



LLM-driven automated literature review and taxonomy generation for powder metallurgy

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HIGHLIGHTS

- A novel two-tier LLM agent framework automates large-scale literature taxonomy.
- 26,254 powder metallurgy papers classified into 15 coherent categories.
- Reveals emerging research patterns and knowledge gaps in powder metallurgy.
- Iterative refinement achieves high confidence through semantic comparison.
- Generalizable methodology applicable across scientific disciplines.

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ABSTRACT

The exponential growth of scientific literature in powder metallurgy presents significant challenges for comprehensive knowledge synthesis. Traditional manual review methods are insufficient for processing large-scale corpora, while existing automated approaches often lack semantic depth and contextual interpretation. This paper introduces a novel framework employing Large Language Model (LLM) agents to automate literature review and taxonomic organization of powder metallurgy research. We analyze 26,254 papers through a structured two-tier methodology. The first tier performs stochastic sampling and iterative classification, generating preliminary topic clusters subsequently refined into coherent categories through agent-based reasoning. The second tier implements contextual comparison and cross-document reasoning, where each paper is analyzed alongside semantically similar studies with iterative refinement until classification confidence reaches a predetermined threshold. This context-aware comparative reasoning distinguishes the proposed framework from conventional single-pass LLM classification approaches. The framework organizes the powder metallurgy literature into 15 coherent categories, revealing emerging research trajectories and knowledge gaps across the field. Expert validation confirms classification reliability, with a 90% unanimous agreement rate and Fleiss' $\kappa = 0.93$. This work contributes methodological innovations in LLM-based scientific knowledge processing and domain-specific insights for powder metallurgy research, establishing a foundation for intelligent literature review systems across scientific disciplines.

1. Introduction

Powder metallurgy (PM) is a foundational technology in materials science and manufacturing that enables the production of near-net-shape components with high precision, reduced waste, and improved microstructural control [1]. PM techniques have found widespread application across automotive, aerospace, medical, and energy industries due

to their ability to process complex geometries and advanced material compositions. Recent decades have witnessed rapid expansion in PM research, driven by advances in additive manufacturing, computational alloy design, and novel sintering technologies. This growth has resulted in an exponential increase in published literature, creating substantial challenges for comprehensive knowledge synthesis and field analysis.

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Traditional literature review methods, including keyword-based searches, manual reading, and statistical bibliometric tools, are increasingly insufficient for processing such large-scale corpora. These approaches struggle to capture deeper semantic relationships, contextual relevance, and cross-domain insights essential for understanding complex material systems. Even advanced bibliometric tools like VOSviewer [2] and CiteSpace [3], while effective for citation network analysis and keyword co-occurrence mapping [4], operate primarily on explicit metadata and citation relationships rather than semantic content analysis. Such methods cannot discern implicit conceptual relationships within full-text content or identify subtle connections between research areas that may not be explicitly linked through citations or keywords. Consequently, synthesizing current knowledge and identifying substantive innovation pathways has become increasingly challenging.

Large Language Models (LLMs) such as GPT-4 and Claude have emerged as powerful tools for scientific text processing, demonstrating strong performance in domain-specific question answering, technical summarization, and code generation tasks [5,6]. However, current applications of LLMs in literature analysis are still limited. Most implementations focus on isolated tasks such as one-shot summarization, keyword tagging, or basic topic extraction [7], lacking the structured approaches necessary for comprehensive knowledge synthesis. These applications rarely incorporate domain-specific taxonomies or employ iterative, multi-document reasoning processes. Consequently, while LLMs show significant potential, they have yet to demonstrate the sophisticated analytical capabilities required for systematic literature synthesis in complex scientific domains.

Taxonomy learning, the process of organizing knowledge into structured categories, represents a fundamental component of literature synthesis. Traditional approaches have relied on rule-based systems and statistical clustering methods, while advanced developments have introduced topic modeling approaches and machine learning-based classification frameworks [8]. Nevertheless, these methods typically fail to capture domain-specific semantic relationships or facilitate meaningful cross-document reasoning. Recent investigations have begun exploring LLM-based taxonomy induction through iterative prompting strategies and chain-of-thought reasoning [9]. Although these approaches demonstrate potential for automated knowledge organization, their application to specialized technical domains such as materials science remains limited.

This paper presents a novel LLM agent-based framework for automated literature review and taxonomy generation in PM. Our method introduces a structured two-tier architecture that addresses current limitations in automated literature analysis. The first tier employs stochastic sampling and iterative classification to generate preliminary topic clusters, which are then refined into coherent categories through systematic agent-based refinement. The second tier conducts contextual comparison and cross-document reasoning, analyzing each paper alongside semantically related studies and iteratively refining the literature classification until confidence surpasses a defined threshold. The primary contributions of this work are:

- A structured two-tier LLM agent architecture for systematic literature analysis that enables scalable knowledge synthesis.
- A methodology that integrates iterative classification with semantic similarity mapping to generate meaningful domain-specific taxonomies.
- A comprehensive application of this framework to 26,254 PM papers, revealing previously unidentified research patterns and knowledge gaps.

The remainder of this paper proceeds as follows: Section 2 reviews related work in automated literature analysis and taxonomy learning. Section 3 details our methodological approach. Section 4 presents the statistical analysis of the PM research patterns. Section 5 presents

a thematic analysis of each category of PM research. Section 6 discusses system capabilities and limitations. Section 7 concludes with implications for future research directions.

2. Related work

2.1. Literature review on PM

Powder metallurgy has attracted extensive research attention due to its critical role in near-net-shape component manufacturing, enhanced material utilization, and advanced alloy development. The existing literature encompasses fundamental processing techniques including powder preparation, pressing, and sintering, as well as emerging technologies such as powder bed fusion (PBF) and metal matrix composites (MMC). Traditional PM reviews have predominantly focused on processing methodologies [10–12], industrial applications [13,14], material systems [15–18], and additive manufacturing integration [19,20]. These reviews typically rely on manual curation and domain expertise to synthesize knowledge across the field.

While such expert-driven reviews provide valuable domain insights, they face significant scalability constraints and cannot rapidly incorporate new literature to identify emerging research directions, whereas automated approaches can systematically process recent publications as they appear. Systematic taxonomic organization of PM knowledge remains largely underdeveloped, with most existing classification efforts relying on basic keyword frequency analysis or simple categorization schemes. These limited approaches struggle to accommodate the exponential growth in literature, lack sufficient semantic depth, and frequently fail to identify interdisciplinary connections or complex subfield distinctions that characterize modern PM research.

2.2. Automation in literature reviews

Traditional systematic literature reviews employ frameworks such as PRISMA [21] to enhance transparency and methodological rigor, yet remain fundamentally labor-intensive and limited in semantic analysis capabilities. Bibliometric visualization tools, including VOSviewer [2] and CiteSpace [3], support automated clustering and network analysis based on co-citation and keyword co-occurrence relationships. However, these approaches are designed primarily for structural analysis rather than semantic content understanding.

Recent developments have increasingly integrated artificial intelligence into automated review processes. Latent Dirichlet Allocation (LDA) [22] enables the extraction of thematic structures from large text corpora through statistical analysis of word distributions. Studies such as Hu et al. [23] have successfully applied LDA-based topic extraction for trend prediction in new energy vehicle literature, while Pavlinek and Podgorelec demonstrated improved semi-supervised classification by combining self-training with LDA topic modeling. These approaches excel at identifying prominent thematic patterns within large datasets [24].

More sophisticated approaches have begun incorporating advanced Natural Language Processing (NLP) techniques. BERTopic [25] utilizes transformer-based embeddings for enhanced topic modeling, with recent applications demonstrating its effectiveness in comprehensive literature analysis and thematic clustering [26,27], while Guedes and Silva fine-tuned transformer language models through contrastive learning to generate enhanced sentence-level embeddings from scientific abstracts, achieving improved clustering performance across computer science and medical domains [28]. While these approaches demonstrate substantial improvements in semantic understanding, they remain fundamentally single-pass systems that lack the capacity for iterative, multi-document reasoning and systematic comparative analysis. Current methods cannot engage in systematic refinement processes, perform cross-paper contextual reasoning, or dynamically adapt taxonomies through iterative agent-based analysis that incorporates domain-specific knowledge and comparative insights across large literature corpora.

2.3. Large language models in scientific workflows

Large Language Models have demonstrated strong capabilities in text summarization, question-answering, and information extraction for scientific texts [29]. Their contextual understanding capabilities surpass those of traditional NLP models, making them particularly suitable for automated literature comprehension and knowledge synthesis tasks.

Recent applications have demonstrated LLMs' effectiveness in scientific knowledge organization and systematic analysis. Cui et al. showed that LLMs can achieve effective cross-domain taxonomy alignment by embedding hierarchical nodes into semantic vector spaces, enabling accurate knowledge integration across domains [30]. Preiss et al. demonstrated that LLMs outperform manual methods in annotating scientific text clusters when provided with carefully designed prompts [31]. Li et al. developed an unsupervised two-stage LLM framework that converts biomedical literature into knowledge graphs containing verifiable statements and semantic embeddings [32]. These approaches illustrate LLMs' capacity for systematic reasoning and structured knowledge synthesis in scientific contexts.

Despite these advances, significant gaps remain in applying LLMs to deep classification tasks within specialized technical domains and in developing systematic approaches for semantic taxonomy generation. Most current implementations focus on summarization or basic clustering tasks, lacking multi-agent reasoning architectures or confidence-based refinement mechanisms. This study addresses these limitations by integrating systematic agent-based reasoning, comparative contextual analysis, and domain-specific taxonomy generation tailored for PM research.

3. Methodology

This section describes the development and implementation of a structured two-tier LLM agent framework for automated literature review and semantic taxonomy generation in powder metallurgy research. The framework overview is illustrated in Fig. 1. The LLM agent-based

methodology operates through three sequential stages. The first stage involves retrieving relevant powder metallurgy literature from Scopus and preprocessing through the removal of incomplete records, non-English entries, and papers from low-credibility venues. The second stage focuses on taxonomy generation, where preliminary label pools are produced through stochastic sampling and iterative classification, subsequently refined into a coherent categorical framework using systematic agent-based reasoning. The third stage performs literature classification by analyzing each paper within the context of semantically similar studies and assigning it to categories based on predetermined confidence thresholds. The second and third stages employ the two-tier agent architecture, and this systematic approach integrates systematic data processing with multi-agent reasoning to enable comprehensive semantic analysis of large-scale literature corpora.

3.1. Data collection and preprocessing

The first step is to build a reliable literature dataset for subsequent analysis by compiling relevant publications in the PM field and preparing a refined corpus for classification, as shown in Fig. 1(a). The literature dataset for this study was collected from Scopus, one of the largest and most comprehensive academic databases globally. Scopus was selected for its extensive cross-disciplinary coverage, rigorous indexing standards, and comprehensive metadata provision for each publication. The search strategy targeted literature related to powder metallurgy published from 1944 through June 2024. The search was conducted in Scopus using the exact phrase “**powder metallurgy**”, with double quotation marks applied to ensure that the two words were searched as a complete term rather than as separate keywords. The search was applied to three fields: title, abstract, and author keywords. A record was retrieved if the exact phrase appeared in at least one of these fields. No document-type restriction was applied during the initial retrieval stage. This strategy was used to capture the full range of powder metallurgy-related publications indexed in Scopus, including research

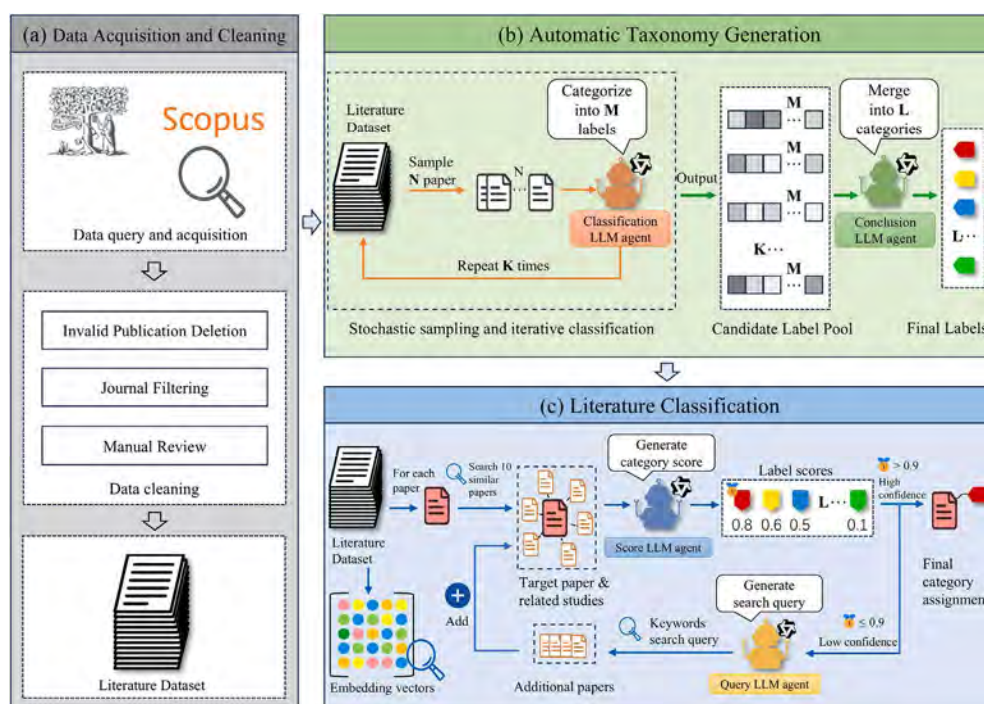


Fig. 1. Overview of the LLM agent framework. (a) Data acquisition and preprocessing: retrieval of powder metallurgy literature from Scopus, removal of incomplete records, non-English entries, and papers from low-credibility venues. (b) Automatic taxonomy generation: creating preliminary taxonomies through iterative sampling and classification, then refining them into a final categorical framework using agent-based reasoning. (c) Literature classification: assigning each paper to a category by comparing it with semantically similar studies and iterating until classification confidence meets predetermined thresholds.

articles, review papers, conference papers, short surveys, editorials, notes, and other document types. No language restriction was applied during the initial search. Language filtering was instead performed during the preprocessing stage. This initial search returned 59,173 records, including bibliographic information such as titles, abstracts, keywords, publication years, document types, source titles, citation counts, author information, and affiliation metadata.

