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A Bibliometric Analysis of Materials Engineering Education: Trends and Their Implications for Research and Education

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ABSTRACT

This paper critically examines the emerging trends, content evolution, and pedagogical innovations in materials engineering education. Using a systematic literature review approach, this study synthesizes key developments in materials engineering education focusing on enrolment trends in materials-related engineering disciplines and their implications for future research and educational practices. The result shows that the rapid technological, environmental, and industrial transformations of the 21st century have redefined the competencies required of materials engineers. As global challenges such as climate change, resource scarcity, digitalization, and sustainable development become more pressing, materials engineering education must undergo significant pedagogical and curricular reform to remain relevant. The findings aim to provide actionable insights for educators, policymakers, and curriculum developers in creating a responsive and sustainable materials engineering education system for the 21st century.

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1. INTRODUCTION

The 21st century has brought rapid technological and industrial advancements that demand a corresponding transformation in engineering education, particularly in materials engineering (Calixtro Jr., 2024; Mohammed, 2023; Ibrahim et al., 2024; Gatta et al., 2023; Pablo et al., 2022; Hassan & Abdulkareem, 2023; Bantilan, 2024). As the world grapples with global challenges such as climate change, resource depletion, the need for renewable energy, and digital transformation, engineers are expected to possess not only technical expertise but also interdisciplinary competencies, critical thinking skills, and sustainable innovation capacity (Tiong & Bakar, 2022; Lantada, 2020; Glushchenko, 2023; Xamidullaeva & Fayzievna, 2023; Sison *et al*., 2024; Khamidullaevna & Muhabbat, 2023). In this context, material engineers play a central role in developing novel materials for emerging technologies, including renewable energy systems, green infrastructure, and advanced manufacturing (De Jong *et al*., 2021). Therefore, the way materials engineering is taught must evolve to equip future professionals with the skills required to address these global demands.

Recent research has highlighted significant trends and innovations in materials engineering education. For instance, some researchers (Álvarez *et al*., 2021) emphasized the integration of sustainability principles and green materials into engineering curricula to align with environmental goals. Similarly, other reports (Liu *et al*., 2015) explored the use of project-based learning to enhance students' problem-solving and design skills in materials engineering. Other reports (Ramsurrun *et al*., 2024; Sison *et al*., 2024) underscored the role of digital tools, such as simulations and virtual labs, in improving conceptual understanding and learner engagement. Moreover, other papers (Olanrewaju *et al*., 2023) advocated for interdisciplinary approaches, combining materials science with entrepreneurship and innovation. Lastly, other studies (Hazrat *et al*., 2023) demonstrated how AI and data-driven methods are increasingly being adopted to personalize engineering education and simulate real-world decision-making environments.

Despite these advances, there remains a notable gap in the systematic integration of pedagogical innovations with updated content frameworks that reflect the actual competencies needed in contemporary materials engineering practice. Most curricula still emphasize traditional content delivery methods with insufficient incorporation of sustainability, digitalization, and interdisciplinary collaboration. Furthermore, there is limited research that evaluates the long-term impact of these innovations on students' preparedness for professional challenges. This gap indicates a pressing need to explore holistic, future-oriented educational models that not only update content but also reform pedagogical strategies in materials engineering education.

This study aims to critically review the current trends, curricular content, and pedagogical innovations in materials engineering education in the 21st century. By synthesizing recent scholarly contributions and identifying both best practices and persistent challenges, this review seeks to provide insights for educators, curriculum developers, and policymakers. The expected impact includes informing the development of a more responsive and future-proof materials engineering education system that better prepares graduates to address complex engineering and societal problems in a rapidly changing world.

2. METHODS

We used a bibliometric approach as the primary method to analyze developments, research trends, and topic networks in the field of materials engineering education using data retrieved from the Scopus database using a combination of keywords: "material" AND “engineering" AND "education" AND "pedagogy" applied to the title, abstract, and keyword fields, covering the publication period from 2015 to 2024. The selection was limited to journal articles, review papers, and conference proceedings. Previous bibliometric studies have been widely conducted across various domains (Ohuangthanasan & Wongsaphan, 2024; Damkan & Chano, 2024; Oya, 2024; Pujiastuti, 2024). We also showed previous studies on bibliometrics, as shown in **Table 1**.

The collected data were then processed using VOSviewer software for bibliometric visualization. The analysis applied a minimum number of occurrences of a term set at 10, out of 11,296 identified terms, yielding 263 terms that met the threshold. From these, 10 of the most relevant terms were selected for further analysis to identify thematic relationships and emerging trends.

As a complementary component, a limited Systematic Literature Review (SLR) was also conducted to explore enrolment trends in materials-related engineering disciplines and their implications for future research and educational practices. This thematic review focused on a curated selection of articles from the bibliometric dataset. The aim was to gain qualitative insights that contextualize the bibliometric findings and highlight the pedagogical and strategic responses to enrolment patterns over the last decade.

Table 1. Previous study about bibliometric analysis.

