RESEARCH PAPER

Drug Delivery Strategies in Sports Medicine: A Bibliometric and Science Mapping Analysis

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Abstract

Research on drug delivery strategies in sports medicine has expanded rapidly due to advances in biomedical engineering, pharmacology, and regenerative medicine. These developments have introduced innovative therapeutic technologies aimed at improving treatment outcomes for musculoskeletal injuries commonly experienced by athletes. However, despite the increasing volume of publications, a comprehensive understanding of the research landscape and emerging trends within this interdisciplinary field remains limited. Therefore, this study aimed to conduct a bibliometric and science mapping analysis of global research on drug delivery strategies in sports medicine. Bibliographic data were collected from a scientific database and analyzed using bibliometric techniques, including keyword co-occurrence analysis, thematic mapping, and network visualization. The analysis was performed using bibliometric tools such as VOSviewer and Bibliometrix to identify major research themes, influential topics, and evolving research trends. The results indicate a steady growth in scientific production over the past two decades, reflecting increasing scholarly interest in targeted drug delivery technologies for musculoskeletal disorders. Key research themes include drug delivery systems, tissue engineering, osteoarthritis, and regenerative therapies such as stem cells and platelet-rich plasma. Emerging topics related to nanomedicine and biologically responsive delivery platforms suggest a growing shift toward precision-based therapeutic strategies. Overall, the findings provide valuable insights into the intellectual structure of the field and highlight future research directions for developing advanced therapeutic solutions in sports medicine.

Keywords: bibliometric analysis; drug delivery systems; sports medicine; tissue engineering; regenerative medicine

How to cite this article: Juezan GI, Fuentes HE, Ligue NJD, Alo MP, Manonggireng AL, Condes RB, Matalandang S. Drug Delivery Strategies in Sports Medicine: A Bibliometric and Science Mapping Analysis. Int J Drug Deliv Technol. 2026;16(14s): 100-109. DOI: 10.25258/ijddt.16.14s.15

Introduction

Sports medicine has increasingly integrated advances from biomedical sciences to improve the prevention, diagnosis, and treatment of sports-related injuries. In particular, Bahr et al. (2020) noted that athletes frequently experience musculoskeletal injuries such as cartilage damage, osteoarthritis, ligament tears, and bone fractures, which require effective therapeutic interventions to restore function and performance. Furthermore, recent innovations in pharmaceutical sciences and biomedical engineering have contributed to the development of advanced drug delivery systems designed to enhance therapeutic efficiency, target injured tissues, and reduce systemic side effects (Mitragotri et al., 2014). In addition, these emerging technologies include nanoparticle-based delivery systems, biomaterials, hydrogels, and regenerative medicine approaches such as stem cell therapy and platelet-rich plasma applications. Yang et al. (2012) highlighted that such biomedical technologies have enabled controlled drug release and improved tissue regeneration in injured tissues. Consequently, drug delivery strategies have become an important component of modern sports medicine and rehabilitation, supporting more effective treatment outcomes and faster recovery among athletes (Kumaran et al., 2018).

Drug delivery technologies aim to improve the pharmacokinetic and pharmacodynamic properties of therapeutic agents by enabling controlled, targeted, and sustained release of drugs at specific sites within the body. According to Mitchell et al. (2020), these systems enhance therapeutic efficiency by optimizing drug

distribution and minimizing systemic side effects. In the context of sports medicine, such technologies are particularly valuable for treating localized musculoskeletal injuries, promoting tissue regeneration, and accelerating recovery (O'Donovan et al., 2020). For instance, biomaterial-based scaffolds and hydrogel systems have been widely explored for cartilage repair and tissue engineering. Li and Mooney (2016) explained that nanomedicine approaches enable more precise drug targeting and improved therapeutic performance in regenerative treatments. Consequently, these interdisciplinary developments have significantly expanded the scope of treatment strategies for sports-related conditions (Papalia et al., 2019).