The dataset underwent systematic multi-stage preprocessing to ensure quality and analytical reliability. In the first step, records were screened for textual completeness and metadata usability. Publications were removed if they lacked an abstract, title, publication year, source title, author information, or other bibliographic fields required for semantic analysis and statistical description. Records with clearly malformed metadata, duplicate entries within the exported Scopus file, or unusable abstract text were also excluded. This step reduced the dataset from 59,173 to 52,810 records.

In the second step, language filtering was applied. Non-English publications were removed based on the language information provided by Scopus and manual checking of records with unclear language labels. This step was necessary because the LLM-based classification and embedding models were applied to English technical text, and mixed-language inputs could reduce semantic consistency. After removing non-English records, 41,521 records remained.

In the third step, publication venue credibility was assessed. Records from low-credibility venues were excluded using recognized predatory journal lists and academic watchlists, including Beall's List [33] and related resources. Venue names from the Scopus export were matched against these lists, and uncertain cases were checked manually before removal. This step was undertaken to reduce the influence of unreliable publication sources and to improve the academic integrity of the corpus. After this filtering step, the dataset was reduced from 41,521 to 26,254 papers.

The final corpus therefore contained 26,254 English-language papers with complete abstracts, usable bibliographic metadata, and acceptable publication credibility. This refined dataset was used for the subsequent LLM-based taxonomy generation and literature classification.

3.2. Automatic taxonomy generation

The second step of our framework focuses on extracting thematic categories from the unlabeled corpus of powder metallurgy literature. This process follows a structured workflow that progresses from generating categories within individual samples to integrating these categories into a unified taxonomy, as illustrated in Fig. 1(b). This method utilizes the inductive capabilities of LLMs and the diversity of data to systematically construct a robust taxonomy from the bottom up.

The process first generates initial labels through local sampling and inductive reasoning. To ensure thematic diversity, we randomly select N abstracts from the entire powder metallurgy literature in each iteration. N is a key parameter that controls the amount of literature included in each sampling iteration, setting the context window for the language model to perform inductive reasoning. Smaller sample sizes reduce computational burden in each iteration, thereby improving processing efficiency while maintaining sampling diversity. These samples are presented to the LLM-based agent via a tailored prompt designed to simulate expert judgment. An example of the prompt used here is provided in Appendix A.1. The prompt positions the agent as a senior researcher in materials science and instructs it to categorize the selected papers into M meaningful categories based on research content, methods, and applications. Each identified category is accompanied by a concise, domain-appropriate label (such as "metal matrix composite") and a brief explanation of the grouping. This iterative classification process enables the LLM to recognize local semantic patterns and topic clusters that may not be immediately evident using statistical methods alone.

To capture the diversity of the field, the sampling and classification process is repeated K times. Each iteration generates a new set of

candidate labels from different segments of the corpus. The final result is a label pool containing $K \times M$ candidate labels. These labels reflect a wide range of terminology and conceptual boundaries. However, since each iteration operates on different literature samples, semantically similar concepts often receive different label formulations across iterations, resulting in semantic redundancy or inconsistency. For example, some labels are semantically very similar (such as "metal-based composite materials" and "composite materials and reinforcement materials") and differ in their degree of specificity. This label pool provides raw materials for refinement in the next stage.

The final stage resolves these inconsistencies by integrating candidate labels into a coherent high-quality taxonomy. This is achieved through the use of semantic merging based on LLM reasoning. The complete set of $K \times M$ candidate labels and their brief explanations are submitted to the LLM agent, accompanied by a new prompt designed to induce systematic thinking. An example of the prompt used here is provided in Appendix A.2. The agent is instructed to act as a taxonomy expert, merging overlapping or redundant categories into L mutually exclusive and well-defined labels. For each final label, the agent must provide a formal definition, a brief domain explanation, and examples of the original labels belonging to the new classification. This method utilizes the semantic understanding ability of the large language model to perform specialized taxonomy consolidation tasks.

Through these comprehensive strategies, the framework transforms dispersed local topics into a structured and scalable classification system. The final output is a set of optimized high-quality labels that cover the main research directions in the field of powder metallurgy. These labels serve as the categorical framework for the next step of contextual literature classification, where each document is analyzed within its semantic neighborhood to achieve precise and reliable classification.

3.3. Literature classification

While the second step constructs a taxonomy across the entire PM literature dataset, the third step classifies individual papers based on the predefined taxonomy. The goal is to assign each paper to the most appropriate category with high confidence, even when documents contain complex, interdisciplinary, or innovative content. To achieve this, we introduce a context-aware classification process driven by LLM agents, as illustrated in Fig. 1(c). The method iteratively enriches contextual information until confident classification is achieved.

Rather than analyzing each paper in isolation, the system leverages semantic context from related literature by retrieving 10 semantically similar papers from the corpus. For each target document, the title and abstract are encoded into dense embedding vectors using the Jina-Embedding-v3 model [34]. All documents in the corpus are similarly represented as vectors in the same embedding space. To identify the most relevant context, the similarity between the target document vector v_t and each candidate document vector v_i is computed using the inner product:

$$\text{similarity}(v_t, v_i) = v_t \cdot v_i \quad (1)$$

The inner product is a standard similarity measure in embedding-based retrieval, as it captures the degree of alignment between two vectors. Larger values indicate stronger semantic relatedness. The top 10 documents with the highest scores are selected as the nearest neighbors. These "neighboring" studies provide immediate research context, helping the model understand how the target paper relates to existing work in the field.

The target document and its neighboring abstracts are presented to the LLM agent, which evaluates how well the document fits within each predefined category from Section 3.2. Rather than forcing a hard assignment, the agent assigns a confidence score between 0 and 1 to each of the L categories, indicating the likelihood that the document belongs to that category. In this study, the framework uses a single-label classification

scheme, with a predefined confidence threshold serving as the acceptance criterion for category assignment. Each paper is assigned to the category with the highest confidence score once the threshold is met. This design was adopted because the primary purpose of the framework is to organize the literature according to each paper's dominant research theme, and assigning each paper to its most representative category helps maintain clear category boundaries and supports coherent thematic analysis.

The confidence threshold is set to 0.9 in this study. This value is used as a conservative acceptance criterion to ensure that only classifications with strong category-level evidence are accepted directly. If the model returns a confidence score above 0.9, the classification is accepted, and the highest-scoring category becomes the assigned label. The prompt used in this step is provided in [Appendix A.3](#).

When the confidence score does not reach the threshold, the classification is considered ambiguous. In this case, the system initiates an adaptive retrieval process. The LLM agent is asked to generate a concise search query of 5 to 10 words that captures the critical distinctions between the competing categories. This query targets technical terms, methods, or applications that can help disambiguate the classification. An example of the prompt is provided in [Appendix A.4](#).

The generated query is then executed using the same embedding-based similarity method to retrieve additional candidate papers from the corpus. These new documents are added to the target paper and its neighboring pool, and the expanded set is presented again to the LLM agent for re-evaluation. If the agent assigns a confidence score above the predefined threshold of 0.9, the process terminates, and the highest-scoring category is taken as the final assigned label. Otherwise, the cycle continues, with the model refining its retrieval and classification until the stopping criterion is satisfied. To prevent the system from entering an infinite loop, the maximum number of iterations is capped at five. If the process reaches the fifth iteration, the model is required to provide a final classification label regardless of the confidence level. In practice, however, the classification usually converges earlier, and no cases in this study required all five iterations.

The choice of 0.9 was determined empirically during method development. We compared several candidate thresholds, including 0.7, 0.8, 0.9, and 0.95, with powder metallurgy experts manually inspecting sampled classification results at each level. Lower thresholds such as 0.7 or 0.8 allowed more papers to be accepted in the first classification round, but increased the risk of premature assignment when semantic distinctions between categories were unclear, particularly for papers with overlapping research themes where the model had insufficient evidence to distinguish the dominant theme from secondary ones. Higher thresholds such as 0.95 substantially increased the number of iterative retrieval cycles while providing only marginal improvement in expert-inspected classification consistency. A threshold of 0.9 was therefore selected as a conservative acceptance criterion that balances classification reliability and computational efficiency: only classifications with strong category-level evidence are accepted directly, while uncertain cases are routed to the adaptive retrieval and re-evaluation process.

3.4. LLM model and hyperparameter selection

In this framework, the Qwen3-235B model [35] is selected as the core language model for all LLM agents. The choice of the Qwen model is based on a few practical considerations. First, the model is globally accessible, which supports reproducibility and scalability across different research environments, while some alternatives may face regional restrictions. Second, it provides a relatively affordable option for processing large volumes of literature, which makes it suitable for studies of this scale. However, the proposed framework is adaptive to other LLM models as well. As more advanced or stable models become available, the framework can accommodate them by replacing the current LLM component, ensuring long-term practicality and sustainability.

The LLM agent framework in [Section 3.2](#) relies on several key hyperparameters that directly influence the quality and stability of the resulting taxonomy. These include:

- **N** – the number of documents sampled in each iteration,
- **M** – the number of categories generated in each iteration,
- **K** – the total number of sampling iterations, and
- **L** – the number of final categories in the taxonomy.

To determine suitable values, we conduct controlled experiments using a random sample of the papers extracted from the full PM literature dataset. The framework is executed 157 times with different combinations of **N**, **M**, **K**, and **L**. For each run, the resulting category labels are evaluated using embedding-based similarity metrics to ensure both semantic quality and consistency.

All candidate labels generated during the taxonomy generation process are first transformed into semantic embedding vectors using Jina-Embeddings-v3 [34]. These high-dimensional embeddings capture the contextual meaning of each label and allow for quantitative comparison across experiments. We then evaluate the outputs using three complementary criteria: cohesion, separation, and stability.

Cohesion describes the internal semantic compactness of each final category. It is calculated as the average cosine similarity between all original sub-labels grouped under the same final category. The cohesion score for category l is expressed in Eq. (2), where C_l is a cluster with n_l sub-labels, and z_i and z_j are embedding vectors of the sub-labels. The global cohesion is the weighted average across all categories, as expressed in Eq. (3). Higher cohesion values imply that the subtopics within a category share a strong semantic similarity.

$$Cohesion(C_l) = \frac{2}{n_l(n_l - 1)} \sum_{1 \leq i < j \leq n_l} \cos(z_i, z_j) \quad (2)$$

$$Cohesion = \frac{1}{\sum_{l=1}^L n_l} \sum_{l=1}^L n_l \cdot Cohesion(C_l) \quad (3)$$

Separation, on the other hand, measures how distinct the categories are from each other. It is computed as the average pairwise distance between the centroids of different categories in the embedding space, as expressed in Eq. (4), where μ_l is the centroid of the sub-label cluster C_l . High separation values indicate that the taxonomy successfully produces categories that are semantically well-differentiated.

$$\mu_l = \frac{1}{n_l} \sum_{i=1}^{n_l} z_i \quad (4)$$

$$Separation = \frac{2}{L(L-1)} \sum_{1 \leq i < j \leq L} \|\mu_i - \mu_j\|_2$$

Stability measures how consistent the framework's outputs are when run multiple times with the same parameters. We assess this in two ways. The first measure, Stab-Jaccard, calculates the textual overlap of the final labels from two independent runs using the Jaccard similarity coefficient. This metric compares the label sets generated by two independent runs of the algorithm and quantifies their literal overlap. As shown in Eq. (5), where L_A and L_B represent the sets of labels obtained in two runs.

$$Stab_{jaccard}(L_A, L_B) = \frac{|L_A \cap L_B|}{|L_A \cup L_B|} \quad (5)$$

The second, Stab-Embed, evaluates the semantic overlap between results from different runs by aligning clusters across runs using centroid embeddings and measuring their similarity. Let run A produce centroids $\{\mu_1^A, \dots, \mu_L^A\}$ and run B produce centroids $\{\mu_1^B, \dots, \mu_L^B\}$, the cosine similarity between each pair of centroids is calculated as:

$$S_{ij} = \cos(\mu_i^A, \mu_j^B) \quad (6)$$

Then we use the Hungarian algorithm to solve the optimal assignment problem to maximize total similarity. If π^* is the optimal mapping,

Table 1
Top 8 best hyperparameter combination evaluation experiment results.

