/impregnation:** thermal mismanagement can cause scorch or inadequate impregnation; this can be addressed via coupled thermo-flow analysis and improved temperature-control strategy [98].
- **Simulation-assisted tread/co-extrusion die optimisation:** thermo-viscoelastic modelling can improve profile accuracy and reduce trial-and-error iteration [19, 95].
- **In-line non-contact measurement:** thickness/profile monitoring and defect detection in production (e.g., PSD-based laser triangulation) [108].

Together, these pathways show how the main research directions can reduce defect rates and start-up scrap, improve dimensional capability, and accelerate die/process development. Table 20 summarises this translation by linking each technology subdomain to typical industrial levers, common failure modes, and the most directly affected KPIs, based on the category-based tagging and the concrete examples cited above.

5.7 Research roadmap: open technical challenges and high-value opportunities

Overall, the conceptual, intellectual, and technology-depth results show an active and expanding literature, while suggesting that technology-explicit extrusion engineering

Table 20 Linking dominant technology subdomains to industrial levers, typical failure modes, and tire-extrusion KPIs

Subdomain (this study)	Typical industrial lever / example	Typical failure mode addressed	Typical KPI impact
Rheology / constitutive modelling	Define stable processing window; anticipate die swell and gauge instability via viscoelastic response	Die swell; gauge drift; melt-fracture / surface defects; unstable draw-down	Dimensional capability; gauge stability; scrap rate
Tooling / flow / die engineering	Flow balancing in multi-compound co-extrusion dies; geometry tuning to hit target profile	Flow imbalance; interface distortion; profile dimensional error; non-uniform residence/thermal history in die	Start-up scrap; tolerance attainment; die-qualification time
Simulation / CAE	Virtual screening of die designs and non-isothermal settings prior to trials	Trial-and-error die iteration; thermal hotspots; unsteady/recirculating flow zones; poor swell prediction	Development time; trial count; energy and material waste
Extrusion hardware / process-window	Screw/thermal/residence-time design to stabilise compound history and mixing	Inconsistent mixing; thermal degradation/scorch risk; batch-to-batch variability; unstable throughput	Uptime; reproducibility; defect rate
Monitoring / control / digitalisation	In-line sensing (temperature/thickness/profile) plus model-based control; data-driven alarms	Late defect detection; uncontrolled temperature excursions; profile drift; quality escapes	Quality escapes; closed-loop robustness; energy efficiency

(tooling, CAE, and control) is less developed than compound/formulation and recycling-oriented streams within the retrieved corpus. In other words, the field shows strong capability for off-line understanding and material-level innovation (formulation, reinforcement, recycling pathways), alongside a smaller but clearly identifiable core focused on die/flow engineering and simulation. Similarly, the category-coverage analysis within the broad tire-extrusion subset indicates an imbalance in emphasis: rheology/constitutive modelling is more common, whereas monitoring/control/digitalisation remains sparsely represented. These patterns motivate a roadmap that strengthens the link between material science advances and robust, controllable manufacturing.

Based on the technology-explicit core and the observed gaps, the following directions appear especially high-value:

1. **Coupled thermo-viscoelastic modelling for profile accuracy.** Develop predictive models that jointly capture non-isothermal rheology, viscoelastic stress, and free-surface effects (e.g., die swell), including multi-compound interfaces, to reduce trial-and-error die iteration and improve dimensional capability.
2. **Die/flow engineering for multi-compound co-extrusion.** Establish systematic design principles for flow balancing, residence-time equalisation, and interface stabilisation in complex tread and sidewall geometries, supported by experimentally anchored validation and benchmark cases.
3. **Process-material coupling under recycled and devulcanised formulations.** Quantify how recycling routes and particle-size distributions modify rheology, scorch safety, and stability margins, and translate these effects into process-window constraints and controllable compounding strategies.

4. **From CAE to decision-making: uncertainty and robustness.** Move beyond nominal simulations by incorporating uncertainty quantification (material variability, thermal fluctuations, wear, feed variability) and robustness criteria tied to quality metrics (gauge stability, interface integrity, defect probability).
5. **In-line sensing and closed-loop stabilisation.** Expand research on non-contact profile/thickness metrology, thermal sensing, and model-based control to mitigate drift, shorten start-up transients, and reduce defect risk—an area that remains comparatively underrepresented in the current corpus.
6. **Digital-twin architectures with physics-informed surrogates.** Develop digital-twin frameworks that combine reduced-order and physics-informed surrogate models with production data streams for real-time prediction, anomaly detection, and adaptive control.