Over the past two decades, research on drug delivery strategies related to sports medicine has grown rapidly across multiple disciplines, including pharmacology, biomedical engineering, tissue engineering, and regenerative medicine. Patra et al. (2018) highlighted that advances in nanotechnology and biomedical innovation have significantly contributed to the development of more effective therapeutic delivery systems. Consequently, the increasing number of scientific publications reflects the growing interest of researchers in developing innovative technologies for sports injury management (Starosolski et al., 2021). However, despite this expanding body of literature, there remains limited comprehensive understanding of the overall research landscape, including major research themes, influential topics, and emerging trends within this interdisciplinary field. Donthu et al. (2021) emphasized that systematic mapping of scientific publications is necessary to better understand the development and structure of a research domain. Therefore, mapping the intellectual structure of the literature can provide valuable insights into how the field has evolved and help identify potential directions for future research (Aria & Cuccurullo, 2017).

Bibliometric analysis has become a widely used methodological approach for quantitatively evaluating scientific publications and identifying patterns within research fields. In particular, Van Eck and Waltman (2017) explained that bibliometric techniques such as keyword co-occurrence analysis, thematic mapping, and network visualization enable researchers to examine the conceptual structure, collaboration networks, and research trends within a specific domain. Furthermore, these analytical approaches provide a systematic method for understanding how scientific knowledge develops over time and across disciplines. In addition, various software tools have been developed to facilitate science mapping and bibliometric visualization. For instance, tools such as VOSviewer and Bibliometrix have been widely used to analyze large bibliographic datasets and reveal relationships among authors, keywords, and research topics (Kurt & Kurt, 2019).

Despite the increasing interest in drug delivery technologies and their applications in sports medicine, bibliometric studies examining this interdisciplinary field remain limited. Moral-Muñoz et al. (2020) emphasized that many existing bibliometric investigations tend to focus on specific therapeutic technologies or biomedical applications rather than offering a comprehensive overview of the broader research landscape. Consequently, this limitation creates a gap in understanding the intellectual structure, research trends, and thematic development within the field. Therefore, a systematic bibliometric investigation is needed to identify major research themes, emerging topics, and the overall development of research on drug delivery strategies in sports medicine.

The present study aims to analyze the global research landscape of drug delivery strategies in sports medicine through a bibliometric and science mapping approach. Using data retrieved from the Lens database and analytical tools such as VOSviewer and Bibliometrix, this study examines publication trends, keyword co-occurrence networks, thematic structures, and emerging research directions from 2000 to 2025. By providing a comprehensive overview of the scientific development of this field, the study contributes to a better understanding of the evolving role of drug delivery technologies in sports medicine and highlights potential avenues for future research.

Research Objectives

The primary objective of this study is to examine the global research landscape of drug delivery strategies in sports medicine using bibliometric and science mapping techniques.

Specifically, the study aims to:

1. Analyze the annual scientific production related to drug delivery strategies in sports medicine from 2000 to 2025.
2. Identify the major research themes and keyword relationships through keyword co-occurrence analysis.

3. Examine the temporal evolution of research topics in the field using overlay visualization.
4. Determine the main research hotspots and thematic structures using density visualization and thematic mapping.
5. Explore the intellectual and conceptual structure of the field by analyzing relationships among cited references, authors, and keywords.

Research Questions

To achieve the objectives of this study, the following research questions were addressed:

1. How has the scientific production on drug delivery strategies in sports medicine evolved over time?
2. What are the dominant research themes and keyword networks within the field?
3. How have research topics in drug delivery strategies for sports medicine evolved over the years?
4. What are the major research hotspots and thematic clusters within the literature?
5. What relationships exist among influential references, authors, and research topics in this field?

Methods

Data Source and Search Strategy

This study employed a bibliometric and science mapping approach to analyze the research landscape of drug delivery strategies in sports medicine. Bibliographic data were retrieved from the Lens.org scholarly database, which integrates publications from multiple scientific repositories including CrossRef, PubMed, and other academic indexing systems. Lens.org was selected because of its broad coverage of multidisciplinary research and accessibility for bibliometric analysis.

A structured search query was developed to capture publications related to drug delivery systems within the context of sports medicine and musculoskeletal injuries. The search string combined key terms associated with drug delivery technologies and sports medicine applications, including “drug delivery,” “drug delivery system,” “targeted drug delivery,” and “controlled release,” together with terms such as “sports medicine,” “sport injury,” “athletic injury,” and “musculoskeletal injury.” The search was conducted in the title, abstract, and keyword fields to ensure comprehensive coverage of relevant publications.