N	M	K	L	Cohesion	Separation	Stab-Jaccard	Stab-Embed
100	5	5	15	0.8226	0.307	0.1135	0.8099
200	5	5	15	0.8216	0.3485	0.1562	0.8001
100	10	5	15	0.7822	0.3738	0.0813	0.7912
150	10	5	15	0.7791	0.3657	0.0718	0.7964
100	5	5	10	0.7753	0.274	0.0374	0.763
200	5	5	10	0.7735	0.3214	0.0399	0.7463
50	5	5	15	0.7668	0.3496	0.035	0.7824
150	5	5	10	0.761	0.318	0.0105	0.7414

Stab-Embed is expressed as:

$$Stab_{Embed} = \frac{1}{L} \sum_{i=1}^L S_{i,\pi^*}(i) \quad (7)$$

High values in both metrics indicate that the taxonomy remains reliable across repeated executions.

Together, these metrics provide a balanced view of taxonomy quality, capturing both the internal consistency and the external distinctiveness of the generated categories, as well as the reproducibility of the framework's outputs.

A representative portion of the experimental results is shown in Table 1. From these observations, we selected $L = 15$ for the final taxonomy. This value provides broad thematic coverage without fragmenting the categories into overly specific or redundant groups. The parameters $N = 200$, $M = 5$, and $K = 5$ were chosen to achieve high stability and balanced cohesion–separation scores while keeping the process computationally efficient. This combination ensures that the final taxonomy is semantically robust, well-differentiated, and reproducible across repeated runs of the framework.

3.5. Expert validation of classification results

To assess the reliability of the LLM-based classification results beyond automated metrics, a formal expert validation study was conducted with domain experts from the China Powder Metallurgy Alliance (CPMA). Five specialists participated in the evaluation, covering diverse subfields of powder metallurgy including sintering and processing technologies, metallic alloys and superalloys, metal matrix composites, ceramic materials, and industrial applications. The panel comprised professors and senior engineers from both academic institutions and industrial organizations.

Sampling. A stratified random sample of 150 papers was drawn from the classified corpus, with 10 papers selected per category through stratified random sampling.

Evaluation protocol. Each paper was independently evaluated by three experts, assigned based on their domain specialization. Experts performed blind evaluations: each expert received the paper title, abstract, and standardized definitions of all 15 categories, but was not informed of the LLM-assigned category or confidence score. Classification agreement was defined under a strict unanimous criterion: a paper was considered correctly classified if all three assigned experts independently selected the same category as the LLM.

Results. The overall agreement rate between LLM classification and expert judgment was 90% (135 out of 150 papers) under the unanimous agreement criterion. When a majority criterion (≥ 2 of 3 experts) was applied, the agreement rate increased to 98% (147 out of 150 papers), indicating that the LLM-assigned categories were consistent with expert consensus in the large majority of cases. The Fleiss' kappa coefficient computed across all 150 papers (3 raters per paper) was $\kappa = 0.93$, indicating almost perfect inter-rater agreement among the expert panel according to the Landis and Koch scale [36].

Category-level agreement rates varied in a pattern consistent with the semantic structure of the taxonomy. Four categories achieved unanimous agreement rates of 100%: Composite Reinforcement

Mechanisms, Metal Matrix Composites, Performance Testing & Evaluation, and Material Processing & Forming. These categories share well-defined and distinct thematic scopes, making them straightforward for expert identification. Eight categories achieved unanimous agreement rates of 90%, reflecting clear but occasionally overlapping thematic boundaries. Moderate agreement rates were observed for Novel Material Development (80%) and Material Characterization & Analysis (80%), reflecting their comparatively broader thematic boundaries. The lowest unanimous agreement rate was observed for Fundamental & Interdisciplinary (70%), a category characterized by the broadest and most heterogeneous thematic scope among the 15 categories, encompassing topics ranging from diffusion kinetics and thermodynamics to industrial informatics and workforce development. Notably, expert disagreements across all categories were predominantly distributed between adjacent semantically related categories rather than dispersed across unrelated ones, reflecting the inherent boundary ambiguity between certain category pairs in the taxonomy.

Representative boundary case. To discuss the inherent challenges of classifying papers with strong interdisciplinary content, we present a boundary case from the Fundamental & Interdisciplinary category, which recorded the lowest unanimous agreement rate in the validation study. The paper, titled “Can GPT Embeddings Enhance Visual Exploration of Literature Datasets? A Case Study on Isostatic Pressing Research” [27], investigates whether GPT-based text embeddings can improve the visual exploration of specialized literature datasets, using isostatic pressing as the application domain. The LLM classified this paper into Fundamental & Interdisciplinary with a confidence score of 0.92, reflecting its cross-disciplinary nature: the primary contribution lies in the application of generative pre-trained transformer embeddings to literature visualization, a methodology that connects fundamental AI techniques with powder metallurgy knowledge discovery rather than advancing isostatic pressing technology itself.

Of the three assigned experts, two independently selected Fundamental & Interdisciplinary as the primary category, consistent with the LLM classification. However, one expert assigned the paper to Material Processing & Forming, reasoning that the subject domain of the study, isostatic pressing, is a core powder metallurgy processing technique, and that the paper's practical value resides in its contribution to the HIP research community. This disagreement illustrates a recurring challenge in single-label classification of interdisciplinary work: whether a paper is categorized according to its methodological contribution or its application domain can lead to genuinely defensible but divergent classifications. Such boundary cases are inherent to the cross-disciplinary nature of modern powder metallurgy research, and are discussed further in Section 6.

4. Statistical analysis

This section provides a quantitative overview of the global research landscape in powder metallurgy, examining publication patterns, impact metrics, keyword trends, and geographic distribution. The analysis aims to identify long-term developments, highlight influential contributors, and reveal shifts in thematic focus over time.

This study analyzed a total of 26,254 publications related to powder metallurgy, covering a span of 81 years, from 1944 to 2024. All publications were retrieved from the Scopus database based on the defined search criteria described in Section 3.1. The dataset includes contributions from 55,205 unique authors and 33,899 institutions, with an average publication rate of 324.1 papers per year, and an average citation count of 21.57 per paper.

Fig. 2 presents the distribution of publication types and their associated citation characteristics. The corpus includes a wide range of document types, with research articles accounting for the majority at 96.2%. Review papers account for only 2.0%, while the remaining share includes short surveys, editorial notes, correspondence, and conference papers. Despite their smaller proportion, review articles demonstrate

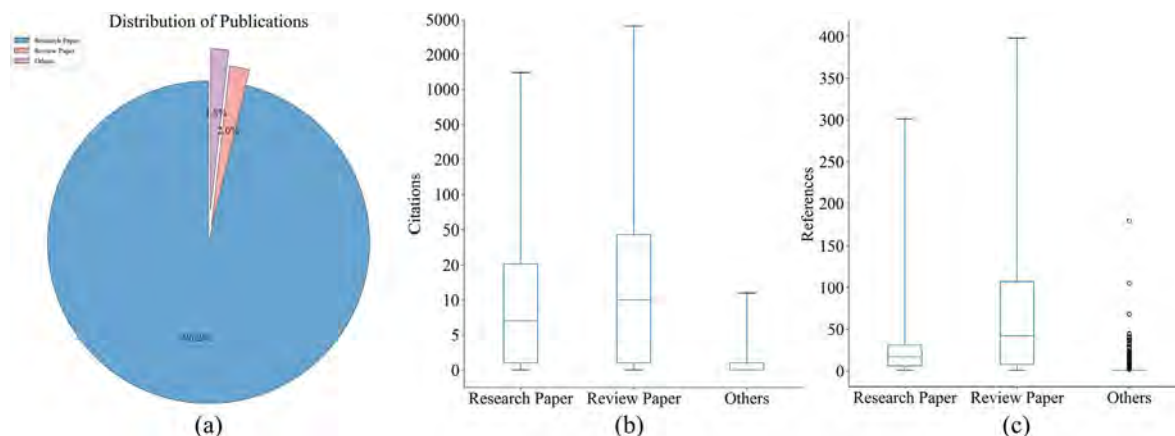


Fig. 2. (a) Distribution of publications by type. (b) Citation counts for each publication type. (c) Reference counts for each publication type.

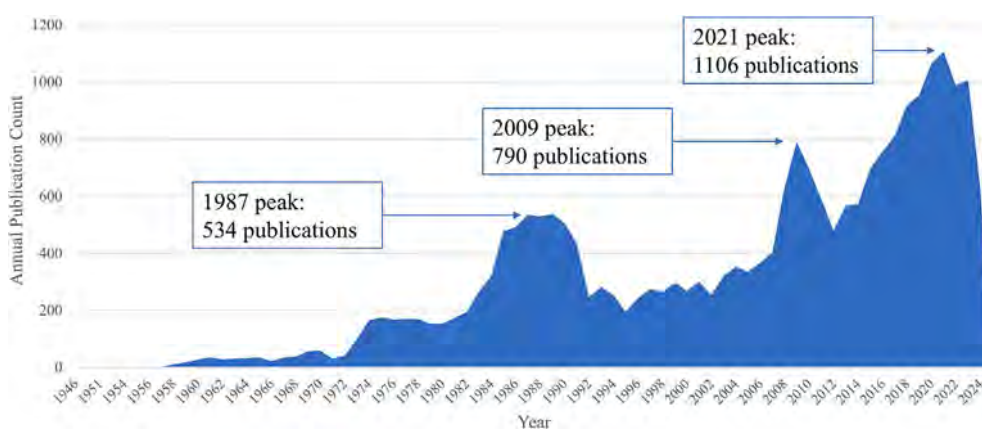


Fig. 3. Annual publication trends in powder metallurgy, highlighting peaks in 1987, 2009, and 2021.

higher average citation counts and reference more sources compared to research papers, suggesting their central role in consolidating and synthesizing knowledge within the field.

Analysis of annual publication trends reveals a steady increase in publication numbers over the observation period, with three notable peaks in 1987, 2009, and 2021, as illustrated in Fig. 3. Thematic analysis of publications during these peak periods indicates that the surge around 1987 was driven by advances in rapid prototyping, ceramic and composite processing, nanocrystalline materials, and mechanical alloying, alongside improvements in high-temperature alloys and composite performance. The 2009 peak corresponded to the emergence of advanced sintering techniques, additive manufacturing methods such as selective laser melting (SLM), graphene synthesis, and the growing use of nanomaterials, titanium alloys, and biodegradable metals in engineering and biomedical applications. The most recent peak, around 2021, reflects innovations in MAX phase and MXene synthesis, binder jet 3D printing, spark plasma sintering (SPS) processing, and the expansion of biomedical applications involving titanium, magnesium, and zinc-based materials, as well as multifunctional composite systems.

Analysis of publishing sources reveals that a concentrated group of journals contributes a substantial portion of the literature. Fig. 4 presents the statistics of the top 10 journals by publication volume. *Powder Metallurgy and Metal Ceramics* leads the list with over 2000 publications. Other major contributors include *Powder Metallurgy*, *Metal Powder Report*, *Materials Science and Engineering: A*, and *Journal of Alloys and Compounds*, each publishing over 1000 documents. In terms of impact,

Journal of Alloys and Compounds, *Materials & Design*, and *Materials Science and Engineering: A* demonstrate the highest average citation counts, indicating their influential role in advancing the field.

Tables 2 and 3 present the 10 most cited research papers and the top 10 most cited review papers in the PM field. Among research articles, the highest-cited studies focus on particle-reinforced aluminum and magnesium alloys [37], demonstrating the enduring importance of composite materials in PM research. Other high-impact papers include studies on performance optimization in high-strength alloys [38–40], novel composite systems [41–43], breakthroughs in novel material synthesis [44], and innovative processing techniques [45,46]. Among review articles, the most influential works are dominated by process-centered topics, particularly in metal additive manufacturing [47,48]. Other high-impact reviews include alternative sintering technologies such as microwave sintering [49], and spark plasma sintering [50]. Reviews focusing on biomedical applications such as titanium alloys [51,52] demonstrate the growing intersection between PM and healthcare technologies.