5.8 Contextualization against prior bibliometric practice in polymer-processing research

Bibliometric synthesis is now used in polymer-processing and manufacturing research to consolidate fields whose contributions are dispersed across polymer chemistry, rheology, process engineering, and sustainability. Most studies follow a similar workflow: (i) collect records from a major citation index, (ii) apply cleaning/deduplication, and (iii) report descriptive performance indicators together with conceptual and intellectual-structure maps. However, polymer-processing domains pose two practical constraints that can weaken comparability and downstream network reliability: coverage bias from single-database retrieval, and metadata incompleteness (missing DOIs, incomplete cited references,

and sparse/heterogeneous keyword fields), which can distort citation-based structures and reduce interpretability.

Against this baseline, the present study aligns with established best practice while explicitly addressing these constraints. First, we integrate Scopus and Web of Science to reduce database-specific indexing bias and to improve coverage of engineering and conference-oriented contributions. Second, we apply a reproducible enrichment pipeline that leverages open scholarly infrastructures (Crossref, OpenAlex, and OpenCitations) together with YAKE-based keyword completion. This design directly targets polymer-processing bibliometric failure modes: it reduces sensitivity of co-citation, bibliographic coupling, and RPYS analyses to missing identifiers and incomplete cited-reference fields, thereby strengthening reproducibility and the robustness of the inferred intellectual lineages.

A further distinction relative to common polymer-processing bibliometrics is the explicit treatment of scope drift in intersectional domains. In tire extrusion, “extrusion” frequently appears as an enabling platform within compound development and recycling streams, which can dominate full-corpus conceptual maps even when the engineering question is process-technology (dies, CAE, and control). To make this ambiguity auditable, we complement standard full-corpus reporting with a deterministic technology-depth sensitivity (scope-control) layer that separates a broad tire-extrusion subset from nested technology-explicit subsets and a category-based engineering synthesis. This step operationalises a frequent but rarely formalised judgement in polymer-processing bibliometrics: whether a retrieved corpus truly represents process technology rather than broader materials-centric proximity.

To support transparency and reuse, the enriched dataset and processing scripts are made openly available via Zenodo (Zenodo DOI: [10.5281/zenodo.18506816](https://doi.org/10.5281/zenodo.18506816)).

5.9 Theoretical and methodological contributions to engineering bibliometrics

This study contributes to bibliometric methodology for engineering process-technology domains in four transferable ways.

First, it formalises terminology-driven scope control as a deterministic sensitivity layer that separates a broad domain corpus from a technology-explicit core using nested marker thresholds. In engineering corpora, conceptual maps can be dominated by high-frequency but process-agnostic terminology (e.g., generic recycling/material-property descriptors). The proposed scope-control layer provides a reproducible mechanism to test whether observed thematic structures persist when the definition of “technology” is tightened.

Second, it introduces an engineering degrees-of-freedom mapping by assigning non-exclusive tags (tooling/flow/die; rheology/constitutive; hardware/process window; CAE; monitoring/control). This bridges descriptive co-word structures to interpretable process-engineering dimensions, enabling bibliometric outputs to be read as actionable technology levers rather than only topic clusters.

Third, the paired use of Author Keywords (DE) and Keywords Plus (ID) under the same sensitivity subsets operationalises a field-triangulation robustness check. Using both views systematically reduces over-reliance on a single keyword field and makes the specificity–generality trade-off explicit.

Fourth, we introduce a rule-based core-paper prioritisation step using an engineering relevance score S computed from title (TI), abstract (AB), keywords (DE), and Keywords Plus (ID). This provides a transparent alternative to citation-only shortlisting by upweighting technology-explicit extrusion signals and downweighting recycling-only drift, producing a compact and reproducible “engineering core” for qualitative synthesis.

5.10 Reproducibility, benchmarking, and standardization implications

The fragmentation of collaboration communities and the low rate of international co-authorship suggest that tire-extrusion research remains strongly shaped by regional ecosystems and local application contexts. This is not inherently negative—industrial confidentiality, equipment specificity, and proprietary compound formulations can constrain cross-site collaboration—but it has clear methodological and practical implications. Without shared benchmarks and reporting conventions, it is difficult to compare extrusion-technology claims across compounds, dies, and plants, and the field’s cumulative evidence base becomes less transferable.