No	Title	References
1	The research trend of statistical significance test: Bibliometric analysis	Al Husaeni *et al.* (2024)
2	A Bibliometric Analysis of Global Trends in Engineering Education Research	Susilawati (2024)
3	Bibliometric Analysis using VOSviewer with Publish or Perish of Chinese Speaking Skills Research	Phuangthanasan and Wongsaphan (2024)
4	Bibliometric analysis using VOSViewer with Publish or Perish of metacognition in teaching English writing to high school learners	Damkam and Chano (2024)
5	Computational bibliometric analysis of research on science and Islam with VOSviewer: Scopus database in 2012 to 2022	Al Husaeni and Al Husaeni (2022)
6	Bibliometric analysis of educational research in 2017 to 2021 using VOSviewer: Google Scholar indexed research	Al Husaeni *et al.* (2023)
7	The role of science and technology fields in education and journal publications at Universitas Pendidikan Indonesia: Bibliometric analysis from 2021 to 2024	Al Husaeni & Nandiyanto (2024)
8	Sustainable packaging: Bioplastics as a low-carbon future step for the sustainable development goals (SDGs)	Basnur *et al.* (2024)
9	Computational bibliometric analysis on publication of techno-economic education.	Ragadhita and Nandiyanto (2022)
10	Assessment of student awareness and application of eco-friendly curriculum and technologies in Indonesian higher education for supporting sustainable development goals (SDGs): A case study on environmental challenges	Djirong *et al.* (2024)
11	Low-carbon food consumption for solving climate change mitigation: Literature review with bibliometric and simple calculation application for cultivating sustainability consciousness in facing sustainable development goals (SDGs)	Nurramadhani *et al.* (2024)
12	Sustainable development goals (SDGs) in science education: Definition, literature review, and bibliometric analysis	Maryanti *et al.* (2022)
13	Management information systems: bibliometric analysis and its effect on decision making.	Santoso *et al.* (2022)

Table 1 (continue). Previous study about bibliometric analysis.

No	Title	References
14	Nutritional research mapping for endurance sports: A bibliometric analysis	Firdaus *et al.* (2023)
15	A bibliometric analysis of chemical engineering research using vosviewer and its correlation with COVID-19 pandemic condition.	Nandiyanto *et al.* (2021)
16	Bibliometric computational mapping analysis of publications on mechanical engineering education using vosviewer	Al Husaeni & Nandiyanto (2022)
17	Bibliometric analysis of engineering research using vosviewer indexed by Google Scholar	Nandiyanto & Al Husaeni (2022)
18	Bibliometric data analysis of research on resin-based brake-pads from 2012 to 2021 using VOSviewer mapping analysis computations	Nandiyanto *et al.* (2023)
19	Strategies in language education to improve science student understanding during practicum in laboratory: Review and computational bibliometric analysis	Fauziah *et al.* (2021)
20	How language and technology can improve student learning quality in engineering? Definition, factors for enhancing students comprehension, and computational bibliometric analysis	Al Husaeni *et al.* (2022)
21	Sustainable development goals (SDGs) in engineering education: Definitions, research trends, bibliometric insights, and strategic approaches	Ragadhita *et al.* (2026)
22	Definition and role of sustainable materials in reaching global sustainable development goals (sdgs) completed with bibliometric analysis	Ragadhita *et al.* (2026)
23	Bibliometric analysis in chemistry education: exploring system thinking skill in water treatment	Ragadhita *et al.* (2023)

3. RESULTS AND DISCUSSION

3.1. Bibliometric Analysis

Figure 1 shows a quite significant development trend in scientific publications from 2015 to 2024. Initially, the number of publications was still relatively low, namely around 21 documents in 2015. However, starting in 2017, there was a significant increase, reflecting the growing interest in the integration between materials science, engineering, and education. This trend has experienced fluctuations, especially a sharp decline in 2020, which was most likely influenced by the impact of the COVID-19 pandemic on research activities. Interestingly, post-pandemic, specifically in 2021, the number of publications increased drastically to reach its highest point, around 47 documents, which shows the increasing need for technology and engineering-based educational innovation. This trend tends to stabilize in subsequent years, with the number of publications remaining high until 2024. Overall, these data show that interdisciplinary topics that combine materials, engineering techniques, education, and pedagogy are increasingly receiving attention, along with the need in the world of education for practice-based teaching methods and materials technology.

Figure 2 shows the distribution of the number of documents by country or region contributing to related research. The United States is the country with the most dominant contribution, with the number of publications far exceeding other countries, reaching almost 200 documents. Interdisciplinary research linking aspects of materials engineering with education and pedagogy is receiving enormous attention in the United States, both in terms of academics, technology, and applications in the world of education. Meanwhile, countries such as India, England, and Russia also showed quite significant contributions, although the number of publications was still far behind compared to the United States. Countries such as

Canada, China, Malaysia, the Netherlands, Spain, and Australia also played a role, but with a relatively smaller number of documents. These findings indicate that research related to the development of materials and engineering-based education is still dominated by developed countries, especially the United States, while contributions from Southeast Asian countries, such as Malaysia, are starting to be seen, although still on a small scale. This also opens up great opportunities for researchers in developing countries, including Indonesia, to expand their contributions to this interdisciplinary field in the future.