Fig. 5 highlights the results of the keyword frequency analysis. Fig. 5(a) illustrates the evolution of the top 10 keyword frequencies over time. The bubble's size represents the keywords' frequency. Early publications frequently employ terms such as “mechanical properties”, “microstructure”, and “sintering”, indicating a focus on foundational research areas of the field. More recent decades show a growing focus on keywords such as “metal matrix composition” and “spark plasma sintering”, indicating a shift towards advanced materials, novel processing technologies, and application-oriented studies. The keyword cloud in Fig. 5(b) further illustrates the diversity of research directions, ranging

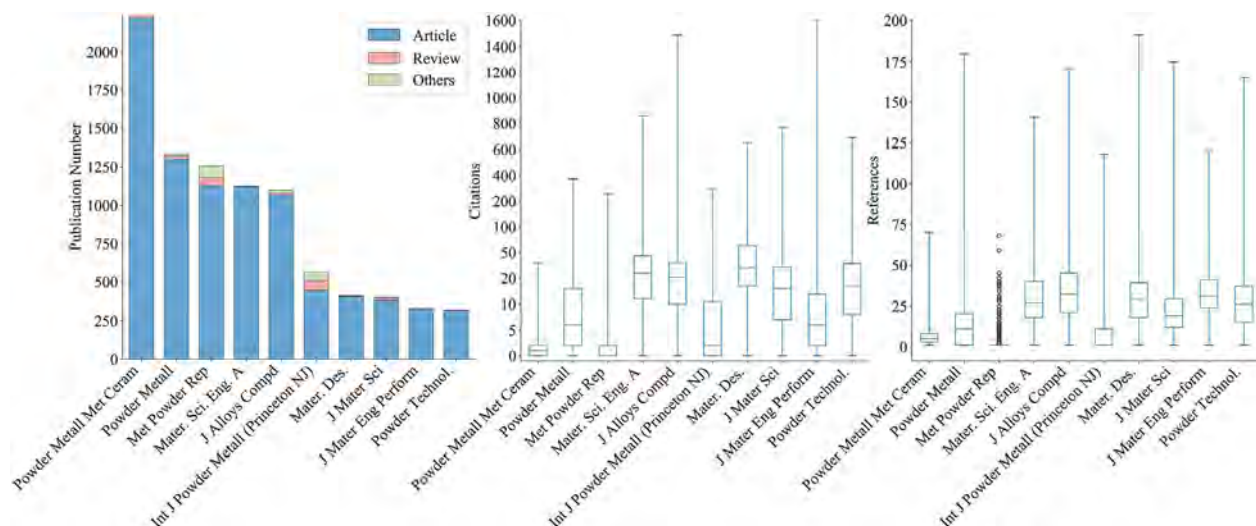


Fig. 4. Top 10 journals by publication count in powder metallurgy.

Table 2

Top 10 most cited research papers in the powder metallurgy field.

No.	Title	First Author (year)	Total Citation	Citation per year
1	Particle reinforced aluminum and magnesium matrix composites [37]	Lloyd, D. J., 1994	2281	73.58
2	Heat treatment of Ti6Al4V produced by Selective Laser Melting: Microstructure and mechanical properties [38]	Vrancken, B., 2012	1485	114.23
3	Rapidly solidified powder metallurgy Mg97Zn1Y2 Alloys with excellent tensile yield strength above 600 MPa [39]	Kawamura, Y., 2001	1120	46.67
4	On the strength of discontinuous silicon carbide reinforced aluminum composites [42]	Nardone, V. C., 1986	1039	26.64
5	Element replacement approach by reaction with Lewis acidic molten salts to synthesize nanolaminated MAX phases and MXenes [44]	Li, M., 2019	892	148.67
6	Design, processing, microstructure, properties, and applications of advanced intermetallic TiAl alloys [40]	Clemens, H., 2013	890	74.17
7	The production and application of metal matrix composite materials [41]	Kaczmar, J. W., 2000	870	34.80
8	Full sintering of powdered-metal bodies in a microwave field [45]	Roy, R., 1999	865	33.27
9	Processing techniques for functionally graded materials [46]	Kieback, B., 2003	858	39.00
10	Reinforcement with graphene nanosheets in aluminum matrix composites [43]	Wang, J., 2012	821	63.15

from alloy development to composite reinforcement and novel sintering technologies.

Fig. 6 presents the top 10 most prolific authors and their publication trends over time. The results indicate that leadership in powder metallurgy research spans multiple generations. In the 1970s and 1980s, the leading authors in PM research were *I. D. Radomysel'skii* and *Valeriy V. Skorokhod* from the National Academy of Sciences of the Ukrainian SSR. They made fundamental contributions to PM, including developing high-strength ferrous and alloyed materials and advancing the theory of sintering, creep, and mechanical behavior of powder materials. In

Table 3

Top 10 most cited review papers in the powder metallurgy field.

No.	Title	First Author (year)	Total Citation	Citation per year
1	Metal additive manufacturing: a review [47]	Frazier, W. E., 2014	4436	403.27
2	A review on selective laser sintering/melting (SLS/SLM) of aluminum alloy powders: Processing, microstructure, and properties [48]	Olakanmi, E. O., 2015	1373	137.30
3	Microwave versus conventional sintering: A review of fundamentals, advantages and applications [49]	Oghbaei, M., 2010	1029	68.60
4	Manufacturing and processing of NiTi implants: A review [52]	Elahinia, M. H., 2012	847	65.15
5	A review on biomedical titanium alloys: recent progress and prospect [51]	Zhang, L., 2019	751	125.17
6	Amorphization by ball milling. A review [53]	Weeber, A. W., 1988	615	16.62
7	Review and extension of normal force models for the discrete element method [54]	Krugger-Emden, H., 2007	437	24.28
8	Surface modification by electrical discharge machining: A review [55]	Kumar, S., 2009	413	25.81
9	A review of multi-physical fields induced phenomena and effects in spark plasma sintering: Fundamentals and applications [50]	Hu, Z., 2020	351	70.20
10	High temperature fatigue of nickel-base superalloys – A review with special emphasis on deformation modes and oxidation [56]	Pineau, A., 2009	350	21.88

the 1990s and 2000s, *Randall M. German* of San Diego State University emerged as a leading researcher, recognized for his contributions to advancing the understanding of sintering and powder injection molding processes. In the 21st century, the PM field has seen a global distribution of leading authors, including *Katsuyoshi Kondoh* (Osaka University, Japan), *Pavel Novák* (University of Chemistry and Technology, Czech Republic), *Yong Liu* (Central South University, China) and *Xuanhui Qu* (University of Science and Technology Beijing, China).

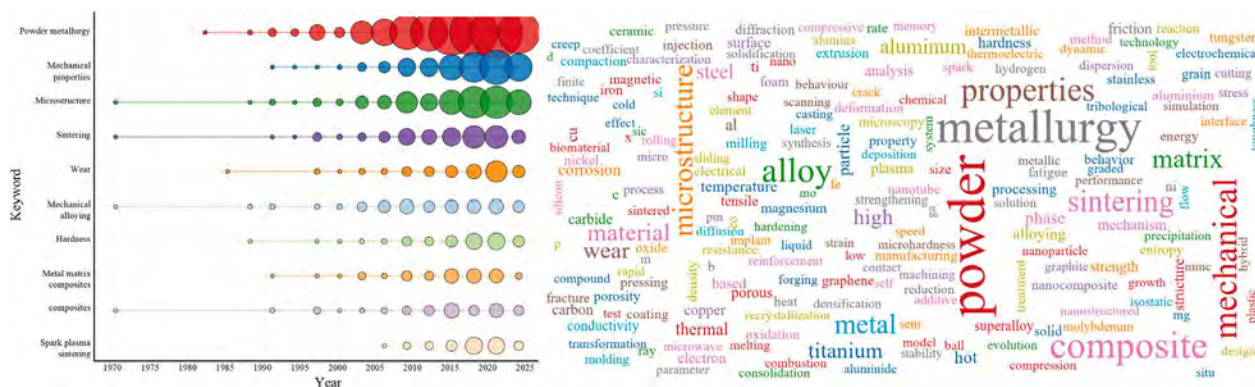


Fig. 5. (a) Evolution of the top 10 keywords over time (sampled every 3 years). The bubble's size represents the keywords' frequency. (b) Keyword cloud for the powder metallurgy literature.

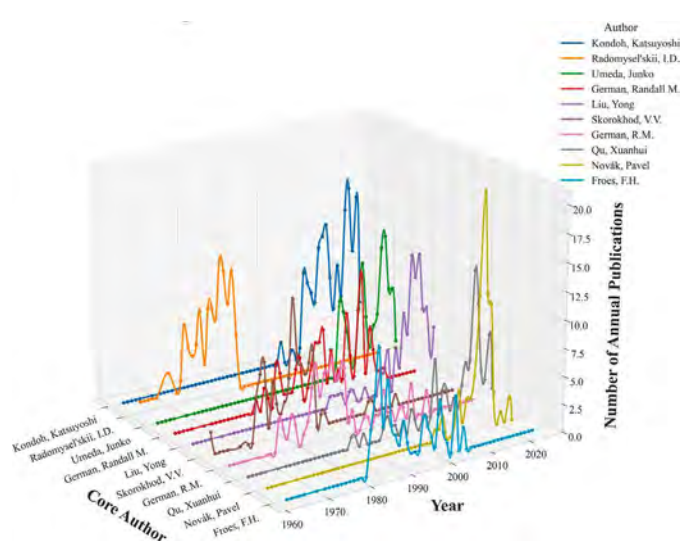


Fig. 6. Top 10 core authors in powder metallurgy and their annual publication trends.

The global distribution of research activity is shown in Fig. 7. Historically, Ukraine played a significant role, particularly through the Academy of Sciences of the Ukrainian SSR. This institution published over 500 papers in PM between 1970 and 1990, contributing significantly to fundamental theories and basic processing techniques. In recent years, Chinese institutions have assumed leadership, with major contributions from institutions such as Central South University, Harbin Institute of Technology, and the University of Science and Technology Beijing, among others. Major research universities and national laboratories currently dominate the global research landscape.

5. Thematic analysis

This section examines the structure of powder metallurgy research by organizing the literature into a coherent taxonomy and exploring the key themes within each category. Fig. 8 illustrates the 15-category taxonomy generated by the proposed LLM agent-based framework. The taxonomy covers the breadth and depth of research in powder metallurgy and its related materials science domains.

These categories provide a structured representation of the current state of the field. Based on the taxonomy similarity, the 15 categories can be further clustered into four groups. We begin with an overview of each category and its associated topics to provide an overall perspective

on the research landscape. This is followed by a more detailed analysis, where the LLM agent examines the complete set of papers in the category, highlights recent representative studies, and identifies the key challenges and application areas within each category.

The first group includes categories that focus on material classes and types. Category 1 focuses on **Ceramics & Composites**. This category focuses on the synthesis of advanced ceramics and ceramic composites, including nitride/carbide ceramics, alumina/zirconia systems, ceramic-matrix composites, and cermets such as WC-Co. Research emphasizes improving hardness and strength while enhancing toughness, aging resistance, and corrosion resistance. High-entropy ceramics, nanoparticle reinforcement, and thermodynamic design strategies are prominent approaches. Category 2 focuses on **Metallic Materials & Alloys**, including high-entropy alloys, titanium alloys, amorphous alloys, and superalloys. This category addresses property optimization through alloying, heat treatment, and advanced forming processes. Key challenges involve balancing mechanical performance with cost efficiency and mitigating brittleness under extreme conditions. Category 3 involves **Nanomaterials & Advanced Materials**. This category includes nanocrystalline materials, quantum dots, nanopowders, and graphene-based 2D materials. Research explores processing-microstructure-property links at the nanoscale, addressing challenges in controlling grain stability and harnessing functional properties for catalysis, energy storage, and structural applications. Category 4 involves **Metal Matrix Composites**. This category highlights SiC/Al composites, Carbon Nanotube (CNT)-reinforced metals, in-situ composites, and diamond/Cu composites. The emphasis is on tailoring microstructures for high strength, wear resistance, thermal conductivity, and lightweight performance. Together, these categories define the core material groups in PM research, where composition and structure fundamentally shape processing routes and performance potential.

Group 2 includes categories related to methods and mechanisms for creating and enhancing materials. Category 5 is **Material Synthesis & Preparation**, including mechanical alloying, powder atomization, additive manufacturing, and spark plasma sintering. This category addresses methods to produce and refine powders and bulk materials with tailored structures and properties. Category 6 focuses on **Material Processing & Forming**. This category investigates powder injection molding, rolling/forging, hot isostatic pressing, and hot/cold pressing. The focus is on processing–microstructure–property optimization, defect control, and the adaptation of advanced forming technologies. Category 7 involves **Composite Reinforcement Mechanisms**, including grain refinement, load transfer, dispersion strengthening, and interfacial reaction strategies. It focuses on optimizing the dispersion and bonding of reinforcements such as CNTs, graphene, and SiC to achieve synergistic strengthening effects. Together, these categories directly relate to

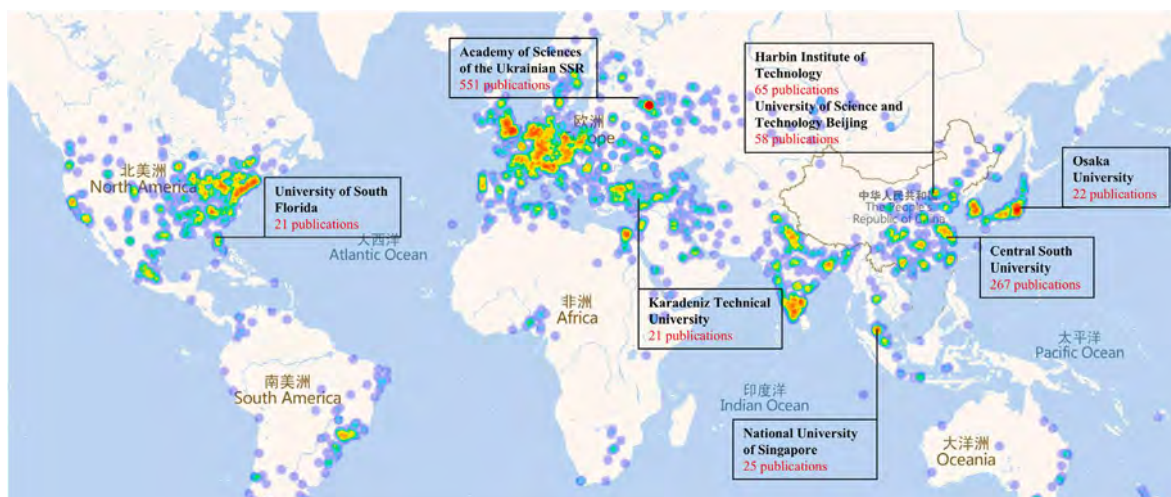


Fig. 7. Geographical distribution heatmap of top research institutions in powder metallurgy.