The initial search yielded 3,070 records. To ensure the relevance and quality of the dataset, several inclusion criteria were applied. The search was limited to publications between 2000 and 2025, reflecting the modern development of advanced drug delivery technologies. Only journal articles were included in the analysis to ensure that the dataset consisted of peer-reviewed scholarly publications. Additionally, records were filtered based on relevant subject areas including sports therapy, rehabilitation, and biomedical engineering.

After applying these inclusion criteria, 637 records remained. Further screening was conducted to remove irrelevant or duplicate records and to ensure consistency with the research focus. A total of 560 records were assessed for eligibility, and after final verification, 517 publications were included in the bibliometric analysis. The literature screening and selection process is illustrated in the PRISMA flow diagram (Figure 1).

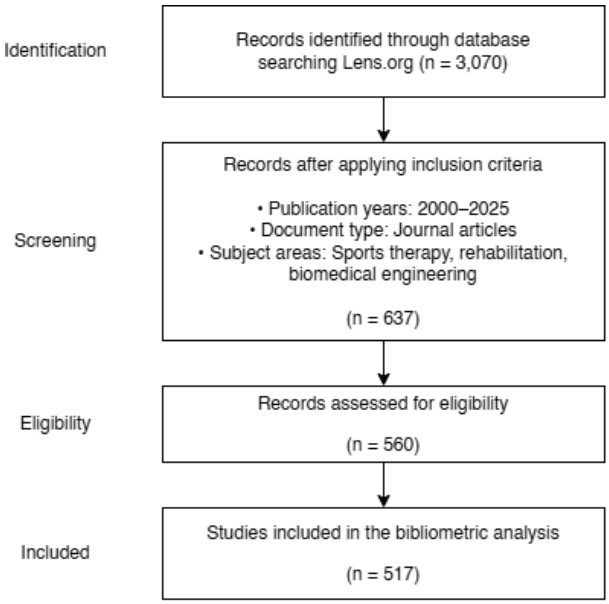

Figure 1. PRISMA Flow Diagram of the Literature Selection Process

Bibliometric Analysis Tools

Two widely used bibliometric software tools were employed to conduct the analysis: VOSviewer (version 1.6.x) and Bibliometrix (version 4.x) implemented through the Biblioshiny web interface in R. VOSviewer was used to generate network visualizations and perform science mapping analyses, including keyword co-occurrence networks, overlay visualization

of research trends, and density visualization of research hotspots. VOSviewer is widely recognized for its ability to construct and visualize bibliometric networks, enabling the identification of relationships among keywords, research themes, and scientific topics.

Bibliometrix was used to perform complementary bibliometric analyses, including annual scientific production and thematic mapping. The Biblioshiny interface allows users to perform advanced bibliometric analyses through an interactive environment, facilitating the identification of thematic structures, conceptual relationships, and knowledge development patterns within the research field.

Data Processing and Analysis

The bibliographic dataset exported from Lens.org was downloaded in CSV format and subsequently imported into VOSviewer and Bibliometrix for analysis. Prior to the analysis, the dataset was examined to ensure consistency in bibliographic fields such as authors, keywords, and publication years.

Keyword Co-occurrence Analysis

Keyword co-occurrence analysis was conducted using VOSviewer to identify the major research themes and conceptual relationships within the field. Author keywords were selected as the unit of analysis because they represent the core topics addressed in each publication. A minimum occurrence threshold of five occurrences per keyword was applied to ensure that only frequently appearing keywords were included in the network visualization. The resulting map illustrates clusters of related keywords that represent dominant research themes in the literature.

Overlay Visualization of Research Trends

To examine the temporal evolution of research topics, an overlay visualization was generated using VOSviewer. This analysis assigns colors to keywords based on the average publication year of the documents in which they appear. Earlier topics are typically represented in cooler colors such as blue or green, while more recent research trends appear in warmer colors such as yellow. This approach enables the identification of emerging research topics and evolving thematic patterns within the field.