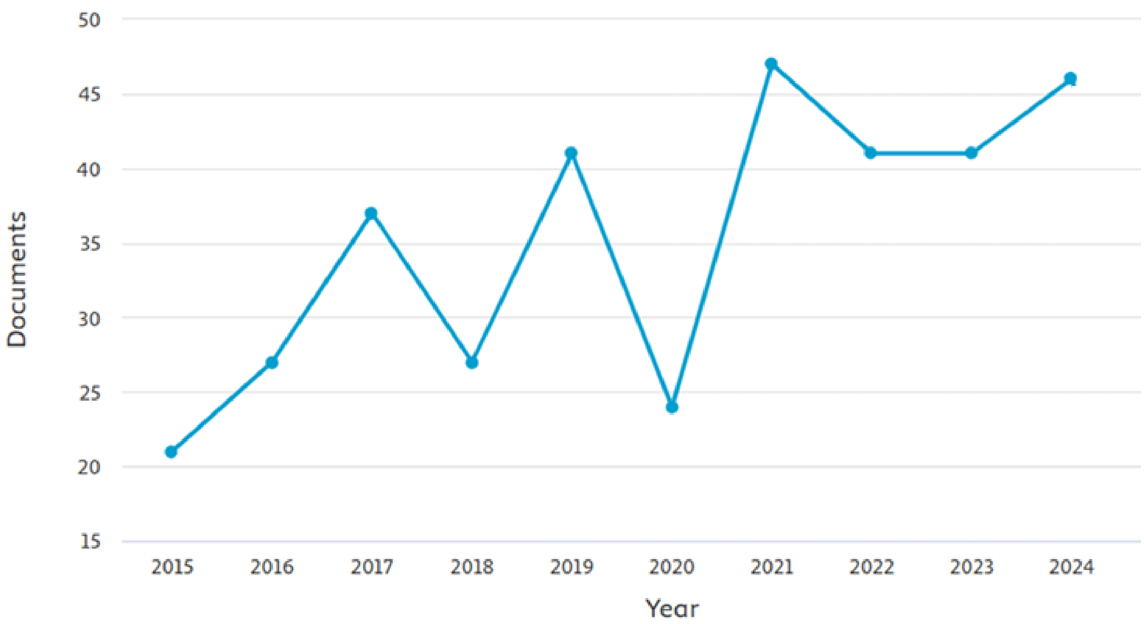

Figure 1. Research trend-related material in engineering education.

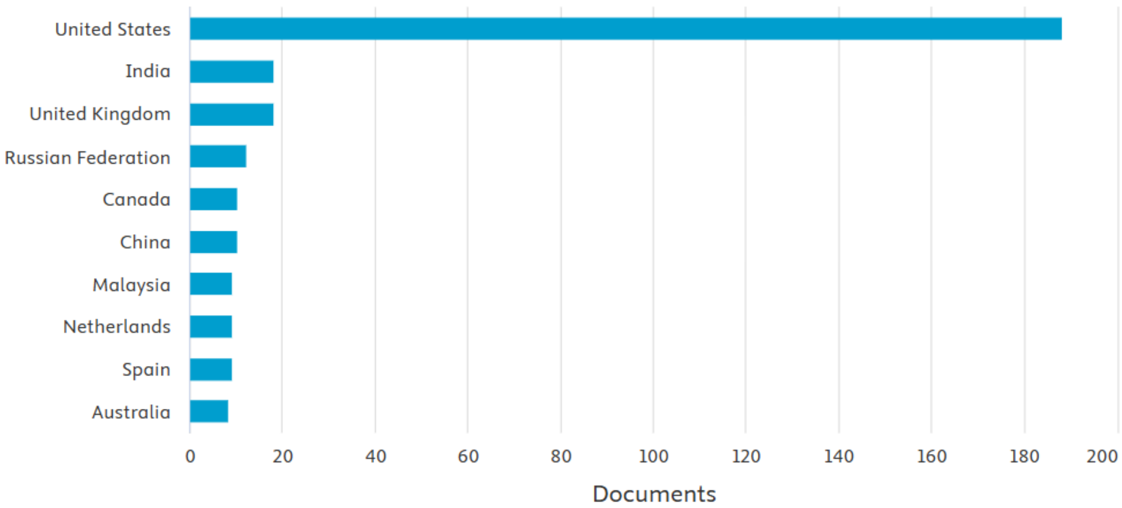

Figure 2. Research trend by country.

Figure 3 shows the distribution of documents based on scientific fields. The field of Engineering (34.1%) dominates the contribution of publications, which shows that research related to materials and engineering is the main focus in this combination of topics. Followed by the field of Social Sciences (26.1%), which reflects the significant involvement of social studies, education, and pedagogy in these researches. Furthermore, the field of Computer

Science contributed 19.1%, reflecting the trend of integrating information technology in materials engineering-based learning and education. Followed by Mathematics (2.7%), Business, Management (2.3%), Physics and Astronomy (2.1%), and Materials Science (2.0%), each of which contributed to strengthening the scientific side, materials development, and its application in the world of education. Other fields such as Arts and Humanities, Psychology, and Decision Sciences make smaller contributions, but still demonstrate the existence of a multidisciplinary approach. Apart from that, the other category (6.5%) shows that there are still other scientific fields that participate, although in smaller numbers. These findings show that topics that combine materials, engineering, education, and pedagogy are cross-disciplinary, with a strong dominance of engineering and social sciences, but still open up space for collaboration from various other disciplines.

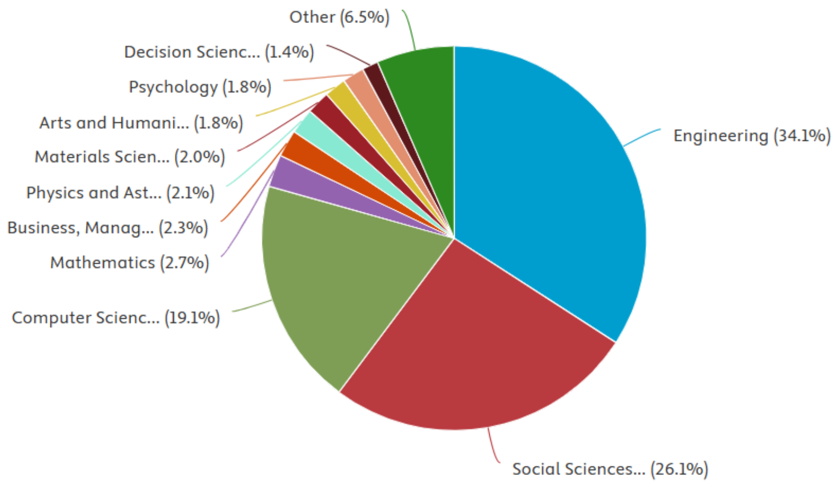

Figure 3. Distribution of related research documents based on scientific fields.