A direct implication of the technology-depth findings is the need for benchmarking at the process-technology level, complementing established practices in materials characterization. For simulation- and die-engineering studies, progress would be accelerated by a small set of reference problems with openly specified die geometries, thermal boundary conditions, and rheological characterization protocols, including explicitly reported test conditions and fitted constitutive parameters. For experimental extrusion investigations, improved standardization of reporting—compound history, processing temperature profiles, screw and die configuration, residence time, and measurement uncertainty—would increase comparability and enable more rigorous cross-study synthesis.

Finally, reproducibility in engineering bibliometrics benefits from transparent and auditable scope definition. The deterministic scope-control layer introduced here (complete

term lists and nested marker thresholds) offers a transferable mechanism to separate broad domain literature from a technology-explicit core. When paired with openly shared scripts and enriched datasets, this approach enables independent reproduction of conceptual structures, systematic testing of alternative operational definitions (e.g., of “technology”), and straightforward extension as emerging themes such as digital twins and closed-loop control become more prevalent.

5.11 Limitations

This study has several limitations. First, the bibliometric corpus is based on Scopus and Web of Science records; therefore, outputs not covered by these databases are not reflected in the quantitative results. In particular, patents were not included in the present analysis, and industrial documentation was not treated as part of the bibliometric dataset. Second, because the search was conducted in English, non-English publications may not be fully captured, which can influence country-level productivity and collaboration patterns. Third, citation-based indicators are affected by citation lag, leading to lower citation counts for recent years. Fourth, although metadata enrichment substantially improved completeness, automated DOI matching and cited-reference reconstruction may still leave residual missingness or occasional mismatches, especially for older records.

6 Answers to research questions

RQ1: How has the research output on tire extrusion evolved from 2000 to 2025 Within the combined Scopus–WoS corpus, the dataset includes 542 publications (2000–2025) and exhibits steady long-term growth, with an annual growth rate of 2.81%. Annual scientific production is modest in the early 2000s, accelerates after 2010, and peaks around 2020. Average citations per document increase toward 2020 and decline after 2021, a pattern consistent with citation-lag effects for recent publications rather than a contraction of research activity.

RQ2: Who are the most influential authors, institutions, and journals contributing to this domain? At the journal level, the Journal of Applied Polymer Science is the leading outlet by production (48 documents) and also ranks highest in local influence and source-impact metrics. Bradford’s Law identifies a core Zone 1 consisting of Journal of Applied Polymer Science, Rubber Chemistry and Technology, and Rubber World, confirming a highly concentrated set of primary publication venues. Beyond the core, Polymer Degradation and Stability and Polymer Testing show strong citation-based performance relative to their publication counts, indicating substantial within-domain impact. At the author level, influence

indicators place Zhang L. and Formela K. among the leading contributors. At the institutional level, Qingdao University of Science and Technology and Beijing University of Chemical Technology emerge as the most influential institutions (PageRank), followed by China University of Petroleum, the University of Massachusetts, and Warsaw University of Technology, reflecting a hub structure dominated by Chinese institutions with notable international partners.

RQ3: What are the dominant research themes in tire extrusion, and how has the thematic focus evolved over time? Keyword frequency analysis indicates that the field is dominated by a materials-and-compounding backbone: rubber (267), rubber compounding (220), and vulcanization (130) are the most recurrent terms, followed by performance and evaluation descriptors such as tensile strength (96). Process terminology is present but less frequent in the full corpus, with extrusion appearing 45 times.

Thematic mapping and thematic evolution across four time slices further show that this compounding/vulcanization backbone persists throughout the period, while later years increasingly incorporate reinforcement and microstructure-oriented descriptors (e.g., carbon black and particle size) alongside sustainability-driven directions such as recycling and devulcanization. Taken together with co-word clusters, these results support a thematic structure organized around (i) rubber formulation and crosslinking science, (ii) reinforcement and performance/property evaluation, (iii) sustainability and end-of-life strategies, and (iv) process-related strands in which extrusion is coupled to materials optimization rather than forming the dominant conceptual center in the full corpus.

RQ4: What patterns of collaboration exist across countries, institutions, and authors? The dataset exhibits a collaborative authorship structure (3.95 co-authors per document on average), but international integration remains limited: only 5.35% of publications involve international co-authorship. Country and institution level networks show strong regional clustering. China is the most central and productive contributor in the country collaboration network, while Poland stands out as a key connector with high betweenness centrality, indicating a bridging role between otherwise weakly connected communities. At the author level, the network is fragmented into distinct collaboration communities; bridging roles are concentrated in a small number of actors (high betweenness; e.g., Zhang L.), facilitating cross-cluster knowledge exchange.