Density Visualization of Research Hotspots

Density visualization was also performed in VOSviewer to identify the most intensively studied research areas. In this visualization, regions with a high concentration of keywords appear in bright colors, indicating research hotspots. This analysis highlights key topics that have received significant scholarly attention within the domain of drug delivery strategies in sports medicine.

Thematic Mapping

Thematic mapping was conducted using Bibliometrix to analyze the conceptual structure of the research field. The thematic map categorizes research themes according to two dimensions: centrality, which reflects the importance of a theme within the overall research network, and density, which indicates the level of development of a particular theme. Based on these dimensions, themes are classified into four categories: motor themes, basic themes, niche themes, and emerging or declining themes. This analysis provides insights into the maturity and relevance of different research topics within the field.

Annual Scientific Production

Annual scientific production was analyzed using Bibliometrix to examine the growth of publications over time. This analysis calculates the number of publications per year within the dataset and visualizes the overall trend of research activity from 2000 to 2025. The results provide insights into the evolution and increasing scholarly interest in drug delivery strategies applied to sports medicine and musculoskeletal injury treatment.

Visualization and Interpretation

The bibliometric results were presented using network maps and graphical visualizations generated through VOSviewer and Bibliometrix. These visualizations allow for the identification of relationships among research themes, emerging trends, and influential topics within the field. The figures generated from the analysis include keyword co-occurrence networks, overlay visualizations, density maps, thematic maps, and annual publication trends. These visualizations collectively provide a comprehensive overview of the development and structure of research on drug delivery strategies in sports medicine.

Results

Annual Scientific Production

The increasing trend in annual scientific production indicates that research on drug delivery strategies in sports medicine has gradually gained attention over the past two decades. The relatively low number of publications in the early years suggests that the integration of drug delivery technologies within sports medicine was still in its initial stage of

development. Beginning in the mid-2000s, a gradual rise in the number of publications became evident, reflecting a growing interest in the application of biomedical innovations for the treatment of sports-related injuries and musculoskeletal conditions. The noticeable growth after 2010 indicates a period where research activity intensified, likely due to advancements in biomaterials, regenerative medicine, and controlled drug delivery systems that support tissue repair and rehabilitation. Although minor fluctuations were observed across several years, the overall upward trajectory demonstrates a sustained expansion of scholarly activity in this field. The significant increase in publication output in the most recent years further suggests that drug delivery strategies are becoming an increasingly important research area in sports medicine, highlighting the expanding interdisciplinary collaboration among biomedical engineering, pharmacology, and sports health sciences in addressing injury treatment and recovery among athletes and physically active individuals.

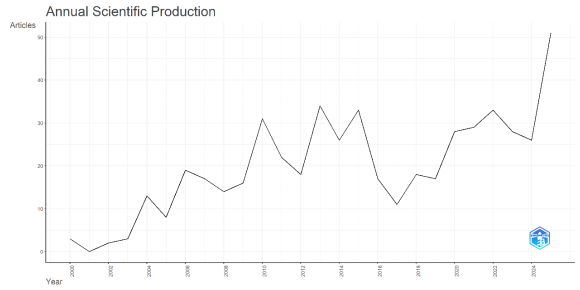

Figure 2. Annual scientific production in drug delivery strategies in sports medicine (2000–2025).

Keyword Co-occurrence Network

The conceptual structure of the research field is illustrated in Figure 3, which presents the keyword co-occurrence network generated using VOSviewer. The network map reveals several interconnected clusters that represent the major thematic areas within research on drug delivery strategies in sports medicine. Prominent keywords such as drug delivery, tissue engineering, and osteoarthritis appear as central nodes in the network, indicating their significant influence and frequent occurrence in the literature. The cluster surrounding drug delivery is strongly linked with related concepts including inflammation, nanomedicine, cartilage, and stem cell therapy, suggesting a strong focus on therapeutic delivery approaches for treating inflammatory and degenerative musculoskeletal conditions. Another major cluster is centered on tissue engineering, which connects with keywords such as biomaterials, hydrogel, extracellular matrix, and scaffolds, highlighting the role of biomaterial-based platforms in supporting tissue repair and regeneration. Additional connections are observed among terms such as stem cells, exosomes, bone regeneration, and platelet-rich plasma, reflecting the integration of regenerative medicine techniques within drug delivery research. Overall, the network demonstrates that the field is characterized by strong interdisciplinary relationships among biomaterials science, regenerative medicine, and therapeutic drug delivery technologies aimed at improving treatment strategies for sports-related musculoskeletal injuries.