Figure 4 shows the results of the network visualization, which shows that the nodes represent keywords or terms that frequently appear in the documents being analyzed, while the connecting lines show the relationship between these keywords based on co-occurrence in the literature. There are several groups (clusters) that are differentiated based on color. The green cluster dominates the left area and contains terms that are closely related to the learning process in class, such as instructor, survey, feedback, class, course material, questions, and lecture. This shows that research related to education in the realm of materials and techniques focuses a lot on learning methods, assessment, and instructor involvement in the classroom. The red cluster, which occupies the right area, contains keywords such as teacher, training, science, mathematics, stem, curriculum, and innovation, indicating a focus on integrating STEM (Science, Technology, Engineering, and Mathematics) education as well as teacher training and curriculum in developing engineering and materials-based education. The blue cluster, spread across the top left to the middle, contains terms such as higher education, peer, interaction, exercise, industry, and performance, representing the relationship between higher education, interaction in the academic environment, and the role of industry in encouraging engineering-based learning performance. In addition, there is a yellow cluster that links keywords such as framework, integration, learning process, and interview, indicating that there is research that focuses on theoretical frameworks and learning integration in the context of engineering and pedagogy. Overall, the results of this visualization show that research related to materials, engineering, education, and pedagogy does not only focus on technical aspects, but is also strong in the areas of learning methodology, educational performance evaluation, industrial integration, and curriculum development. The dense relationship between keywords indicates the high level of interdisciplinarity between the fields of engineering, education, and pedagogy in the analyzed literature.

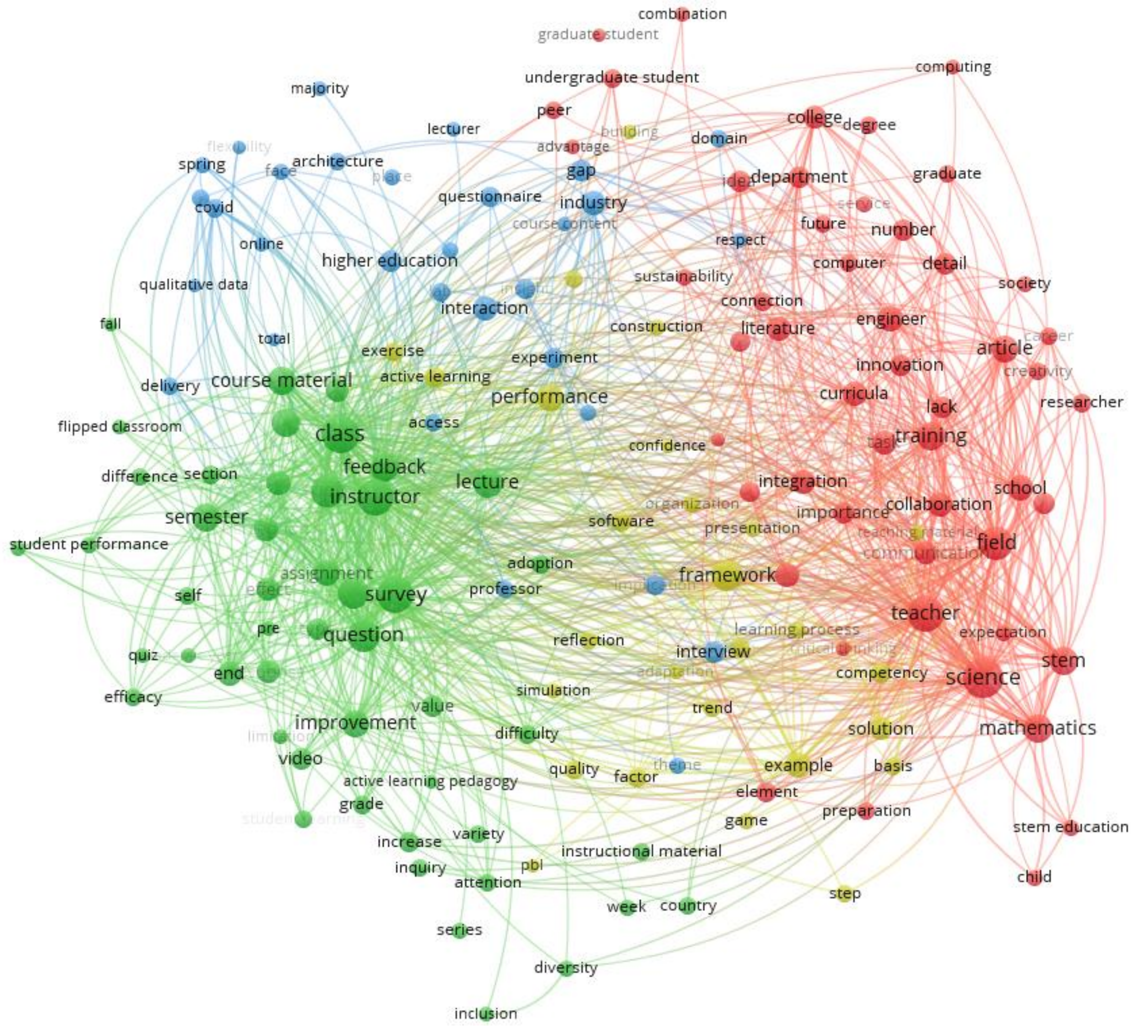

Figure 4. Network visualization of related research networks.