RQ5: Which publications and intellectual foundations have had the greatest impact on tire extrusion research? The field’s intellectual structure is supported by a small number of consolidated reference lineages that repeatedly anchor the knowledge base. Co-citation analysis reveals three major intellectual clusters: (i) polymer composites

and elastomer modification, (ii) foundational polymer theory and vulcanization/crosslinking, and (iii) rubber recycling/devulcanization and sustainability. The historiograph further indicates an evolutionary pathway in which early influential work on composite materials feeds into later contributions increasingly oriented toward sustainability and rubber recycling. Together, these results show that current research fronts are grounded in durable foundational theory while being progressively shaped by recycling- and sustainability-driven developments.

RQ6: Within technology-explicit tire-extrusion studies, what engineering subdomains dominate, and which remain sparse? The technology-depth sensitivity layer shows that technology-explicit extrusion engineering represents a relatively small share of the literature retrieved by the tire+extrusion query. From the full corpus ($n=542$), a broad tire-extrusion subset ($n=167$; 30.8%) is identified, and two nested technology-explicit subsets are obtained using strong-technology markers: a strict subset ($n=52$; 9.6%; ≥ 1 marker) and a technology-dense subset ($n=28$; 5.2%; ≥ 2 markers). Within the broad subset, category coverage (non-exclusive) indicates that rheology/constitutive markers are most prevalent (20.4%, $n=34$), whereas monitoring/control markers are sparse (1.2%, $n=2$), with intermediate representation for tooling/flow/die (7.2%, $n=12$), extrusion hardware/process-window (6.0%, $n=10$), and simulation/CAE (4.2%, $n=7$). Overall, the technology-explicit engineering emphasis is dominated by rheology and process-material coupling, while in-line sensing, closed-loop control, and digitalisation remain underrepresented, highlighting clear opportunities for future work in advanced monitoring and control of tire extrusion.

7 Conclusion

This study provides a consolidated, reproducible bibliometric synthesis of tire-extrusion research published between 2000 and 2025 by integrating Scopus and Web of Science records and enhancing metadata completeness through automated enrichment (DOIs, corresponding authors, keywords, and cited references). The merged and deduplicated corpus comprises 542 unique publications and reveals steady long-term growth (2.81% annual growth rate), with a production increase after 2010 and a peak around 2020.

Across the full corpus, the conceptual structure is dominated by a durable materials-and-compounding backbone. High-frequency and thematically central terms are concentrated around rubber, rubber compounding, and vulcanization/crosslinking, with performance descriptors (e.g., tensile strength) strongly represented. Thematic mapping and evolution further indicate that these foundations persist across

the entire period while later years increasingly incorporate reinforcement/microstructure descriptors and sustainability-driven directions such as recycling and devulcanization. In this sense, much of the literature retrieved under tire+extrusion framing treats extrusion primarily as an enabling platform for compound development and evaluation rather than as the main object of process-physics and control research.

At the level of influence and knowledge hubs, a concentrated set of journals anchors the field (with *Journal of Applied Polymer Science* leading by production and source influence, and a small Bradford core), while author and institution indicators highlight a hub structure dominated by Chinese institutions alongside notable international contributors. Collaboration is present in co-authorship terms (3.95 co-authors per document on average), but cross-border integration remains limited (5.35% international co-authorship), and network structure is fragmented into regional and community clusters with only a small number of bridging actors.

A central methodological contribution of this work is the technology-depth sensitivity (scope-control) layer, introduced to address terminology-driven scope drift and to separate broad domain literature from an extrusion-engineering technology core. Starting from the full corpus ($n=542$), the rule-based approach identifies a broad tire-extrusion subset ($n=167$; 30.8%) and two nested technology-explicit subsets defined via strong-technology markers: a strict subset ($n=52$; 9.6%) and a technology-dense subset ($n=28$; 5.2%). Within the broad subset, non-exclusive engineering-category tagging indicates that rheology/constitutive markers are most prevalent, followed by tooling/flow/die, extrusion hardware/process-window, and simulation/CAE, whereas monitoring/control markers are rare. This quantitative separation clarifies that explicitly technology-oriented extrusion engineering constitutes a relatively small but distinct core within the searchable tire-extrusion literature, dominated by rheology and process-material coupling and supported by die/flow design and CAE, while in-line sensing, closed-loop control, and digitalisation remain underrepresented.