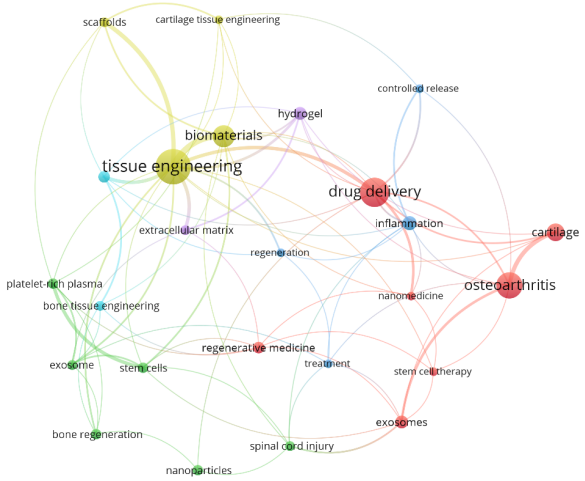

Figure 3. Keyword Co-occurrence Network of Research on Drug Delivery Strategies in Sports Medicine

Overlay Visualization of Research Trends

The temporal evolution of research topics in drug delivery strategies in sports medicine is illustrated in Figure 4, which presents the overlay visualization generated using VOSviewer. In this visualization, the color gradient represents the average publication year of the keywords, where earlier research topics appear in cooler colors such as blue and purple, while more recent topics are shown in warmer colors such as green and yellow. The map indicates that earlier studies in the field were primarily associated with foundational themes such as cartilage, controlled release, and biomaterials, which served as the initial scientific basis for drug delivery research in musculoskeletal treatment. As the field

progressed, newer themes began to emerge, including tissue engineering, drug delivery, and osteoarthritis, which appear near the central region of the network, reflecting their increasing importance in recent studies. The visualization also highlights emerging topics represented by warmer colors, such as exosomes, stem cell therapy, and spinal cord injury, suggesting that recent research is expanding toward regenerative medicine and advanced biological therapies. Overall, the overlay map demonstrates a clear progression in research focus from traditional biomaterial-based delivery systems toward more advanced regenerative and nanotechnology-based therapeutic approaches aimed at improving treatment outcomes for sports-related musculoskeletal injuries.

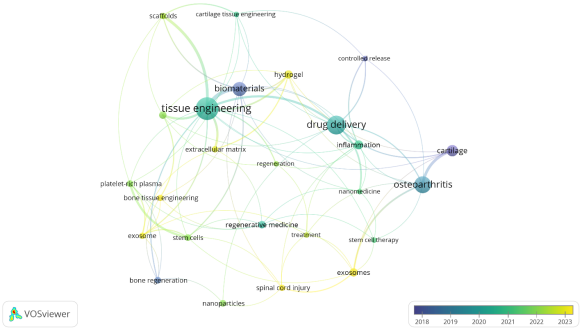

Figure 4. Overlay Visualization of the Temporal Evolution of Research Topics

Density Visualization of Research Hotspots

The density visualization of keyword occurrences is presented in Figure 5, highlighting the areas of highest research concentration within the field of drug delivery strategies in sports medicine. In this visualization, brighter colors such as yellow represent keywords with higher occurrence frequency and stronger connections within the network, while cooler colors such as green and blue indicate topics with relatively lower density. The map shows that tissue engineering, drug delivery, and osteoarthritis appear as the most prominent and densely connected research topics, suggesting that these areas form the central focus of the literature. These high-density clusters indicate that a large number of studies have explored the development of biomaterial-based therapeutic systems aimed at improving tissue repair and treating degenerative joint conditions commonly associated with sports injuries. Surrounding these central themes are related research topics such as biomaterials, hydrogel, cartilage, and inflammation, which further highlight the integration of material science and biomedical approaches in drug delivery research. Additional areas of moderate research activity include stem cells, exosomes, platelet-rich plasma, bone regeneration, and nanoparticles, reflecting the growing interest in regenerative medicine and biologically driven therapeutic strategies. Overall, the density map reveals that research in this field is strongly centered on the intersection of drug delivery technologies, biomaterials, and regenerative therapies, which collectively contribute to advancing treatment approaches for sports-related musculoskeletal injuries and degenerative conditions.