Figure 5 is the result of an overlay visualization using VOSviewer, which depicts research developments related to the keywords "materials AND engineering", "education", and "pedagogy" based on the time period of publication. This visualization utilizes color gradations to show temporal trends, where blue to purple represents older publications (around 2019), while green to yellow indicates newer publications (up to 2021). From **Figure 5**, it can be seen that terms such as class, survey, instructor, question, and course material are dominated by bluish green, which indicates that this topic was actively discussed in the period from 2020 to 2021. Terms such as integration, framework, and interview are in the yellowish green area, indicating that these topics are starting to receive attention in newer publications. Several terms, such as efficacy, combination, and preparation, are marked in bright yellow, indicating that these themes appear in the most recent research trends. Meanwhile, terms such as diversity, inclusion, instructional materials, and student learning are still predominantly colored blue, indicating that more research on this matter was carried out in the early period (2019-2020). This visualization provides a comprehensive overview of how topics in the fields of materials, engineering, education, and pedagogy continue to develop and shows the direction of recent trends that can provide opportunities for future research.

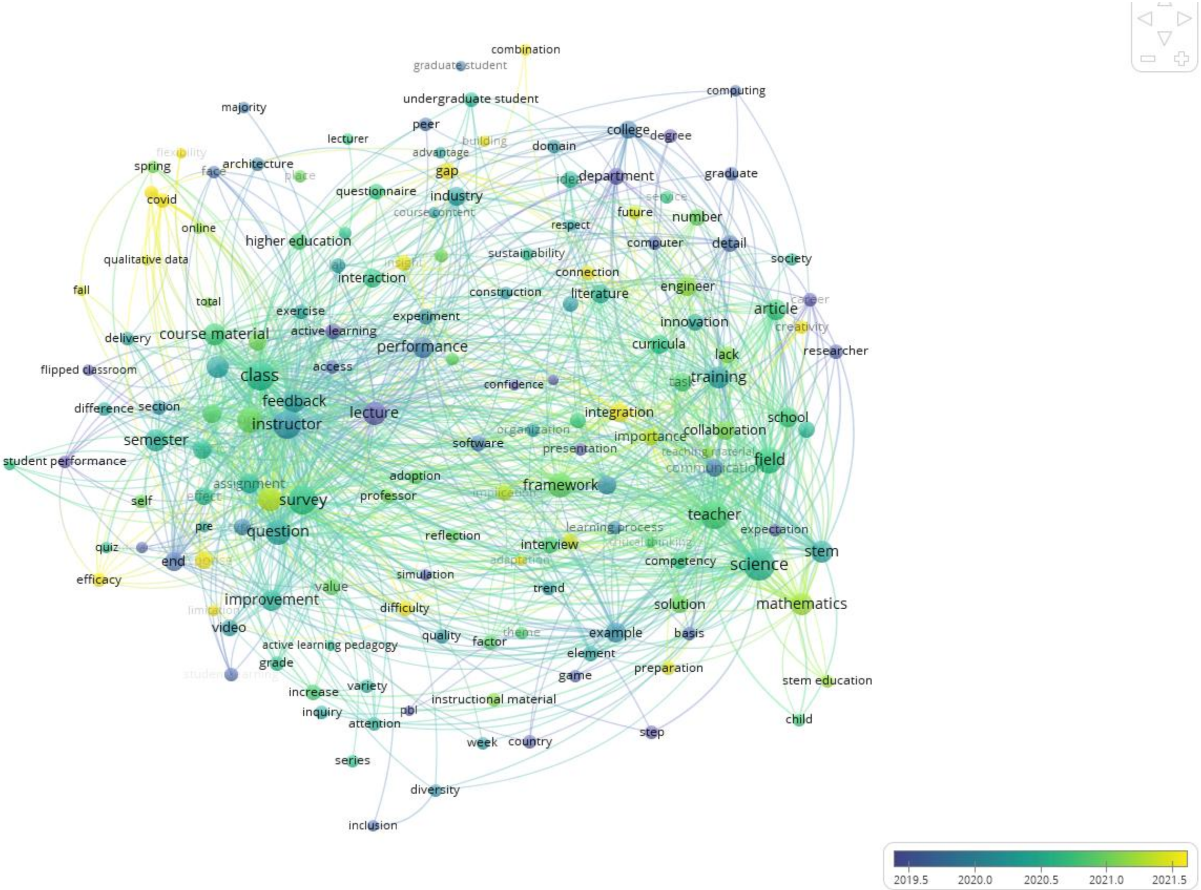

Figure 5. Overlay visualization of related research networks.

3.2. Enrolment Trends of Materials in Engineering

3.2.1. Relating Engineering and Materials

The Materials Science and Engineering (MSE) paradigm is a core conceptual framework that links the manufacturing process of a material (processing), its internal composition or structure (structure), and the resulting properties (properties) (Gomez *et al*., 2022; Goswani *et al*., 2023). This paradigm serves as the main foundation in understanding and engineering materials to meet the needs of various engineering applications. The relationship between these three elements is causal and interdependent (Gomez *et al*., 2022). That is, how a material is processed will determine its internal structure, and that structure will ultimately determine the functional properties of the material. This model is not only important in research and industry, but also very crucial in the development of materials engineering education curricula (Gomez *et al*., 2022).

The first element of this paradigm is processing, which includes all stages of material processing from raw materials to their final usable form (see **Figure 6**). Processing can be categorized into three main types, namely: (i) chemical processing, such as mining, extraction, refining, and synthesis of raw materials; (ii) structural processing or shape formation, which includes mechanical deformation, precipitation, and powder processing; and (iii) biological processing, such as biosynthesis and self-assembly, which are beginning to develop in biomaterial engineering and environmentally friendly technologies. This processing greatly determines the micro and macro structure of the material and affects its final performance (Roeder, 2010).