Fig. 8. Systematic classification of powder metallurgy research, organized into 15 main categories.

manufacturing and processing techniques, from powder preparation to forming and strengthening methods.

Group 3 includes categories that focus on understanding and linking material structures to their performance. Category 8 is related to **Properties & Microstructures**. This category links microstructural features such as defects, phase transformations, and grain size effects to mechanical performance. Studies employ advanced manufacturing methods alongside Scanning Electron Microscope (SEM), Transmission Electron Microscope (TEM), and X-ray Diffraction (XRD) analysis to elucidate structure–property relationships and guide property enhancement. Category 9 focuses on **Material Characterization & Analysis**. This category aims to characterize structural, morphological, and compositional attributes, focusing on experimental techniques such as thermal analysis, XRD, SEM, and TEM. The research addresses precision, efficiency, and applicability to complex systems, with an increasing emphasis on non-destructive testing. Category 10 involves **Performance**

Testing & Evaluation. The study here examines creep, fatigue, mechanical behavior, and tribological properties under diverse environmental conditions. A key emphasis lies in developing accurate and rapid testing methods, including machine vision and hyperspectral imaging, for both quality control and performance prediction. Category 11 is **Material Design & Modeling**. This category develops computational and analytical tools to predict material behavior and optimize design. It covers topics such as molecular dynamics, finite element analysis (FEA), CALPHAD, and first-principles calculations. Together, these categories deal with measuring, analyzing, and predicting how structure affects behavior, using experimental, analytical, and computational tools.

Group 4 includes categories that focus on application-specific performance and cross-disciplinary material development. Category 12 is **Novel Material Development**, including self-healing materials, high-entropy ceramics, biodegradable metals, and metamaterials. This category targets application-driven materials design. Efforts focus on integrating strength, ductility, corrosion resistance, and functional properties, especially for biomedical, catalytic, and environmental uses. Category 13 focuses on **Functional Materials & Applications**. This category includes thermoelectric materials, shape memory alloys, porous materials, and magnetic materials. Research integrates microstructural engineering with functional performance optimization for applications ranging from electronics to structural components. Category 14 involves **High-Temp & Special Environment**. This category includes materials such as nuclear materials, oxidation-resistant alloys, thermal barrier coatings, and refractory metals. Studies address stability, creep resistance, and oxidation behavior under extreme conditions. Category 15 is related to **Fundamental & Interdisciplinary**. Including topics such as diffusion kinetics, energy storage materials, thermodynamics, and biomaterials, this category connects fundamental materials science with cross-disciplinary applications in energy, environment, and healthcare. Overall, these categories target materials for specific environments or functions, integrating insights from multiple disciplines, including energy, biomedical, and extreme-condition applications.

Table 4 summarizes the distribution of publications and citations across research categories. The results show that research activity in powder metallurgy is heavily concentrated in four areas: **Metal Matrix Composites**, **Material Synthesis & Preparation**, **Material Processing & Forming**, and **Metallic Materials & Alloys**. Together, these categories account for nearly 80% of the total literature, indicating their central role in driving the field's development. The dominance of these areas indicates that most research efforts have focused on advancing core processing technologies and developing structural materials with

Table 4
Distribution of publications and citations across research categories in PM.

No.	Category	Total paper Count	Percentage	Total Citation	Average Citation
1	Metal Matrix Composites	6018	22.93%	153,775	25.55
2	Material Synthesis & Preparation	5127	19.53%	90,615	17.67
3	Material Processing & Forming	4920	18.74%	76,526	15.55
4	Metallic Materials & Alloys	4827	18.39%	85,322	17.68
5	Properties & Microstructures	1280	4.88%	24,334	19.01
6	Nanomaterials & Advanced Materials	752	2.86%	22,595	30.05
7	Material Design & Modeling	612	2.33%	14,662	23.96
8	Ceramics & Composites	604	2.30%	12,281	20.33
9	Functional Materials & Applications	520	1.98%	13,750	26.44
10	Material Characterization & Analysis	474	1.81%	6539	13.80
11	High-Temp & Special Environment	416	1.58%	9983	24.00
12	Novel Material Development	398	1.51%	9298	23.36
13	Performance Testing & Evaluation	164	0.62%	2217	13.52
14	Composite Reinforcement Mechanisms	74	0.28%	3189	43.09
15	Fundamental & Interdisciplinary	68	0.26%	1656	24.35

improved properties. This includes continuous innovation in powder production, sintering, and consolidation methods, as well as sustained progress in alloy design and composite development. **Composite Reinforcement Mechanisms** has the highest average citation count of all categories, at 43.09 citations per paper, despite a relatively small total number of papers. This demonstrates a broad interest in fundamental research on interfacial strengthening and load-transfer effects that could go beyond PM into the fields of composite science and nanotechnology. Similarly, **Nanomaterials & Advanced Materials** also show a high average citation, indicating the global interest in nanostructured systems.

Fig. 9 illustrates the yearly distribution of publications across the 15 identified research categories. In the early stage, **Material Processing**

& **Forming, Metallic Materials & Alloys, and Material Synthesis & Preparation** are the dominant categories. This early focus suggests that foundational work in processing routes and alloy development laid the groundwork for a variety of subsequent studies. From the 1980s to the 2000s, there was a steady increase in publication counts across most categories, with particularly strong growth in **Material Processing & Forming, Nanomaterials & Advanced Materials, Properties & Microstructure, and Ceramics & Composites**. This period corresponds to the global expansion of PM manufacturing and the integration of new sintering processes, advanced materials, and composite technologies into industrial practice. **Metal Matrix Composites** showed a significant surge after 2010, reflecting the increasing research interest in developing lightweight, high-strength materials using advanced composite reinforcement techniques. **Metallic Materials & Alloys** also experienced strong growth during this period, indicating continued investment in advanced alloy development.

Throughout history, the most notable change is the shift from process and alloy-focused research during 1970–2000 to composite-focused research in the 2011–2020 decade. This change highlights a broader transition in PM from process optimization to performance-driven material design, made possible by more mature manufacturing techniques and the adoption of advanced characterization methods.

5.1. Group 1: Material classes and types

The first group focuses on research that is organized around the type of material system studied in powder metallurgy. It includes ceramics and ceramic-based composites, metallic alloys, nanomaterials, and metal matrix composites. Fig. 10 presents the four categories in this group, with each category also including closely related subtopics that reflect its most relevant research themes. The central theme is to understand how different material classes can be designed, tailored, and optimized for performance.

Research in **Ceramics and Composites** primarily focuses on the synthesis, microstructure, and properties of advanced ceramic-based materials, including high-entropy ceramics, cermets, and composite ceramics. The main goal is to enhance key mechanical properties such as hardness, fracture toughness, and wear resistance, while addressing persistent challenges like low-temperature degradation (LTD) and corrosion. For example, Chen et al. developed high-entropy ceramic-based cermets in the (Ti, W, Mo, Nb, Ta)(C_{0.78}, N_{0.22}) systems. These materials integrate the high-entropy effect to lower synthesis temperatures while maintaining a balance between hardness and fracture toughness [57].

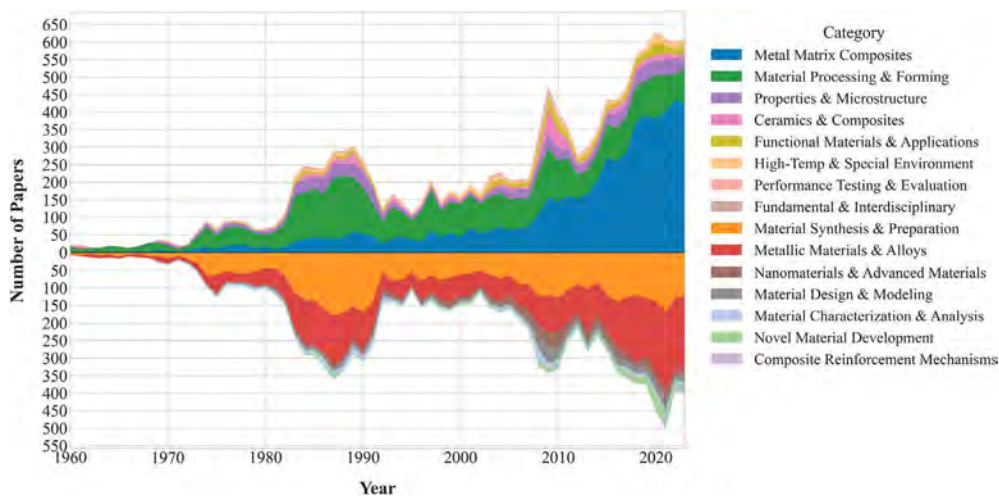


Fig. 9. Stacked area graph showing the annual evolution of publications per category from 1960 to 2023. The first half of the categories is displayed at the top, and the second half is displayed at the bottom for clarity.

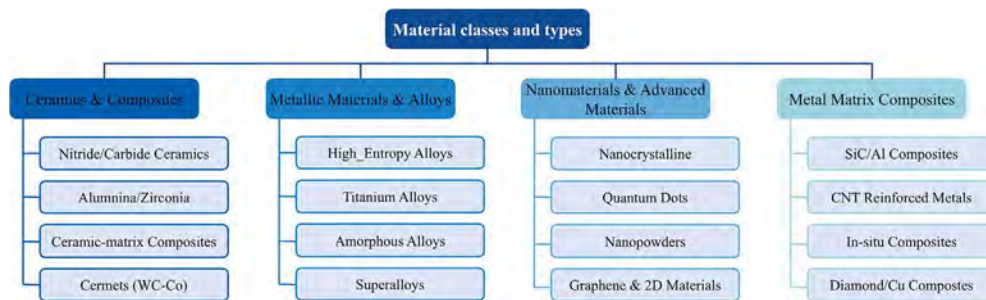


Fig. 10. Taxonomic structure of material classes and types group. Each of the four categories (Ceramics & Composites, Metallic Materials & Alloys, Nanomaterials & Advanced Materials, and Metal Matrix Composites) contains four representative subtopics.

Another major focus is on zirconia-based ceramics, particularly cation-stabilized systems designed to address LTD. Zhang et al. study on stabilizing zirconia demonstrates how cation doping can improve resistance to LTD while preserving mechanical reliability [58]. Reinforcement through particulate and intragranular dispersion is also a common strategy to increase toughness and wear resistance. Composites such as $\text{Al}_2\text{O}_3/\text{SiC}$ and $\text{ZrO}_2\text{-SiC/MoSi}_2$ utilize ultrafine particle addition to promote grain refinement and suppress crack propagation [59,60]. Studies have also explored MAX phase ceramics like Ti_3AlC_2 . The incorporation of elements such as silicon into the Ti–Al–C system modified both the microstructure and the fracture mechanism, resulting in increased toughness and oxidation resistance [61]. Additionally, Ti(C,N)-based cermets have attracted attention for their mechanical strength, corrosion resistance, and tribological performance. Many studies have examined the effects of Ti(C,N) particle size, carbon content, and additive elements on overall composite behavior [62,63]. Overall, these findings show that combining ultrafine ceramic phases with metallic binders can significantly improve wear resistance. Such advances make ceramics and composites highly versatile materials with applications ranging from automotive brake pads to critical temperature sensors and structural components, highlighting their growing importance in both industrial and technological sectors.

The **Metallic Materials and Alloys** category includes research focused on adjusting microstructures through heat treatment, alloying, and thermo-mechanical processing to enhance mechanical and functional properties. Powder metallurgy is frequently used as the primary fabrication method, offering flexibility in controlling composition and refining microstructures. Key challenges include balancing strength and ductility, managing precipitate coarsening, and optimizing processing parameters to prevent issues such as excessive grain growth or phase instability. Titanium alloys are a major area of focus.