Figure 5. Density visualization of research hotspots in drug delivery strategies in sports medicine.

Thematic Map of Research Themes

The conceptual structure of the research field is further illustrated in Figure 6, which presents the thematic map generated using Bibliometrix. The map classifies research themes according to two dimensions: centrality, representing the relevance of a theme within the overall research field, and density, indicating the degree of development of a particular theme. Based on these dimensions, the themes are organized into four quadrants: motor themes, basic themes, niche themes, and emerging or declining themes. In the motor themes quadrant, topics such as regenerative medicine, platelet-rich plasma, and stem cells appear as well-developed and highly important themes, suggesting their strong influence and continued development in drug delivery research related to sports medicine. The basic themes quadrant includes central but less developed topics such as drug delivery, inflammation, and cartilage tissue engineering, indicating that these themes form the fundamental knowledge base of the field. In the niche themes quadrant, specialized topics such as stability, generalization, perturbation, and computational fluid

dynamics are observed, reflecting well-developed but more isolated research areas with limited integration into the broader research network. Meanwhile, the emerging or declining themes quadrant contains topics such as interstitial fluid pressure and mesoporous silica nanoparticles, which may represent either newly emerging research directions or areas that have received relatively limited attention in recent years. Overall, the thematic map reveals that research on drug delivery strategies in sports medicine is strongly centered on regenerative therapies, biomaterial development, and targeted therapeutic delivery systems aimed at improving treatment outcomes for musculoskeletal injuries.

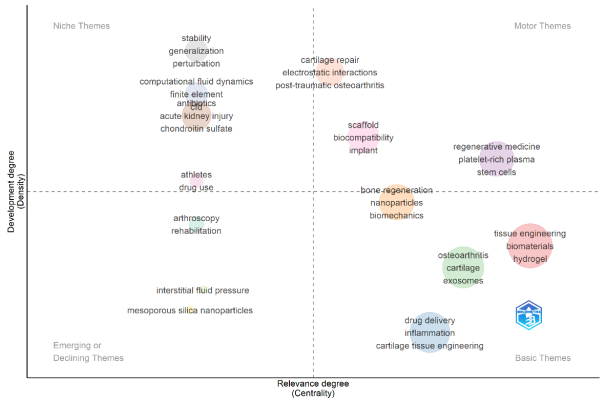

Figure 6. Thematic map of research themes in drug delivery strategies in sports medicine.

Discussion

The bibliometric findings indicate that research on drug delivery strategies in sports medicine has steadily expanded over the past two decades, reflecting the growing integration of biomedical engineering, pharmacology, and regenerative medicine within musculoskeletal health research. In particular, Ballestar and Li (2017) noted that targeted drug delivery technologies have become increasingly relevant for addressing complex sports-related injuries, particularly those involving cartilage degeneration, inflammation, and impaired tissue regeneration. Consequently, the increasing annual scientific production suggests that researchers are placing greater emphasis on innovative therapeutic solutions for sports injury management. Moreover, the observed rise in publications after 2010 likely corresponds with technological advancements in biomaterials, nanotechnology, and regenerative therapies, which have enabled the development of more precise and localized treatment approaches for orthopedic conditions (O'Brien, 2011). Furthermore, these developments highlight the growing recognition that conventional systemic treatments may be insufficient for managing joint injuries and degenerative conditions. As a result, researchers have increasingly explored controlled and site-specific therapeutic delivery systems as alternative treatment strategies (Barranco, 2016).