From an industrial and translational standpoint, the identified technology subdomains map directly to controllable levers and plant-relevant outcomes. Rheology/constitutive modelling supports processing-window definition and stability (die swell, gauge control, surface quality), tooling/flow/die studies translate material response into geometry and co-extrusion flow balancing, simulation/CAE reduces trial-and-error through virtual evaluation, and hardware/process-window studies target residence-time and thermo-mechanical history management. Table 20 summarises this translation by linking the dominant technology subdomains to typical industrial levers, common failure modes, and the most directly affected KPIs, thereby bridging bibliometric evidence with manufacturing decision variables.

Overall, this work contributes both a structured understanding of how tire-extrusion research has evolved and a reproducible mechanism to isolate and characterise the technology-explicit extrusion-engineering core. The findings motivate clear future directions: strengthening in-line monitoring and closed-loop control for robust profile and co-extrusion, expanding digitalisation and digital-twin-oriented work in extrusion contexts, and improving reporting standards for experimental and simulation studies (geometry, boundary conditions, rheological protocols, and uncertainty) to enable higher comparability and more rigorous cross-study synthesis. By sharing the enriched dataset and scripts openly, the study enables direct reproduction, sensitivity testing of alternative scope definitions, and straightforward extension as emerging themes mature.

7.1 Supplementary information

The materials include: (i) the enriched Scopus–Web of Science dataset analysed in this study; (ii) the Python pipeline used for data cleaning, metadata enrichment, and bibliometric analysis; (iii) the rule-based Python script used to construct the broad tire–extrusion subset and the technology-focused strict and technology-dense subsets; and (iv) additional sensitivity figures, including the DE thematic map for the technology-dense subset and the full list of frequent keywords. All materials are publicly available via Zenodo (Zenodo DOI: [10.5281/zenodo.18506816](https://doi.org/10.5281/zenodo.18506816)).

Appendix A: Search queries used for data retrieval

To ensure comprehensive coverage of tire extrusion research, advanced Boolean search strategies were implemented in both Scopus and Web of Science. The following queries were used:

A.1 Scopus search query

```
TITLE-ABS-KEY ( "extrusion process"
OR "rubber extrusion" OR "polymer
extrusion" OR "profile extrusion" OR
"co-extrusion" OR "continuous extru-
sion" OR "hot extrusion" OR "cold
extrusion" OR "screw extruder" OR
"extruder design" OR "rubber compound-
ing" OR "rubber mixing" OR "rubber
processing equipment" ) AND TITLE-
ABS-KEY ( "tire" OR "tire manufactur-
ing" OR "tire production" OR "tire
```

```
components" OR "green tire" OR "smart
tire" OR "tire compounding" OR "tread
extrusion" OR "sidewall extrusion" OR
"innerliner extrusion" OR "elastomer
processing" OR "vulcanization" ) AND
PUBYEAR > 1999 AND PUBYEAR < 2026
AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR
LIMIT-TO ( DOCTYPE , "re" ) OR LIMIT-
TO ( DOCTYPE , "cp" ) ) AND ( LIMIT-TO
( LANGUAGE , "English" ) )
```

A.2 Web of Science (WoS) Search Query

```
TS=("extrusion process" OR "rubber
extrusion" OR "polymer extrusion"
OR "profile extrusion" OR "co-extru-
sion" OR "continuous extrusion" OR
"hot extrusion" OR "cold extrusion"
OR "screw extruder" OR "extruder
design" OR "rubber compounding" OR
"rubber mixing" OR "rubber processing
equipment") AND TS=("tire" OR "tire
manufacturing" OR "tire production"
OR "tire processing" OR "tire compo-
nents" OR "tire engineering" OR "tread
extrusion" OR "sidewall extrusion" OR
"innerliner extrusion" OR "green tire"
OR "smart tire") AND LA=(English) AND
DT=(Article OR Proceedings Paper OR
Review) AND PY=(2000–2025)
```

A.3 Inclusion criteria

- **Timeframe:** Publications from 2000 to 2025
 - **Language:** English only
 - **Document Types:** Articles, Review Papers, and Conference Proceedings
- These queries were optimized to maximize recall while maintaining domain relevance, following standard practices in bibliometric methodology.

Appendix B: Rule-based subset definitions and term lists

This appendix reports the rule-based term lists used to define technology-focused subsets. The filtering was applied to the concatenated text fields TI, AB, DE, and ID. A record was included in the *broad tire–extrusion subset* if it contained at

least one tire-context term and at least one extrusion-related term. Technology-focused subsets were then defined by additionally requiring a minimum number of *strong technology marker* hits (≥ 1 for the strict subset; ≥ 2 for the technology-dense subset).