Ma et al. studied powder metallurgy $\alpha+\beta$ titanium alloys and demonstrated that precise control of solution and aging parameters can significantly improve the strength–ductility balance [64]. Yan et al. investigated Ti–Nb–Ta alloys showing that reducing interstitial oxygen via YH_2 addition can enhance ductility without sacrificing strength, highlighting the role of oxygen control in titanium alloy optimization [65]. Copper–iron alloys are also well studied. Zhang et al. studied Cu–Fe alloys, showing that varying Fe content directly influences yield strength and electrical conductivity, emphasizing the interplay between solid-solution strengthening and electron scattering mechanisms [66]. Magnesium alloys are another major research area. Wang et al. reviewed that using a high-strength extrusion approach enables magnesium alloys to achieve a rare combination of high strength and ductility, broadening their potential for lightweight structural applications [67]. In terms of nickel-based superalloys, research addresses performance under demanding service conditions. Studies on thermo-mechanical fatigue crack growth and hot deformation behavior provide insight into how grain boundary strengthening, phase stability, and precipitation control affect long-term performance [68,69]. The category also includes

tungsten-heavy alloys and TZM (Ti–Zr–Mo) alloys, which are engineered for extreme environments. Dai et al. studied W–Ni–Cu alloys showing how quenching temperature affects microstructure and mechanical properties at both room temperature and cryogenic conditions [70]. Similarly, TZM alloys benefit from the incorporation of cubic zirconia (c-ZrO_2), coupled with severe deformation and annealing, which together enhance the strength–ductility synergy [71]. Overall, these studies highlight the importance of understanding the interplay between microstructural evolution and mechanical performance. Potential applications in this category span aerospace and automotive industries to advanced nuclear reactors, where high-performance, lightweight, and radiation-resistant materials are crucial.

Research in the **Nanomaterials and Advanced Materials** category focuses on microstructural design and innovative synthesis techniques to achieve significant performance improvements in metallic and composite systems. Studies use powder metallurgy and severe plastic deformation to create three-dimensional heterogeneous nanostructures in copper, tungsten, and magnesium-based composites. The goal is to use nanostructural control to boost the combination of strength and ductility, while also adding functional properties such as radiation resistance and catalytic activity. A key challenge involves achieving precise control of microstructural features like grain size and distribution to balance strength and ductility.

Li et al. demonstrated superior strength–ductility synergy in 3D heterogeneous-nanostructured metals. By combining multiple grain-size regimes within a single material, it is possible to activate distinct deformation mechanisms that operate cooperatively, overcoming the traditional trade-off between strength and plasticity [72]. Similarly, in nanocrystalline tungsten and tungsten-based materials, innovative preparation methods and microstructural refinement have yielded unprecedented hardness, wear resistance, and stability under extreme conditions, making them promising for high-temperature and radiation-intensive applications [73]. Magnesium alloys also feature prominently in this category. For example, Yu et al. showed that in bulk nanocrystalline AZ61 magnesium alloys containing titanium, hot pressing temperature and annealing conditions critically affect microstructural evolution and compressive strength [74]. Beyond structural applications, this category also covers functional nanomaterials. The graphene–ZnO nanorod composite, produced via ultrasound-enhanced synthesis, illustrated how nanostructured hybrids can deliver superior photocatalytic activity due to synergistic light absorption and charge transfer effects [75]. Han et al. investigated the synthesis of bulk nanostructured Al alloys with extreme Mg supersaturation, which opens opportunities for high-strength lightweight alloys [76]. These advancements have broad implications for applications in structural materials, energy, and environmental technologies, including fusion reactor components, high-strength alloys, and efficient catalysts.

Research on **Metal Matrix Composites** aims to combine low density with high strength, wear resistance, and thermal management. The work commonly uses powder metallurgy, spark plasma sintering,

co-deposition, and related techniques. The primary focus is to design the interface, control the reinforcement, and adjust the matrix microstructure to achieve targeted performance. A significant challenge is achieving a balance between high-temperature strength and light weight, often addressed by tailoring the microstructure and interfacial bonding.

Lu et al. proposed $\text{Ti}_{40}\text{Nb}_{15}\text{Mo}_{30}(\text{NbC})_{15}$ as a path to high strength at densities below $7 \text{ g}\cdot\text{cm}^{-3}$. The design strategy tailors element distribution to strengthen at elevated temperatures without a mass penalty [77]. Ahmadian et al. balanced nano-SiC and multi-walled carbon nanotubes (MWCNTs) via mechanical alloying and SPS, reporting concurrent improvements in hardness and electrical performance due to complementary strengthening and reduced scattering [78]. Zhang et al. applied co-deposition to embed CNTs uniformly in Cu, preserving CNT integrity and enhancing bonding, which improved the strength–conductivity trade-off [79]. Ding et al. compared fly ash morphologies in PM aluminum foams, showing that $\sim 1 \text{ wt\%}$ mullite whiskers produced greater stability and strength than spherical particles [80]. Bai et al. reported oxide-dispersion-strengthened Al with $\sim 5 \text{ nm}$ MgO particles distributed coherently in the matrix. The alloy suppresses vacancy diffusion and achieves unusual strength and creep resistance up to $\sim 500^\circ\text{C}$ [81]. Wear- and impact-critical applications further motivate hard-phase MMCs. Zhang et al. fabricated Cu/WC/diamond composites by powder metallurgy. The approach targets simultaneous wear resistance and thermal transport for tooling and heat-spreading parts [82]. Interface control also plays a key role in tungsten heavy alloy/steel systems. Meng et al. demonstrated W diffusion into Fe and the formation of $\text{Fe}_3\text{W}_3\text{C}$ at the interface, mapping the interfacial phases and clarifying the mechanism that ensures robust joining [83]. Collectively, these advances show how MMCs address the dual demands of mechanical performance and functional reliability, highlighting their broad potential in aerospace, automotive, and electronic industries where high-performance materials are indispensable.

5.2. Group 2: Processing, synthesis, and reinforcement

The second group focuses on the methods and mechanisms of material creation and improvement. It covers powder preparation, advanced forming processes, and reinforcement strategies. Fig. 11 displays the three categories in this group, each with the four most relevant subtopics. Research here emphasizes the role of synthesis and processing in controlling microstructure, reducing defects, and improving performance.

Material Synthesis and Preparation represents a critical research area within materials science, covering everything from fundamental theory to practical application. This category emphasizes the use of various powder metallurgy techniques and innovative synthesis methods to control and improve microstructures, thereby increasing mechanical properties and functional performance. Main methodologies include

advanced powder production, optimizing sintering processes, and customized heat treatment protocols, each designed to achieve precise control over densification behavior, phase evolution, and defect distribution. The primary challenges involve achieving high densification without compromising the uniformity of the microstructure or the mechanical integrity of the final product.

Wang et al. showed that powder rounding modification of Nd–Fe–B powders improved flowability and alignment, resulting in higher coercivity and remanence in sintered magnets [84]. Wang et al. demonstrated that irregular blend powders can still deliver high-density Ti–48Al–1Fe with good mechanical properties after optimized sintering, offering a low-cost route to near-net-shape TiAl components [85]. Another area focuses on fast or assisted sintering to shorten thermal cycles. Induction-heating sintering produced fully densified powder-metallurgy Ti alloys in minutes, confirming superior densification efficiency versus conventional furnace heating [86]. Hot oscillatory pressing (HOP) also accelerates densification. In W–Cu refractory alloys, shorter sintering times increased density, hardness, strength, and conductivity; excessive time promoted grain growth and property loss. HOP outperformed conventional hot pressing at the same time, indicating a clear processing advantage [87]. Hydrogen-assisted processing has also gained attention. TiH_2 -based routes use dehydrogenation to drive phase transformation, diffusion, and pore closure. Kuang et al. examined phase evolution and densification mechanisms in TiH_2 to produce high-ductility Ti–6Al–4V, and clarified the connection between transformation sequence and ductility improvements [88]. Similarly, Ma et al. proposed a master-alloy pre-hydrogenation (MAPH) that enables nearly full-density TC16 (Ti–3Al–5Mo–4.5V) with strong tensile properties, overcoming porosity associated with blended elemental routes [89]. The potential applications of these materials span aerospace, electronics, biomedical, and high-temperature engineering, where their superior properties offer significant advantages. Overall, this research direction is pivotal for advancing the development of high-performance materials through innovative and cost-effective synthesis and processing techniques.

Material Processing and Forming is a central research domain in powder metallurgy, focusing on the use of advanced manufacturing methods to manipulate microstructural evolution and improve mechanical performance. Core techniques include hot deformation, hot isostatic pressing (HIP), linear friction welding (LFW), and selective laser melting (SLM), often supported by experimental characterization tools such as optical microscopy, electron backscatter diffraction (EBSD), and finite element modeling. The goal is to control defect formation, refine grain structures, and optimize phase distributions to meet demanding service requirements. The key challenges in this field include controlling porosity, preventing defects like intergranular cracks, and optimizing process parameters to achieve consistent and reliable results.

Hot deformation of titanium alloys and superalloys is a key research area. For example, hot rolling of high-performance PM TA15 titanium alloys has been shown to significantly refine microstructures, reduce porosity, and improve tensile strength and ductility through controlled recrystallization [90]. Similarly, hot oscillatory forging of PM superalloys improved elongation and stress–rupture life compared with conventional forging, highlighting its ability to enhance high-temperature performance [91]. Advances in constitutive modeling have further strengthened this field. An enhanced Drucker–Prager–Cap (DPC) model, incorporating solid-state yield strength, has enabled more accurate predictions of densification behavior and final strength during compaction, thereby reducing reliance on costly experiments [92]. Advanced joining techniques, particularly LFW, have also demonstrated promise in joining dissimilar Ni-based superalloys. Geng et al. reported that optimized LFW parameters can produce defect-free joints that retain mechanical integrity under high-temperature conditions, offering significant benefits for fabricating integrated aerospace components [93]. Warm die compaction similarly improved the density and mechanical

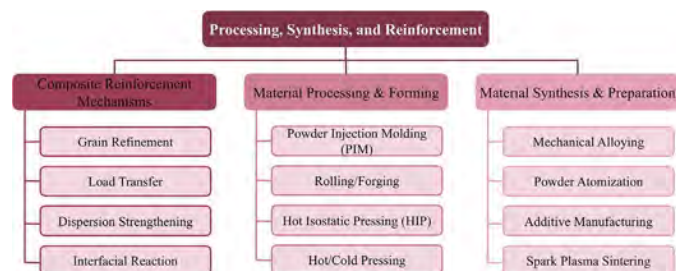


Fig. 11. Taxonomic structure of processing, synthesis, and reinforcement group. Each of the three categories (**Material Synthesis & Preparation**, **Material Processing & Forming**, and **Composite Reinforcement Mechanisms**) contains four representative subtopics.

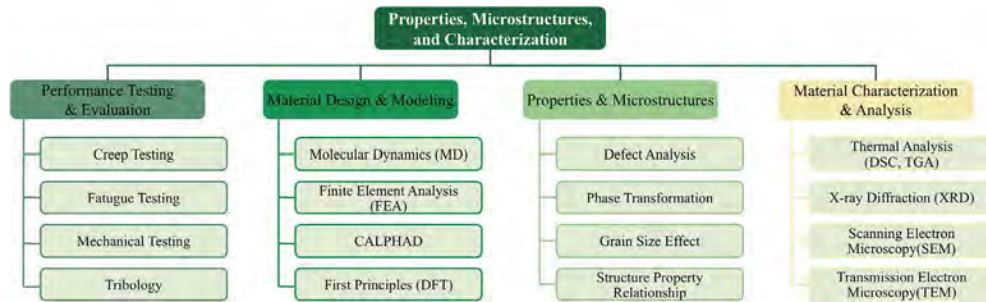


Fig. 12. Taxonomic structure of properties, microstructures, and characterization group. Each of the four categories (**Properties & Microstructures**, **Material Characterization & Analysis**, **Performance Testing & Evaluation**, and **Material Design & Modeling**) contains four representative subtopics.

properties of iron-based powders. Operating at elevated die temperatures reduced internal stresses, promoted uniform density distribution, and enhanced dimensional stability after sintering [94]. The potential applications of these processing technologies are vast, ranging from aerospace and automotive components to energy and biomedical devices, where high-strength, lightweight, and durable materials are essential.

Composite Reinforcement Mechanisms examines how nanoscale reinforcements strengthen metal matrices with an emphasis on dispersion quality, interface design, and multi-mechanism synergy. Key mechanisms include load transfer, Orowan bypass, thermal-mismatch hardening, grain refinement, and dislocation storage. Studies use powder metallurgy, hot pressing, extrusion, and in-situ growth to place reinforcements for the best effect. The main challenges involve mitigating agglomeration, improving wettability, and balancing strength with ductility.

Yang et al. grew CNTs directly on Ti particles and then blended the CNTs@Ti hybrid into Al. The approach suppresses CNT agglomeration and improves interfacial bonding. The study reported higher strength with minimal ductility loss, attributing the gains to combined load transfer and Orowan effects at refined length scales, demonstrating that carrier-assisted in-situ growth is an effective strategy for stable CNT-metal interfaces [95]. Mohammed et al. analyzed a CNT-reinforced Al-Cu-Mg alloy with a bimodal grain structure, showing that fine grains increased strength, coarse grains retained ductility, and CNTs transferred load while pinning dislocations. The work quantified these effects and explained the improved strength-ductility balance [96]. Li et al. combined CNTs with Mg₂Si nanoparticles in a magnesium matrix via powder thixoforming, finding that the hybrid produced larger improvements than either phase alone [97]. Titanium matrix composites reinforced with carbonaceous nanofillers also demonstrated concurrent gains in strength and plasticity when interfaces were engineered. Dong et al. identified Orowan strengthening, efficient load transfer from graphene nanoplatelets, and in-situ reaction products at the interface as the main contributors, linking interface chemistry directly to macroscopic performance [98]. A modeling and experimental study on CNT/Al-5Mg composites showed that high-energy ball milling, hot pressing, and extrusion must ensure uniform CNT dispersion and preserve CNT integrity to realize the predicted strengthening effects [99]. Overall, advances in reinforcement mechanisms highlight how nanoscale design and interface engineering can achieve superior strength-ductility synergy. These strategies open pathways to lightweight, high-performance structural materials for aerospace and automotive sectors, as well as biomedical implants, where enhanced mechanical reliability is essential.