The keyword co-occurrence network further demonstrates that the research field is strongly centered around interconnected themes such as drug delivery, tissue engineering, and osteoarthritis, which collectively form the conceptual core of the literature. In particular, Bradley (2018) noted that biomaterial-based platforms such as hydrogels, scaffolds, and extracellular matrix systems play a crucial role in supporting both structural tissue repair and controlled therapeutic release. Consequently, these biomaterial-related terms frequently appear in the literature, indicating that many current studies focus on designing advanced biomaterial platforms for musculoskeletal regeneration. Moreover, the prominence of osteoarthritis-related keywords highlights the clinical significance of degenerative joint diseases within sports medicine. Hunter and Bierma-Zeinstra (2019) emphasized that athletes and physically active individuals often experience cartilage damage and chronic joint inflammation, which require effective and targeted therapeutic interventions. In this context, biomaterial-assisted delivery systems have emerged as an essential strategy for enhancing therapeutic efficacy while minimizing systemic side effects. As a result, these technologies contribute to improved treatment outcomes for various musculoskeletal disorders (Shi et al., 2016).

The overlay visualization of research trends suggests that the thematic focus of the field has gradually shifted from traditional biomaterial and controlled-release studies toward more advanced regenerative and biologically driven therapies. In particular, Murray et al. (2017) highlighted that emerging topics such as exosomes, stem cell therapy, and nanomedicine reflect the growing interest in biologically active therapeutic strategies designed to stimulate tissue regeneration and regulate inflammatory responses. Consequently, these developments indicate a significant transition from purely material-based delivery systems toward more integrated regenerative platforms. Mao and Mooney (2015) explained that modern therapeutic strategies increasingly combine biomaterials, biologics, and cellular therapies to enhance tissue repair and regenerative outcomes. However, despite the promising

therapeutic potential of these innovations, several challenges remain in translating these technologies into clinical practice. For instance, issues related to biological standardization, manufacturing scalability, and regulatory approval continue to pose significant obstacles in the development of advanced regenerative treatments (Trounson & McDonald, 2015).

The thematic map provides additional insight into the maturity and structural composition of the research field by distinguishing between motor, basic, niche, and emerging themes. In particular, Andia and Maffulli (2013) noted that topics such as regenerative medicine, stem cells, and platelet-rich plasma represent motor themes, indicating that these areas are both highly developed and central to the advancement of sports medicine research. Meanwhile, foundational themes such as drug delivery, inflammation, and cartilage tissue engineering continue to serve as essential research domains that support ongoing scientific development and innovation (Robinson et al., 2016). Furthermore, the presence of emerging themes related to nanoparticle-based delivery systems and microenvironmental factors suggests that future research may increasingly focus on precision-targeted therapeutic strategies capable of improving drug delivery efficiency and enhancing tissue regeneration. Frantz et al. (2015) emphasized that understanding the biological microenvironment is critical for designing advanced biomaterial-based delivery systems. Collectively, these findings indicate that the future direction of drug delivery research in sports medicine will likely involve multidisciplinary collaboration aimed at developing advanced, biologically responsive delivery platforms. As a result, such innovations may enhance recovery, reduce inflammation, and support long-term musculoskeletal health among athletic populations (Webber & Langer, 2017).

Conclusion

In conclusion, this bibliometric and science mapping analysis provides a comprehensive overview of the research landscape on drug delivery strategies in sports medicine over the past two decades. The findings reveal a steady growth in scientific production, reflecting the increasing integration of biomedical engineering, pharmacology, and regenerative medicine in addressing musculoskeletal injuries among athletes. Furthermore, the keyword co-occurrence and thematic analyses indicate that the field is strongly centered on interconnected themes such as drug delivery systems, tissue engineering, and osteoarthritis, with emerging research directions emphasizing regenerative medicine, nanomedicine, and biologically driven therapeutic strategies. The thematic map also highlights the central role of regenerative therapies, including stem cells and platelet-rich plasma, as key drivers of innovation within the field. Overall, these results suggest that future research will likely focus on multidisciplinary and precision-targeted therapeutic approaches that combine biomaterials, biologics, and advanced delivery platforms to enhance tissue regeneration, reduce inflammation, and improve recovery outcomes in sports-related musculoskeletal conditions.

Statement of Ethics

This study involved the analysis of publicly available bibliographic data retrieved from the Lens.org scholarly database and did not include human participants or identifiable personal information. Therefore, ethical approval was not required.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

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