The second stage is the structure or internal structure of the material, which can be studied at three levels: molecular, crystalline, and microstructure. Molecular structure includes parameters such as molecular weight, conformation, crystallinity, and polymer chain orientation, which greatly affect polymers and biomaterials. Crystalline structure involves aspects such as defects, composition, grain size, and morphology, which are very important in metals and ceramics. Microstructure includes porosity, phase fraction, texture, and gradation, which greatly determine the final mechanical and functional properties of a material. This structure is a direct result of the processing process and is the main determinant of material properties (Roeder, 2010).

The third component is the properties or properties possessed by the material, which are the response of the material to external conditions based on its internal structure. These properties are very broad and are classified into various categories, including mechanical properties (such as tensile strength and hardness), chemical (corrosion resistance, reactivity), electrical (conductivity, resistance), magnetic, thermal (conductivity and thermal expansion), optical (transparency, refractive index), and biological properties (biocompatibility, bioactivity). In the context of engineering, understanding these properties is essential for selecting the right material according to design needs and its operational environment (Roeder, 2010).

This paradigm is not linear in one direction, but rather influences each other in a feedback loop. For example, different processing methods can produce different microstructures, and these structures can be further modified to produce certain properties. On the other hand, the need for certain properties in an application will determine the type of structure and process that must be applied to achieve it (Song *et al*., 2006). In the context of materials engineering education, this paradigm provides a logical and systematic foundation for students to understand how materials are designed and selected, and why different types of processing or structures can produce different performance (Halbe *et al*., 2015).

By teaching the Processing–Structure–Properties paradigm in a comprehensive and applicable way, 21st-century materials engineering education can bridge scientific theory with the practical needs of industry and cutting-edge technology. This is also a key factor in increasing the attractiveness of the materials engineering discipline, as students can see the direct link between manufacturing processes, the final properties of materials, and the role of materials in solving global challenges such as energy, the environment, and health (Huang *et al*., 2021). This paradigm, when presented with innovative pedagogical approaches such as project-based learning and the use of digital simulations, will be a strategic instrument to attract students and increase the enrollment trend in materials engineering.

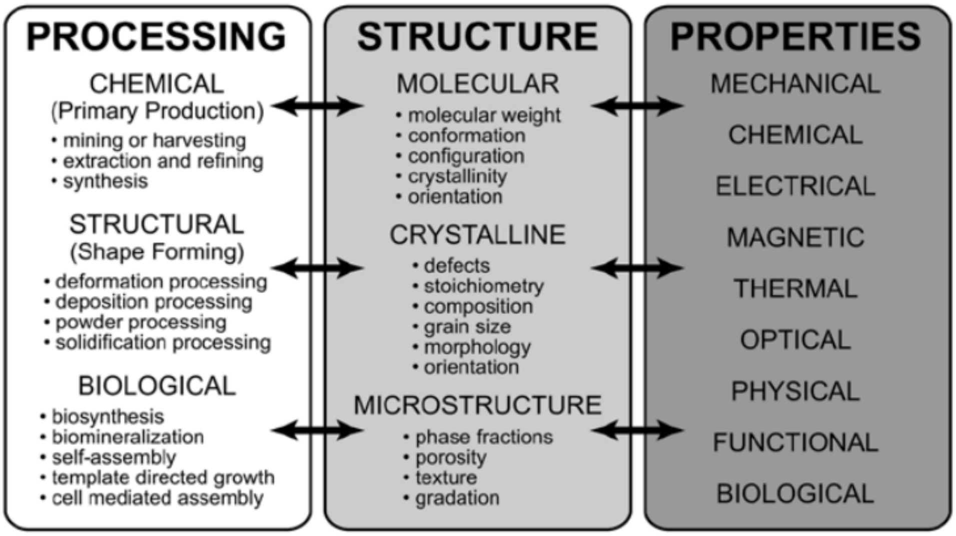

Figure 6. Illustration of the processing-structure-property of the material science and engineering paradigm (Roeder, 2010).

3.2.2. Implications for Research and Education

The development of paradigms in materials science and engineering, from the classical linear model to the systemic and integrated approach, has had a far-reaching impact on the direction of materials engineering research and education in the 21st century. The Processing–Structure–Properties–Performance paradigm has not only become a powerful scientific framework, but has also shaped the way materials engineers think about designing new materials and selecting materials for specific applications (Braha & Maimon, 2002). The expansion of this model to include aspects such as function, design, sustainability, and material life cycle has led to new challenges and opportunities in both research and higher education curricula.

3.2.2.1. Implications for research in materials engineering

Figures 7 and **8** show a visual representation of a contemporary paradigm in materials science and engineering known as the processing-structure-function-stimulus (PSFS) approach. **Figures 7** and **8** present the conceptual framework in a three-sector concentric circle format, each representing three major aspects of materials engineering: processing on the left, structure on the bottom, and function on the right. What distinguishes Figure 3 is the addition of a stimulus dimension at the top, emphasizing that materials are not merely passive, but are also able to actively respond to their environment.

Figures 7 and **8** illustrate a new paradigm in materials science and engineering that shows how processing, structure, and function are interrelated at various levels of scale, from the smallest, such as atoms and molecules, to the largest, such as organs or systems. These three aspects are depicted in the form of concentric circles (the larger the scale, the further outward). In the processing sector, basic processes such as chemical synthesis and biosynthesis are the initial formation of material structures, which can then be modified through processes such as polymerization, crystallization, and thermal treatment, to the formation of shapes and assembly of systems. All of these processes produce material structures that are arranged at various levels, from molecular and macromolecular structures, crystalline and cellular structures, to the final form of organs or systemic devices (Roeder *et al*., 2010).