5.3. Group 3: Properties, microstructures, and characterization

The third group focuses on understanding the relationship between structure and performance. It includes work on microstructural

evolution, property testing, advanced characterization methods, and computational modeling. Fig. 12 presents the four categories, each with four main subtopics in this group. The main focus is to understand how microstructures, including grain size, phase distribution, and defect density, affect key properties such as strength, ductility, toughness, and durability.

Research in **Properties and Microstructures** focuses on how processing routes control microstructural features and, in turn, determine mechanical and functional performance. Powder metallurgy, advanced thermo-mechanical treatments, and additive manufacturing provide precise control over grain size, phase morphology, and defect content. Characterization tools such as SEM, TEM, and XRD track the evolution of these features under varied processing and environmental conditions. A key challenge is balancing the trade-offs between strength and ductility, which are strongly influenced by phase size, distribution, and defect structures.

Studies on PM fine-grained duplex steels show that the volume fraction and distribution of martensite and retained austenite strongly influence deformation mechanisms. A balanced phase ratio enhances both strength and ductility, while a non-uniform distribution promotes early strain localization and fracture [100]. In PM FGH97 nickel-based superalloys, interrupted cooling after forging modifies the γ' precipitate size and distribution, producing significant changes in microhardness. Controlled cooling schedules therefore tailor hardness for high-temperature applications [101]. For HIPed/FGed PM superalloy joints, interface microstructural refinement enhances load transfer and improves tensile performance at 750 °C. Fine precipitates at the bonded interface reduce local softening and maintain joint integrity during high-temperature service [102]. In PM Ti-6Al-4V alloys, high-temperature forging triggers spheroidization of lamellar α structures. This transformation improves workability and reduces anisotropy in mechanical properties [103]. Long-term thermal exposure of novel PM Ni-based superalloys shows that the coarsening of γ' precipitates correlates with reduced tensile strength, underscoring the need for microstructural stability at service temperatures [104]. These studies highlight the critical role of microstructural control and stability in determining performance. Understanding mechanisms such as recrystallization, spheroidization, and interfacial energy effects provides a foundation for tailoring properties. Potential applications span aerospace components, where high-temperature strength and long-term stability are essential, to biomedical implants, where controlled microstructures enhance biocompatibility and reliability.

The **Material Characterization and Analysis** category examines how characterization methods connect microstructure to properties in powder-based systems. The field spans microscopy, diffraction, spectroscopy, and thermal analysis, with an emphasis on quantitative imaging and model-based interpretation. Major challenges include achieving accurate and reproducible measurements in complex and heterogeneous materials, such as ultra-fine powders and composites, and developing universal calibration models for properties like moisture content

in pharmaceuticals. The integration of advanced imaging and machine vision technologies is also increasingly important for real-time, non-contact, and high-precision measurements.

Near-infrared spectroscopy supports process monitoring for powders. Zhang et al. built “universal” models for moisture quantification in β -lactam powder injections and showed how calibration transfer extends model use across batches and instruments. The study demonstrates robust prediction after model updating and validates the approach against reference methods [105]. Reliable shape descriptors further reduce operator bias in image analysis. The modified Feret “best-fit rectangle” method combines Feret diameters with least-second-moment minimization to produce rotation-invariant measures of elongation and angularity, keeping computation simple while improving robustness [106]. X-ray fluorescence offers rapid, direct, multi-element quantification in dry powders. Li et al. measured 25 elements without dissolution and reported detection limits and matrix-correction strategies that generalize to many particulate systems, supporting routine elemental screening in powder workflows [107]. Whole pattern Rietveld-Fourier analysis also provides lattice and size-strain data in nanoscale metals. Work on ultra-fine nickel powders used coupled XRD and TEM to extract particle size distributions and to separate microstrain from domain size, illustrating how diffraction and imaging converge on consistent metrics [108]. Non-destructive lock-in thermography (LIT) can visualize density gradients and cracks in green PM compacts. Sebastian et al. established LIT as a predictive imaging tool for flaw prevention and showed how phase-sensitive processing raises signal-to-noise for early porosity detection, supporting preventive NDE during pressing before sintering [109]. The potential applications of these methods range from improving the quality and reliability of industrial components, such as automotive parts, to enhancing the efficiency and sustainability of manufacturing processes, and ensuring the safety and efficacy of pharmaceutical formulations.

The Performance Testing and Evaluation category examines how researchers measure, monitor, and validate the performance of powder-metallurgy materials and parts. The work spans on-line metrology for gears, optical and spectral non-destructive evaluation, mechanical testing of architected lattices, machining wear assessments, energetic safety of metal powders, and dynamic response of porous metals.

On-line metrology has moved from slow contact tools to hybrid optical systems. Yu et al. introduced a combined laser-vision approach for on-line measurement of small-module PM gears. The system fuses line-laser scanning with camera imaging, calibrates with a precision block, and validates accuracy against a gear measurement center, thereby meeting both speed and precision requirements for production inspection [110]. In parallel, machine-vision pipelines now detect typical PM gear defects. An improved SHGA-PSO algorithm enhances feature extraction and classifier optimization, raising recognition accuracy for broken teeth, abrasion, scratches, and cracks compared with GA-, PSO-, and GA-PSO-based baselines [111]. Safety-oriented performance testing addresses dust explosion risks in fine metal powders. Experiments in vertical ducts show that aluminum oxide inertants suppress aluminum dust explosions more effectively when the Al_2O_3 is submicron. However, at high powder concentrations and low inerting ratios, submicron Al_2O_3 can promote combustion, highlighting the need for size aware dosing [112]. Optical and spectral NDT has also extended accessible signals beyond the visible spectrum. Yan et al. integrated hyperspectral imagery with machine learning to quantify powder quality for additive manufacturing. Their system detects contamination and predicts the usability of recycled powder, enabling quantitative acceptance criteria before a build [113]. These studies collectively address the challenges of achieving high accuracy and efficiency in both laboratory and industrial settings, while ensuring the reproducibility and reliability of test results. Potential applications span aerospace, automotive, and consumer electronics, as well as safety-critical environments, where optimized testing strategies enhance functionality, durability, and safety.

The Material Design and Modeling category investigates how models connect processing, structure, and properties in powder metallurgy

systems. The work spans physics-based constitutive laws, phase field sintering, microstructure reconstruction, and data-driven prediction. Studies combine experiments with simulations to forecast flow stress, densification, texture, and performance under service conditions. The main challenges include accurately representing complex microstructures, developing efficient and reliable simulation methods, and validating models against experimental data.

Yang et al. modeled the rheology across temperature and strain-rate windows and linked stress softening to dynamic recrystallization (DRX) and phase evolution. Their model explains why higher temperatures or lower strain rate lowers flow stress. It also guides safe processing windows for forgings [114]. Microstructure reconstruction enables virtual testing of porous metals made by PM. Xu et al. rebuilt three-dimensional porous bronze by simulating compaction and sintering, then verified the digital twins against real porosity metrics and flow predictions. The framework supports parametric studies without expensive iterations [115]. Aluminum agglomeration remains a critical multi-physics problem in energetic PM composites. Liu et al. coupled experiments with numerical models to track particle clustering during combustion and its impact on burning behavior, quantifying how packing and ignition conditions control agglomerate size and persistence [116]. Machine learning further augments constitutive modeling where microstructure evolves rapidly. Wen et al. developed an ML-assisted physical model that predicts flow stress, DRX kinetics, and grain size for a novel PM nickel superalloy. The hybrid model outperformed traditional forms and reduced the data burden for map construction [117]. Design tasks also adopt ML. A data-driven pipeline selected copper-based brake pad recipes that stabilize the friction coefficient while limiting wear and thermal fade under high-speed service. The model recommends compositions and validates them against tribological tests [118]. The potential applications of this research include the optimization of solid rocket propellant formulations, the design of high-performance brake pads for high-speed trains, and the development of advanced powder metallurgy processes for aerospace and automotive industries. Overall, the integration of theoretical modeling with experimental validation is crucial for advancing the design and performance of next-generation materials.

5.4. Group 4: Functional applications and interdisciplinary fields

The fourth group focuses on application-specific performance and cross-disciplinary material development. It covers novel material development, functional material applications, high-temperature and extreme-environment materials, and broader cross-disciplinary topics. Fig. 13 presents the four categories, each with four main subtopics in this group. The focus is on tailoring materials to meet the demands of specific environments and technologies, ranging from biomedical implants to energy storage, thermoelectric systems, and aerospace components.

Novel Material Development tracks how powder-based routes enable biofunctional metals, catalytic high-entropy alloys, and advanced electron-emission materials. The studies combine design tools such as Density Functional Theory (DFT), rapid screening, and surface texturing with processes like SPS and laser etching. The goal is to combine microstructural control with specific functions like antibacterial activity, corrosion resistance, or catalytic efficiency. Key challenges include balancing mechanical performance with functional properties and ensuring long-term stability and durability.

Work on Ti-Cu systems shows why SPS remains attractive for biomedical alloys. Recent SPS fabricated Ti-xCu alloys achieved tensile strengths of roughly 575–810 MPa with 11–29% elongation, while maintaining clean, fine microstructures [119]. Copper addition also provides intrinsic antibacterial activity, which is valuable for implant safety. Mo- and Cu- modified β -Ti alloys extended this idea to multifunctional behavior. A functionally graded porous Ti-Mo-Cu alloy demonstrated good corrosion resistance, strong antibacterial response, and acceptable cytocompatibility, indicating promise for load-bearing implants [120]. A

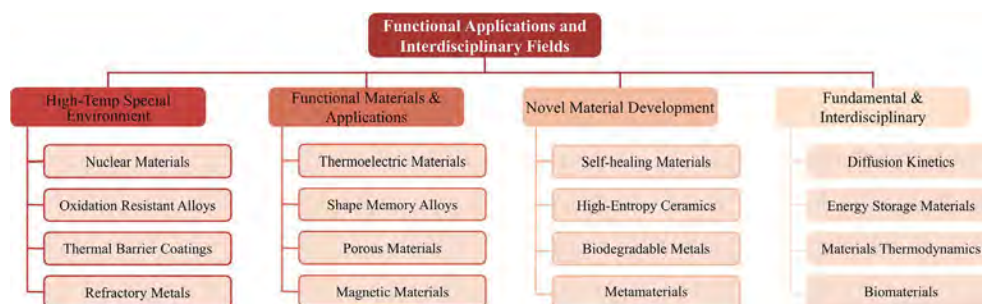


Fig. 13. Taxonomic structure of functional applications and interdisciplinary fields group. Each of the four categories (**Novel Material Development**, **Functional Materials & Applications**, **High-Temperature & Special-Environment Materials**, and **Fundamental & Interdisciplinary**) contains four representative subtopics.

related “function–structure integrated” Ti–15Mo–11Cu composition balanced mechanical compatibility with antibacterial performance, showing that composition and porosity can be co-designed [121]. Systematic tests on Ti–10Mo–xCu further quantified the trade-off: strength increases with Cu content, while ductility decreases as Ti₂Cu forms; an intermediate 3wt% Cu level offers a practical balance [122]. Low modulus β -type alloys also targeted bone matching stiffness and corrosion control. Powder metallurgical Ti–Nb–Zr–Mg alloys produced by mechanical alloying and SPS form β/α microstructures and show improved corrosion behavior, suggesting a path to durable, compliant implants [123]. Ti–Au systems add a different functionality. A recent study reported strong antibacterial efficacy and good biocompatibility in Ti–Au, with evidence that the alloy perturbs bacterial redox homeostasis [124]. Porous Ti35Zr28Nb scaffolds fabricated by powder metallurgy complemented these chemistries by matching trabecular bone mechanics and promoting osteointegration [125]. The potential applications of these materials range from orthopedic implants and dental prosthetics to electrocatalysts for hydrogen evolution in seawater, highlighting their significance in advancing both medical and sustainable energy technologies.

Functional Materials and Applications examines how powder-enabled routes deliver thermoelectric, magnetic, damping, and safety functions while preserving mechanical reliability. The studies combine composition design with microstructural control and validate performance using diffraction, microscopy, and device-level testing. A recent field review summarizes the breadth of functional metal powders and maps applications in electronics, energy, biomedical devices, and flame-retardant systems [126]. Challenges in this field include balancing multiple properties, such as thermoelectric efficiency and mechanical strength, and ensuring reproducibility in large-scale applications.