B.1 Tire-context terms (regular-expression patterns)

- **Tire terms:** `\btire\b, \btyre\b`
- **Tire components:** `\btread\b, \bside\s*wall\ / \sidewall\b, \binner\s*liner\b / \binnerliner\b, \bcarcass\b, \bbead\b, \bbelt\b, \bcap\s*ply\b, \bapex\b, \bchafer\b`

B.2 Extrusion-related terms (regular-expression patterns)

- **Extrusion family:** `\bextr(?:ud|us)\w*\b`
- **Equipment/process:** `\bextruder(?:s)?\b, \bco[-\s]?extr(?:ud|us)\w*\b, \bcross[-\s]?head(?:s)?\b, \bextrusion\s*head(?:s)?\b`
- **Tooling:** `\bdie(?:s)?\b, \bextrusion\s*die(?:s)?\b, \bdie\s*swell\b`
- **Profiles:** `\bprofile\s*extr(?:ud|us)\w*\b`

B.3 Strong technology markers (regular-expression patterns)

Strong markers were used to identify records explicitly addressing extrusion technology, including die/flow engineering, rheology/viscoelastic modelling, CAE/simulation, and monitoring/control.

- **Die/flow engineering:** `\bdie\s*design\b, \bprofile\s*die\b, \bmanifold\b, \bflow\s*channel\b, \bflow\s*distribution\b, \bdie\s*swell\b, \bcross[-\s]?head\b, \bcalibrat\w*\b, \bpressure\s*drop\b, \btemperature\s*(control|profile)\b.`

- **Extruder/screw design and residence time:** `\bscrew\s*design\b, \bcompression\s*ratio\b, \bld\b / \bl\s*\s*d\b, \bresidence\s*time\b.`
- **Rheology/viscoelastic/constitutive modelling:** `\bviscoelastic\w*\b, \brheolog\w*\b, \bconstitutive\b, \bgiesekus\b, \bfene[-\s]?p\b, \boldroyd\b, \bphandien[-\s]?tanner\b/\bptt\b.`
- **CAE/simulation:** `\bfinite\s*element\b / \bfem\b, \bcfd\b, \bcomputational\s*fluid\b, \bansys\b, \bpolyflow\b, \bopenfoam\b, \bcomsol\b, \bnumerical\s*simulation\b, \bflow\s*simulation\b.`
- **Monitoring/control/digitalization:** `\bdigital\s*twin\b, \bprocess\s*monitor\w*\b, \bin[-\s]?line\b / \bon[-\s]?line\b, \bsensor\w*\b, \bmodel\s*predictive\b/\bmpc\b.`

B.4 Recycling/devulcanization terms (used for drift penalty in relevance scoring)

These terms were not used to exclude records from the subsets, but were used to penalize recycling-only drift in the relevance ranking.

- `\brecycl\w*\b, \bdevulcan\w*\b, \bcrumb\s*rubber\b, \bground\s*tire\s*rubber\b / \bgtr\b, \bpyrolysis\w*\b, \breclaim\w*\b`

Appendix C: Representative technology-focused studies by engineering category

This appendix summarizes representative studies underlying the category-based technical synthesis reported in Section 4. The tables are intended to make the role of process variables, operating windows, constitutive behavior, tooling decisions, simulation inputs, and monitoring approaches more explicit.

Table 21 Appendix Table A1. Representative rheology and constitutive-behaviour studies linking process variables to extrusion-relevant response