The structure formed through processing will determine the function of the material. On the functional side, the properties displayed range from the most basic such as molecular and surface properties, to complex functions such as component performance (e.g. artificial bones or sensors) and systemic functions (e.g. the ability of an implant to restore body movement or detect biological changes) (Salonitis *et al*., 2010). In the first figure, the stimulus dimension is added, emphasizing that the function of the material is now not only derived from a fixed structure, but also in response to external signals or stimuli such as pressure, electric fields, temperature, or biological signals. These stimuli are integral to the design of modern materials such as adaptive biomaterials, smart polymers, and biological sensors (Roeder, 2010).

Overall, these two figures illustrate a paradigm shift from a linear and static approach to a dynamic, systemic, and responsive framework, where processing, structure, function, and stimulus do not stand alone but are interrelated in complex causal relationships. This visualization is very useful in designing and directing modern materials research because it allows scientists to map the influence of a process on the internal structure and how the structure determines the function of the material in the face of real-world stimuli. Thus, this paradigm is not only a tool for understanding but also a strategic map in the development of systems-based materials research and technology. The implications of the processing-structure-function-stimulus paradigm for materials engineering research are also summarized in **Table 2**.

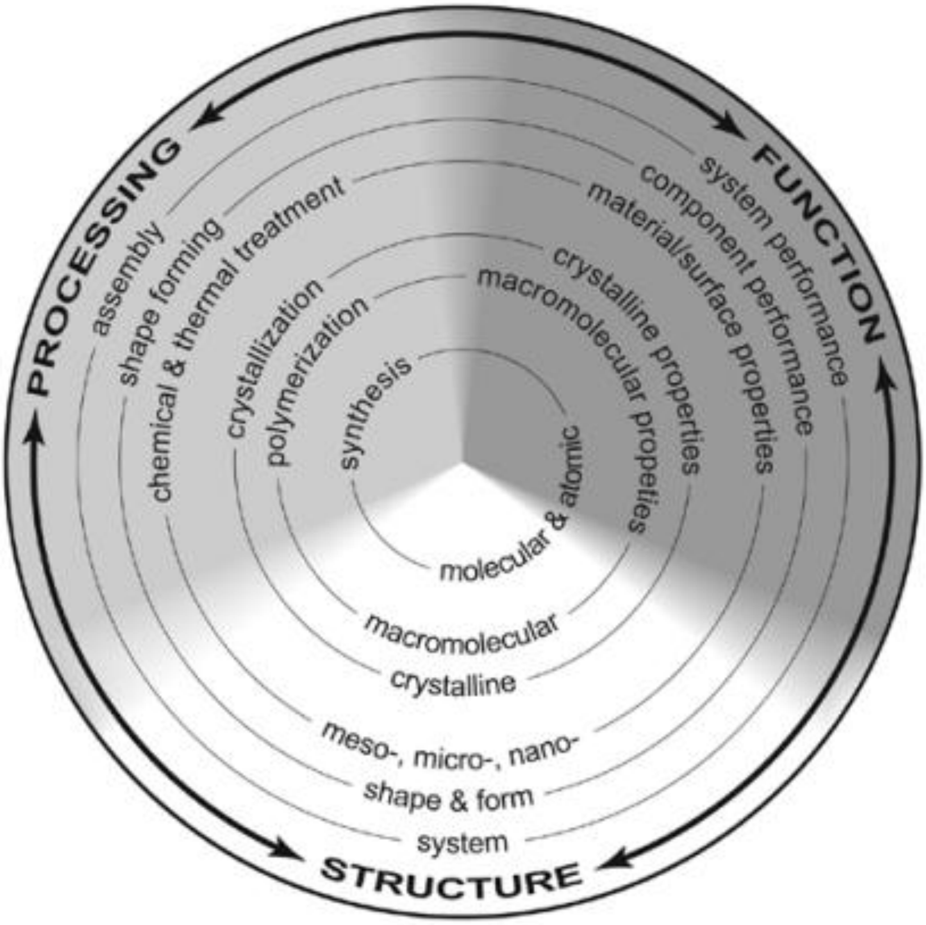

Figure 7. New paradigms in materials science and engineering (Roder, 2010).

