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The evolving landscape of pharmacotherapy for spinal cord injury

Three decades of progress and future prospects

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Abstract:

Background: Pharmacological interventions for spinal cord injury have shifted from symptom management to complex regenerative strategies over the past three decades. This study aimed to systematically synthesize this trajectory and identify emerging research paradigms.

Methods: A bibliometric analysis was conducted using the Web of Science Core Collection. A total of 3,470 original research articles published between 1992 and 2025 were retrieved. Network analysis (via CiteSpace) was performed to decode publication trends, collaborative patterns, and the evolution of research foci.

Results: Research foci transitioned from generalized antiinflammatory strategies toward targeted molecular pathways and regenerative mechanisms. The United States maintained historical leadership in citation impact, while China demonstrated explosive growth in research output since 2022. Key research hotspots evolved from traditional small-molecule drugs to advanced frontiers, including nanomedicine, biomaterial scaffolds, exosomes, hydrogels, and cell-free therapies.

Conclusions: Pharmacotherapy for spinal cord injury is transitioning toward precision medicine. Combinatorial strategies integrating advanced drug delivery systems with targeted drugs represent a promising trajectory toward functional neural repair.

Abbreviations: MP = methylprednisolone, SCI = spinal cord injury, WoS = web of science.

Keywords: nanomedicine, neural regeneration, pharmacological trends, research paradigm shift, spinal cord injury

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1. Introduction

Spinal cord injury (SCI) often leads to patients losing motor and sensory functions. About 180,000 new cases occur every year, which causes a heavy economic burden to society and families simultaneously.[1] The prognosis of SCI is poor, and many people suffer the consequences throughout their lives. SCI is divided into traumatic and nontraumatic etiologies. The former type of SCI is more commonly seen.[2] With the development of spinal deformity surgery, distraction SCI,[3] which is the most dangerous iatrogenic injury problem along with the surgery, has become an urgent problem to be solved.[4]

Since the 1990s, many scholars have begun to pay attention to the possibility of drug treatment for SCI.[5,6] The main idea is to control neural inflammation or promote nerve regeneration. Hormonal drugs represented by methylprednisolone (MP) have been widely used in the acute stage of SCI.[7] However, criticisms suggest that the side effects outweigh the potential neural protection effect.[8] In recent years, the concept of drug therapy has expanded, and new concepts, such as stem cell therapy and nanomedicine systems, have emerged, bringing hope for the drug therapy of SCI.

The bibliometric analysis method can synthesize existing research in related fields, explain the development

of a subfield through the analysis of a large number of documents, reveal the cooperation and relationship between research fields, countries, and authors, and find current research hotspots. In this study, we adopt a broad operational definition of "pharmacotherapy" that encompasses not only traditional small-molecule drugs (e.g., MP, riluzole) but also advanced therapy medicinal products. This inclusion is justified by the evolving regulatory landscape where biologics, cell-based therapies, and exosome-derived agents are increasingly evaluated as "living drugs" or bioactive therapeutics aimed at modifying the pathological microenvironment.[9] We conducted this bibliometric analysis to synthesize the development and changes in drug therapy for SCI to reveal the research hotspots and expand the current understanding of SCI drug therapy.

2. Materials and methods

2.1. Data acquisition and retrieval strategy

The Web of Science (WoS) database was used to search for publications on drug therapy for SCIs. We used the search terms "SCI", "drug therapy" and "pharmacological treatment" to find the related studies in WoS core collection. No restriction on language was set. The retrieval time span was set from 1992 to 2025. This period was selected to capture over three decades of intellectual trajectory, beginning from the early 1990s when pharmacological interventions for SCI first gained significant global attention. The exclusion criteria were as follows: (1) meeting abstracts, editorials, letters, and corrections; (2) articles not related to biological or pharmacological interventions (e.g., purely biomechanical studies or epidemiological surveys without a treatment focus).

2.2. Bibliometric analysis and visualization

The analysis of the number of national, institutional, and journal publications and the research areas was realized through the "analyze results" of WoS. Journal impact factors and category quartiles were acquired from the 2024 journal citation reports (Clarivate Analytics, Philadelphia). The trend in publications over the years was visualized by Microsoft Excel 2016.

CiteSpace version 6.4.R1[10,11] was utilized to visualize the structural and temporal patterns of the scientific domain. We employed betweenness centrality to identify pivotal nodes (hubs) connecting different clusters and burst detection algorithms to capture rapid increases in scientific interest, indicative of emerging trends. WoS data were converted to txt format for further analysis. We analyze citations of publications, co-authorship of countries/institutions/authors, co-citation of authors/journals/references, and co-occurrence of keywords. In the visual map, various nodes represent countries/institutions/journals/authors/references/keywords. The size of the nodes represents the amount of publications/citations/frequency of occurrence; different colors represent clusters/the average appearing year; and the thickness of the line represents the strength of the link between the nodes. A dual-map overlay for journals was constructed. We conducted cluster analysis for co-cited references and keywords, and detection of references and keywords with intense citation bursts. The parameters of CiteSpace were set as follows: link retaining factor (LR = 3), look back years (LBY = 5), e for the top N (e = 1), time span (1992–2025), years per slice (3), links (strength: cosine, scope: within slices), selection criteria (g-index: k = 25), and minimum duration for keyword/phrase (m = 2).