Study/topic	Rheology / constitutive focus	Key variables	Representative data	Main rheological insight
Ultrasonic devulcanization of tire rubber	Frequency-dependent complex viscosity and curing-torque behavior	Mesh size; ultrasonic amplitude; devulcanization temperature	Ultrasonic frequency 40 kHz; power-law index 0.06 for devulcanized rubber and 0.02 for devulcanized rubber	Devulcanization level changed viscosity response and die-pressure behavior; finer rubber devulcanized more easily
Dynamic devulcanized GTR/HDPE	Rheology linked to residence time and devulcanization kinetics	Screw speed; feeding mode	Blend 60 wt% GTR / 40 wt% HDPE; devulcanized GTR with 26 wt% toluene solubles	Good processing depended on matching residence time to devulcanization kinetics
LLDPE/EPDM/SRT blends	G' , G'' , complex viscosity, and DSC-linked thermal behavior	Partial replacement of EPDM by SRT	Extrusion temperatures 180/190/200/200/210 °C	SRT did not strongly increase G' , G'' , or complex viscosity
Reclaimed EPDM / virgin EPDM blends	Stress relaxation, DMTA, frequency sweep, curing behavior	Screw speed; reclaiming-agent content	Screw speed 40/80/120 rpm; agent 0/1.5/3 phr; barrel temperature 280 °C; best condition 120 rpm and 3 phr	Reclaiming conditions significantly altered storage modulus and relaxation behavior
DGTR from industrial single-screw extruder	Mooney viscosity, dynamic rheology, processability vs. structure	Barrel temperature; screw speed	Devulcanized tensile strength 11 MPa; elongation at break 370%	Moderate shear gave a good balance between devulcanization, processability, and properties
HDFS/GTR/HDPE composite with TESPT + MAPE	Shear viscosity and stress during extrusion	MAPE level; TESPT level	Composition 30 : 21 : 49 HDFS:GTR:HDPE; best dual system 5% MAPE + 1% TESPT	Coupling agents had synergistic effects on viscosity/stress and improved mechanical response
Recycled tire fibers / GTR / LLDPE	Melt rheology and DMA	RTF content; screw speed; compatibilizer	RTF 10/25/50 wt%; screw speed 110/180/250 rpm	Melt modulus and viscosity increased with RTF loading and compatibilization; melt rheology was highly sensitive to interface quality
Tri-composite tire tread co-extrusion	Constitutive fitting for viscoelastic simulation	Inflow rate; traction speed; die angle; thickness	Simulation size error < 6%	PTT-based rheological fitting supported accurate viscoelastic co-extrusion simulation

Table 22 Appendix Table A2. Representative tooling, flow, and die-engineering studies and their process-sensitive design variables

Study/topic	Tooling / die feature	Key variables	Representative data	Main engineering implication
Cap-ply rubber extrusion head	Extruder head with revised temperature-control strategy	Temperature distribution; control mode; vulcanization behavior	Qualitative thermal-control comparison reported	Improved thermal uniformity reduced scrap and energy consumption
Tri-composite tire tread co-extrusion	Co-extrusion die and die-plate design	Inflow rate; traction speed; convergence angle; die thickness; pressure/velocity/shear-rate fields	Tread size error < 6%	Simulation supported die design and tread-shape prediction
Short-fiber radial orientation in tread extrusion	Die with hinder dam	Expansion ratio; expanding angle	Best expansion ratio 3–4; orientation angle 70°–80°	Die geometry guided radial fiber orientation
Flow control in tire sidewall die	Face-relieved die	Die-face relief; local flow balance	Comparative die-design result reported	Improved thin-edge filling and reduced tearing risk
Inverse die design for rubber profiles	Inverse extrudate-based profile die design	Reference swell; material properties; operating conditions	Good agreement reported	Enabled faster prediction of die profile for target extrudate shape
2024 tire tread co-extrusion mold design	Mold/channel design	Two-material mass flow rates; non-isothermal flow; rheology; geometry	Minor local simulation–experiment differences	Supported channel optimization and improved co-extrusion design

Table 23 Appendix Table A3. Representative operating-window variables in extrusion hardware and processing-window studies relevant to tire-related extrusion systems

Study/topic	Extrusion hardware / key variables	Representative data	Engineering takeaway
Dynamic devulcanized GTR/HDPE blends	Twin-screw extruder; screw speed; feeding mode; residence time vs. devulcanization kinetics	60/40 wt% devulcanized GTR/HDPE; devulcanized GTR with 26 wt% toluene solubles	Good performance depended on matching rubber residence time to devulcanization kinetics
Continuous thermomechanical devulcanization of GTR	Co-rotating twin-screw extruder with special plasticizing-unit configuration; feed rate; screw speed; shear force; residence time	Qualitative screw-speed/feed-rate dependence reported	Devulcanization degree increased with higher screw speed and feed rate when sufficient shear was generated
Passenger-car tire devulcanization upscale	Co-rotating twin-screw extruder with low-shear screw design; time-temperature profile; screw speed; fill factor	Scale-up from 15 g/batch to 2 kg/h; feed size 1–3.5 mm	Process window deliberately shifted toward low shear to reduce chain damage while maintaining devulcanization
Waste-rubber recycling extruder design	Intermeshing counter-rotating twin-screw extruder; screw geometry; temperature; screw speed	$L/D = 10$; selected operating conditions around 170 °C and 30 rpm	Hardware geometry strongly affected devulcanization quality
Passenger-car tire devulcanization with DBD	Twin-screw extruder redesigned around devulcanization-aid melting behavior; shear level; residence time; downstream milling	DBD melting point 140 °C; milling at 60 °C; devulcanized tensile strength 8 MPa; strain at break 160%	Changing chemistry required process redesign and low screw speed due to residence-time constraints
Reactive compounding of GTR + PP elastomeric alloys	Co-rotating twin-screw extruder; screw design; feeding protocol; screw speed; throughput; residence-time distribution	Residence-time-distribution effect reported qualitatively	Residence-time distribution width was more critical than mean residence time alone
Single-screw reclaimator case study	Single-screw extruder reclaimator; temperature; residence time; feed organization	Qualitative operating dependence reported	Stable product quality depended on both machine settings and homogeneous feed logistics