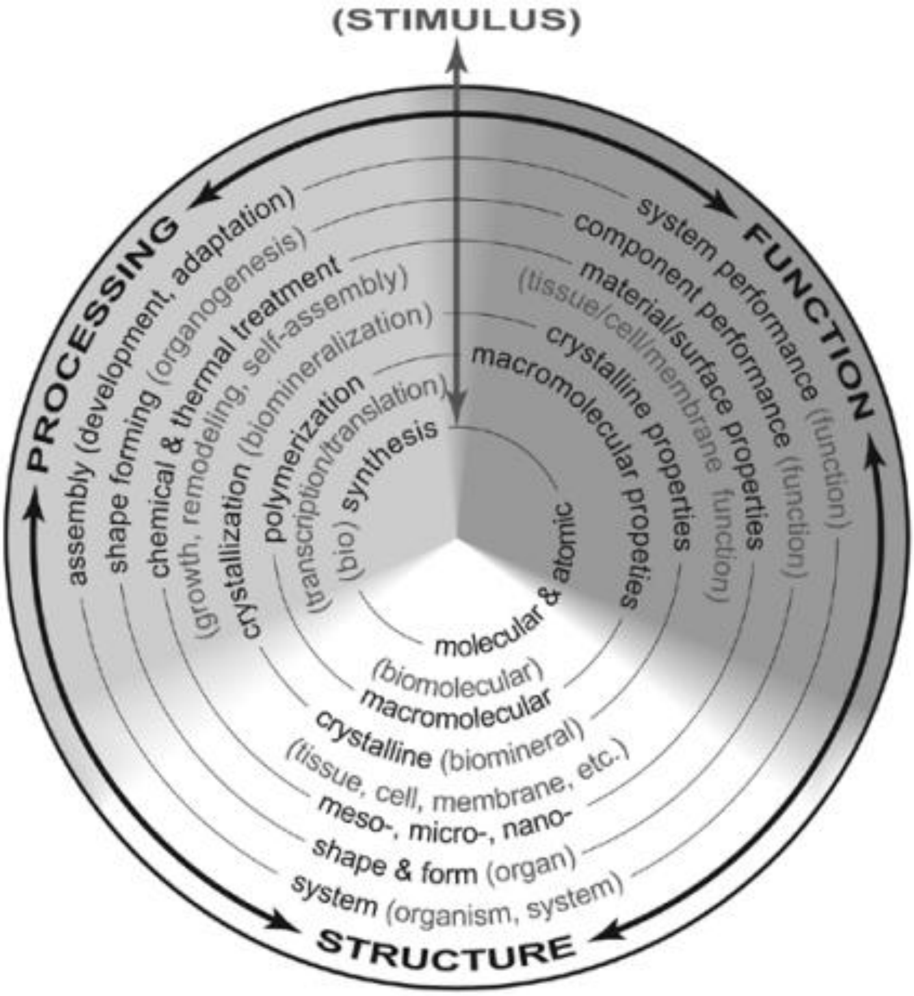

Figure 8. A new paradigm in materials science and engineering with the addition of stimulus aspects (Roder, 2010).

Table 2. Implications of new paradigms for materials engineering research.

Paradigm Aspects	Impact on Materials Engineering Research
Scale Hierarchy (Length Scale)	Developing design and analysis approaches from atoms, molecules, networks, to systems.
Response to Stimulus	Developing responsive materials that are adaptive to the environment (biological, mechanical, chemical)
Integration of Biology and Materials	Enabling biomaterial design based on biological understanding and human-body interactions
Multiscale Prediction and Simulation	Improving design and testing efficiency through computing and materials informatics
Transdisciplinary	Encouraging collaborative work between materials, biomedical, AI, and systems scientists
Clinical Failure Evaluation	Provides a systemic framework for analyzing failure causes beyond the physical properties of the material.

3.2.2.2. Implications of materials engineering in education

Implications of Materials Engineering in Education emphasize that materials engineering education must adapt to the paradigm shift in materials science that is now moving towards an interdisciplinary, systemic, and function-based approach (Tom *et al.*, 2024). This means that the curriculum is not sufficient to simply teach basic properties of materials such as crystal structure or mechanical strength, but must prepare students to understand the relationships between processing, structure, function, and even environmental stimuli in the context of real systems (Roeder, 2010).

The implication is that materials engineering education must integrate multi-scale and multi-domain approaches (see **Table 3**) (Khan & Wells, 2023), thus students are able to see the relationship between material structure at the microscopic level and macroscopic performance in engineering or biological systems. This encourages the need for project-based teaching, problem-based learning, and the use of visual aids such as the PSF (Processing–Structure–Function) loop model, thus students can understand the complexity of material design and application in the real world (Roeder, 2010).

In addition, with the increasing use of materials in biotechnology, health, renewable energy, and adaptive technology, materials engineering education must also open up space for cross-disciplinary collaboration and introduce the concepts of responsive and biomimetic materials early on. Curricula that adopt this approach will prepare students not only as technical experts but also as solution designers who are able to integrate science, engineering, and social contexts in the development of future materials (Tom *et al*., 2024).

Table 3. Implications of the materials engineering paradigm for education.

Paradigm Aspects	Implications for Materials Engineering Education
Multiscale Approach	Students need to understand the relationship between the structure and function of materials from the atomic scale to the system (macro and micro).
Integrasi Processing-Structure-Function	Learning must teach the causal relationships between processes, structures, and functions in a variety of application contexts.
Interdisciplinary	The curriculum should facilitate cross-disciplinary (biomedical, environmental, electrical, etc.) for systems-based materials design.
Response to Stimulus	Students are taught to design responsive materials (pH, temperature, pressure) according to functional needs.
Function and System-Based Design	Focus on students' ability to design materials to fulfill specific functions in a particular system.
Visualization and Paradigm Models	Diagrams such as the PSF are used to help intuitively understand the relationships between material dimensions.
Active and Contextual Learning	Methods such as problem-based learning (PBL) and project-based learning (PJBL) are needed.
Adaptive Technology Readiness	Students need to be introduced to material simulation, modeling, and AI integration from the start of their studies.

4. CONCLUSION

Materials engineering education in the 21st century must move beyond traditional, siloed teaching approaches and adopt an integrated, adaptive, and innovation-oriented framework. The rapid pace of technological advancement, along with complex global challenges such as climate change, resource scarcity, and digital disruption, necessitates a paradigm shift in how future materials engineers are educated. They must not only master technical competencies but also demonstrate interdisciplinary literacy, systems thinking, sustainability awareness, and critical problem-solving skills. This study affirms that the incorporation of the Processing-Structure-Properties-Function-Stimulus (PSPFS) paradigm into engineering curricula offers a comprehensive and logical structure for understanding the behavior and design of advanced materials. By emphasizing the interconnections between how materials are processed, their microstructure, resulting properties, intended functions, and external stimuli, the PSPFS model helps students bridge the gap between theory and real-world application.

5. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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