Thermoelectric alloys illustrate the value of grain boundary control. In n-type Bi₂Te₃, boron additions during one-step sintering inhibited grain coarsening and mitigated donor-like effects, which raise both mechanical robustness and power factor [127]. A complementary strategy decomposed MgB₂ in Bi₂Te₃ based composites to trigger Gibbs adsorption and Zener pinning at boundaries. The approach strengthens the alloy and sustains high device efficiency over 300–473 K [128]. Half-Heusler TiNiSn showed another path: micro- and nano-scale Cu additions tune microstructure and improve thermoelectric response after consolidation [129]. In oxide systems, La doping in ZnO converged the conduction band and increased the density of states near the Fermi level, which boosts electrical transport and supports higher thermoelectric output [130]. Magnetic and magnetocaloric materials highlight composition–process coupling. Bi³⁺ substitution in M-type barium hexaferrites produced powders that display coexisting ferroelectric and ferromagnetic signatures when processed by conventional powder metallurgy routes [131]. For room temperature magnetic refrigeration, MnFe(P,Si,B) compounds showed strong sensitivity to green compaction pressure: modest changes in pressure alter intergranular

secondary phase distribution and produce large gains in isothermal entropy change [132]. In hard magnetic intermetallics, Ge substitution in MnBi shifted transformation temperatures and enhanced coercivity, which improves low-temperature magnetic performance [133]. Safety-critical applications also benefit from powder-enabled design. Copper foams placed in dust conduits slowed flame front propagation and increased quenching effectiveness during powder deflagration, with performance dependent on foam parameters and dust chemistry [134]. The potential applications of these materials span various industries, including aerospace, electronics, energy, and 5G technology, where these materials can be used in devices requiring high performance and reliability. The development of new processing techniques and the integration of novel dopants and additives are crucial for overcoming these challenges and realizing the full potential of functional materials.

Research on **High-Temperature and Special-Environment Materials** in powder metallurgy aims to enhance the high-temperature creep resistance, oxidation behavior, and mechanical properties of materials such as Ni-based superalloys, TiAl intermetallics, and Mo alloys. Key methods include microstructural analysis, creep testing, and oxidation studies under various conditions. The challenges involve understanding and mitigating the mechanisms of creep damage, such as grain boundary cavitation and dislocation dynamics, and improving the stability of protective oxide layers.

Recent work on advanced PM Ni-based superalloys has mapped creep regimes between 760 and 815 °C and 480–620 MPa, linking life to Monkman-Grant metrics and clarifying damage evolution across stages. These tests showed how microstructure and stress combine to control rupture, which supports process-window design for turbine disks [135]. In Ni–10Al alloys at 1100 °C, Ta promoted Al₂O₃ scale formation but excessive additions caused destabilizing tantalates. Y improved adhesion but led to inhomogeneous NiO. Combined Ta–Y additions suppressed these effects and stabilized alumina growth, enhancing oxidation resistance [136]. Grain size also influenced oxidation resistance. Nanocrystalline Ag–20Cu–30Cr oxidizes more slowly than coarse-grained material at a fixed temperature after an initial transient, and its kinetics follow multi-stage parabolic laws [137]. Oxide dispersion strengthening provided further improvements. Nanoscale La₂O₃ in Mo refined fibrous grain structures, raised the apparent stress exponent and activation energy, and improved creep resistance between 1000 and 1400 °C. A constitutive model captured the enhanced rate sensitivity [138]. Intermetallics showed parallel advances. PM Ti–45Al–10Nb formed protective oxide architectures between 850 and 950 °C, where TiO₂ and Al₂O₃ dominated with dispersed Nb-rich phases stabilizing the scale. The result was better oxidation resistance than in lower-Nb TiAl alloys [139]. Creep rupture studies on high-Ta PM superalloys revealed mechanism shifts with temperature and stress, including mixed crack modes within the same test, which underscores the need for composition-specific lifing rules [140]. Interface-engineered composites

push TiAl further. In situ semicoherent MAX phase (Ti_2AlC) precipitation at γ/γ and γ/α_2 interfaces pins lamellae, increases high temperature strength, and slows oxidation through scale densification. Spark plasma sintered nanocomposites highlight this route to stability [141]. The potential applications of these materials range from aerospace and automotive industries to high-temperature structural components in energy systems.

The **Fundamental and Interdisciplinary** category highlights how powder metallurgy research intersects with broader scientific, industrial, and societal concerns. This area integrates concepts such as diffusion kinetics, thermodynamics, and biomaterials with cross-disciplinary applications in energy, environment, and healthcare. Reports represent a key type of contribution in this category, often addressing issues that connect powder metallurgy with broader industrial and societal concerns, such as industrial practice, education, and health frameworks. Worker health remains central to social license. A Metal Powder Report feature examined hardmetal risks in production settings, reflecting long-running concerns around cobalt-tungsten exposures [142]. Education and workforce development are another recurring theme. An industry article documented the rapid expansion of PM education programs alongside sector growth. The report described new training routes and formal curricula meant to meet production demand and raise quality standards. These initiatives align workforce skills with evolving materials and regulations [143]. Another article reported an Automated Information System (AIS) in PM. The project developed an information system that compiled materials, processes, and testing methods in powder metallurgy, with a focus on fractography. It supported faster knowledge transfer and standardization between research and industry [144]. These articles and reports illustrate the breadth of the fundamental and interdisciplinary theme. They demonstrate how powder metallurgy connects to policy, health, education, and digital innovation, while also highlighting the need for careful validation of scientific claims.

6. Discussion

One key consideration in the development of the LLM-based taxonomy framework is the selection of hyperparameters, particularly the number of final categories L . In this study, we used a systematic evaluation strategy that combines four complementary metrics to help tune these parameters, including cohesion, separation, and stability (both Jaccard- and embedding-based). These metrics provide a more balanced and reliable assessment of category quality, ensuring that the taxonomy is consistent and semantically meaningful. Although the exact category size for the PM field is not fixed, we found that using between 10 and 15 categories provides the most consistent structure. Choosing fewer categories often results in overly broad groupings, which can dilute important thematic differences. On the other hand, using too many categories may lead to redundancy. For example, larger category sizes often generate categories such as “*material properties and microstructure*”, “*material microstructure and phase transition*”, and “*material properties and applications*” that overlap and reduce clarity. Given the size and diversity of the PM field, we believe that 10 to 15 categories offer a practical compromise for including the core topics while maintaining manageable details. For smaller or more focused domains, fewer categories may be sufficient to represent the thematic structure, and the proposed framework can adjust accordingly to reflect the appropriate scope of the research field. This finding suggests that LLMs exhibit processing constraints similar to human categorical reasoning principles, making them particularly effective for literature organization tasks that require balancing granularity with comprehensibility.

Another factor that affects the classification result is the non-deterministic behavior of LLMs. Running the same prompt multiple times may produce slight variations in classification. Despite this

variability, we observed strong consistency across categories in our sample tests. Categories like “*Material Processing & Forming*”, “*Metallic Material Alloys*”, “*Metal Matrix Composite*”, “*Material Characterization & Analysis*”, and “*Performance Testing*”, etc., frequently appear. This suggests that LLMs are reliable in capturing core research topics and dividing them into clear groups. The emergence of consistent core categories indicates that certain research themes represent well-established knowledge structures that appear reliably across different model outputs and prompt variations.

The structure and quality of the input data also influence classification results. Initially, we used full-text documents to guide the labelling and categorization of literature. However, the processing time was significantly higher. As a result, we switched to using abstracts only to improve the efficiency of the framework. However, since abstracts only provide a high-level summary but may lack key experimental or contextual details, it could affect the accuracy of the classification. We also excluded any non-English papers, especially those written in Chinese and Russian. Although this helps maintain linguistic consistency in LLMs, it may introduce geographic or regional biases in the final classification. Due to this exclusion, some research fields may be underrepresented. Additionally, the analysis primarily relies on general-purpose large language models, which may introduce inconsistencies when dealing with highly technical or domain-specific content. LLMs may also struggle with unclear or complex abstracts, and results may vary depending on input quality.

Another limitation of the current classification scheme is that it represents each paper by one dominant theme. This design is suitable for constructing a clear and interpretable taxonomy, but it may oversimplify papers with strong interdisciplinary content. Powder metallurgy research is often interdisciplinary, and some papers naturally span multiple categories. For example, a paper on metal matrix composites may simultaneously involve material synthesis, processing optimization, microstructural characterization, and performance evaluation. The confidence score vector generated during classification partly addresses this issue by indicating secondary category relevance, but these secondary signals are not utilized in the current analysis. Future work will extend the framework toward multi-label classification to better capture cross-category relationships and interdisciplinary research patterns.

A significant advantage of our LLM agent-based approach over traditional algorithmic methods lies in its adaptability to rapidly advancing language model capabilities. As LLMs continue improving in reasoning abilities and domain knowledge, our framework can readily incorporate advanced language models without requiring architectural modifications. This adaptive capacity ensures that classification accuracy and semantic understanding improve systematically as underlying language models advance, providing a sustainable long-term solution for automated literature analysis. The scalability and generalization potential of this approach extend beyond powder metallurgy to other technical and scientific domains requiring large-scale literature organization.

7. Conclusions

This study presents a novel and scalable LLM agent-based framework that automates the literature review process in the powder metallurgy field, generating meaningful topic structures from a large collection of academic papers. We propose a two-tier structured framework that processed and analyzed over 26,000 powder metallurgy papers collected from Scopus. It uses a combination of stochastic sampling, context-aware classification, and iterative reasoning to build a multi-level taxonomy and extract thematic insights. The results show that LLM agents, when guided by structured prompts and contextual enrichment, can produce accurate, nuanced, and semantically rich classifications.

One of the key contributions of this study is the systematic application of an LLM-based framework to analyze the PM domain

comprehensively. Using this approach, we organized the PM literature into 15 coherent categories, examined the semantic topic of each category, and traced their evolution over time. For each category, we highlighted representative publications and discussed their scientific contributions and implications. In addition, we conducted a statistical analysis of the entire corpus, covering publication trends, author and institutional productivity, keyword evolution, and geographic distribution. Together, these results provide a comprehensive overview of the structure, development, and diversity of PM research, offering new insights and a structured reference for future investigations in the field.

The framework's modular design and adaptability to advancing LLM capabilities position it as a valuable tool for automated scientific knowledge organization across multiple technical domains. As demonstrated through its successful application to powder metallurgy, the methodology's reliance on semantic understanding rather than domain-specific heuristics enables systematic extension to other scientific fields requiring comprehensive literature analysis. This work establishes a foundation for intelligent literature review systems that can evolve with advancing language model capabilities, providing sustainable solutions for managing the exponential growth of scientific literature.

CRedit authorship contribution statement

Xiang Li: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ling Chen:** Validation, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Botao Zhang:** Writing – review & editing, Writing – original draft, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Zhibin Niu:** Visualization, Methodology, Data curation. **Yiming Yuan:** Writing – original draft, Investigation.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used OpenAI ChatGPT to assist with language editing, sentence refinement, and improving the clarity and readability of the manuscript. The author(s) reviewed and edited the output as needed and take full responsibility for the content of the published article.

Declaration of competing interest

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

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Appendix A. Prompts used for agent reasoning

A.1. Prompt used for initial labels generation

Prompt – Initial Category Generation

Please divide the following {len(sample_df)} papers into {self.config.categories_per_itr} categories. For each category, provide a concise label name and a detailed classification rationale.

Formatting requirements:

Label: [Label Name]

Rationale: [Classification rationale, explaining why these papers belong to this category, including key features and commonalities]

Paper Abstracts: {abstracts_text}

Please strictly follow the format. Each label must have a corresponding rationale.

A.2. Prompt used for semantic merging and taxonomy generation

Prompt – Category Merging

Merge the following {len(label_pool)} labels into {self.config.final_categories} core categories: {labels_text_str}

Requirements:

1. Provide a clear and precise label name for each category
2. Provide a detailed description explaining the characteristics and scope of this category
3. List which original labels were merged into this category (use their numbers)

Format:

Final Label: [Name]

Description: [Detailed description]

Merged Labels: [Original label numbers, separated by commas]

A.3. Prompt used for literature taxonomy scoring

Prompt – Label scoring

Please assign a relevance score (from 0.0 to 1.0) for the target paper under each of the following classification labels, based on the target paper and its related studies.

Target Paper:

Title: {target_paper.title}

Abstract: {target_paper.abstract}

Related Studies: {context}

Classification Labels: {'', '.join(labels)}

Return the scores in strict JSON format, as follows: {"Label1": 0.85, "Label2": 0.45, "Label3": 0.10}

A.4. Prompt used for ambiguity resolution query

Prompt – Label Disambiguation

Analyze the following paper, which shows classification uncertainty across several competing labels. To clarify this ambiguity, generate a short and precise English search query (5–10 words). The query should help locate comparative literature that highlights the distinctions between these labels.

Target Paper:

Title: {target_paper.title}

Abstract: {target_paper.abstract}

Competing Labels: {'', '.join(competing_labels)}

Task:

Produce a search query that captures the subtle differences in the paper's core technology, methodology, or application area. Return only the query string — no explanations, prefixes, or extra text.

Example Queries:

"interfacial reaction mechanism in SiC/Al composites"

Data availability

Data will be made available upon request.

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