Table 24 Appendix Table A4. Representative CAE and simulation studies addressing process variables in tire-related extrusion systems

Study/topic	CAE / simulation approach	Inputs / variables studied	Validation / quantitative data	Main design insight
Cap-ply extrusion head temperature control	CFD analysis of rubber flow in extruder head with experimental thermal mapping	Temperature-control strategy; vulcanization behavior; rheology; temperature distribution	Validated with thermographic imaging and Arduino-based sensor data	Thermal control in the head is critical to avoid premature vulcanization and poor impregnation; improved control reduced scrap and energy use
Rubber extrusion process FEM	Finite element model using Euler–Lagrange coupling	Extrusion parameters; extrusion swell/expansion behavior	Qualitative agreement reported	Simulation captured swell/expansion and supported process-parameter optimization
Tri-composite tire tread co-extrusion	3D viscoelastic numerical simulation with experiments; ANSYS POLYFLOW; PTT constitutive model	Inflow rate; traction speed; die convergence angle; die thickness; velocity, pressure, and shear-rate fields	Simulation/experiment tread-size error < 6%	Provided a predictive model for tread shape and die swell, supporting die-plate design and process optimization
Tire sidewall die flow balancing	Finite element simulation for die-internal flow design	Die face relief versus back-relieved and unrelieved designs	Comparative design result reported	Face-relieved dies improved thin-edge filling, eliminated tearing, and avoided local velocity minima
Inverse profile die design	Simple finite element computation using inverse extrudate concept	Reference swell; extruder characteristics; operating conditions; material properties	Good agreement reported with 3D theory and experiments	Enabled faster prediction of die profile for target extrudate shape, reducing trial-and-error
2024 tire tread co-extrusion mold design	Non-isothermal CFD/FEA co-extrusion simulation; Polyflow; PTT; Arrhenius viscosity model	Two-material mass flow rates; shear frequencies; mold-channel geometry; geometric dimensions	Simulation matched experiments with only minor local differences	Numerical simulation supported mold-channel optimization and reduced development effort
Tire-cord thermal stabilization / heating box	Steady-state thermal/fluid analyses of heating system	Dowtherm-A inlet mass flow; chamber top-surface geometry	Required flow 0.0035 kg/s at 300 °C; inclined top improved heat transfer by 3.5%; total condensation-surface heat transfer 1008 W	Surface geometry and flow rate strongly affected heat-transfer efficiency and thermal distribution

Table 25 Appendix Table A5. Representative monitoring and sensing approaches in the technology-focused tire-extrusion literature

Study/topic	Monitoring / sensing method	What is measured	Main process role / takeaway
Cap-ply extrusion process	Thermographic imaging + Arduino Uno with sensors/modules + supporting CFD	Temperature distribution in the extruder head	Thermal monitoring supported comparison of two temperature-control strategies and enabled a revised strategy that reduced scrap and electricity use
Tire manufacturing laser sensing	Non-contact PSD-based laser triangulation sensors	Thickness, profile position, overlap/splice presence, radial runout, lateral runout, and sidewall-surface condition	Enabled in-line dimensional monitoring, guidance, inspection, and defect detection across tire-manufacturing steps

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Materials Availability Not applicable.

Data Availability The bibliometric dataset generated and analysed during the current study is openly available at Zenodo (DOI: [10.5281/zenodo.18506816](https://doi.org/10.5281/zenodo.18506816)).

Code Availability The Python scripts used for data processing, meta-data enrichment, and analysis are openly available at the same Zenodo repository (DOI: [10.5281/zenodo.18506816](https://doi.org/10.5281/zenodo.18506816)).

Declarations

Conflicts of Interest The authors declare that they have no competing interests.

Ethical Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

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