3. Results

3.1. Bibliometric analysis of annual publication output from 1992 to 2025

A total of 3,470 publications about drug therapy for SCI were identified in the WoS database between 1992 and 2025. The distribution depicting years of publication and the number of citations received is presented in Figure 1. The highest number of published studies was in 2025 (244 papers); the number of annual documents showed a linear growth trend. ($y = 5.9176x$, $R^2 = 0.966$).

3.2. Distribution of countries and institutions

A total of 109 countries worldwide contributed to the research on drug therapy for SCI. As shown in Table 1, the United States (1,221 publications, 35.18% of all articles) is the most productive country, followed by China (807, 23.26%), Canada (252, 7.26%), and Italy (233, 6.71%). As shown in Figure 2, time-series analysis indicates that China has experienced explosive growth in research output in recent years (2022–2025), becoming the most dynamic research entity in this field. The overall network density (0.0959) reflects the formation of a highly mature and closely integrated international collaboration mechanism in this field.

The top ten productivity academic institutions were concluded in Table 1, with the University of California System (128 publications, 3.68%) and the US Department of Veterans Affairs (95 publications) as the leading institutions, eight of the top ten most productive institutions are based in the United States. Betweenness centrality analysis—indicated by purple rings—identifies critical "bridge" nodes that facilitate international knowledge exchange; the institutional hubs such as Ahvaz Jundishapur University of Medical Sciences (0.11) and the University of California San Diego (0.09) demonstrate high centrality despite not having the highest absolute publication counts. Furthermore, temporal evolution analysis using tree rings shows that while Western institutions possess long-standing research foundations, Chinese institutions, notably the Chinese Academy of

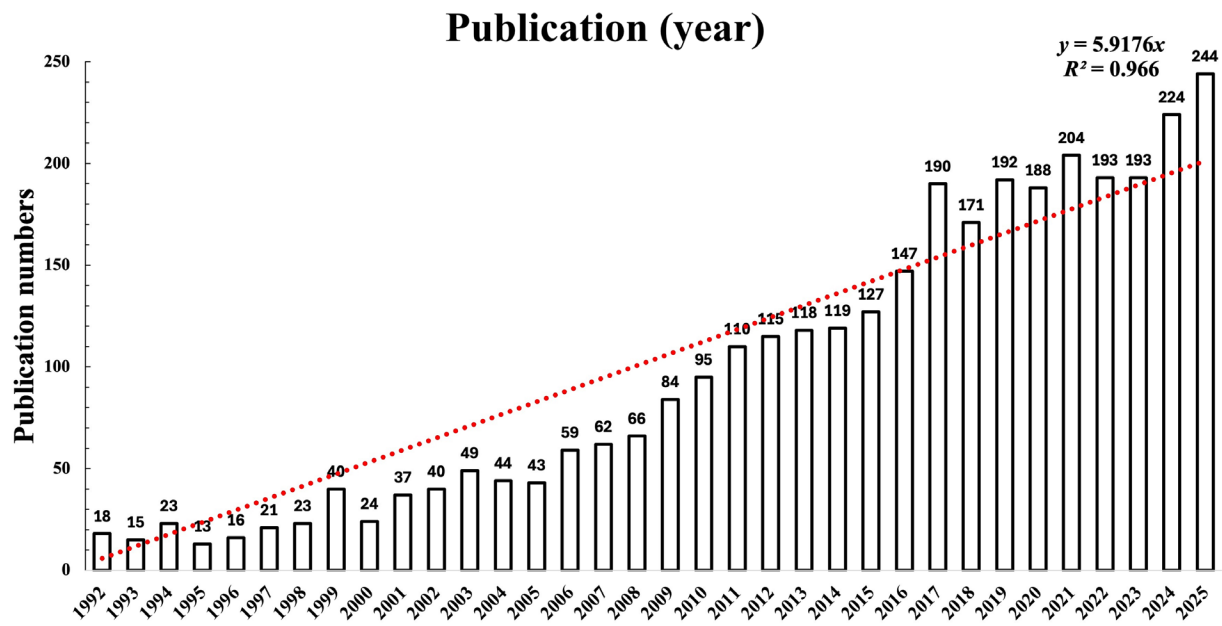


Figure 1. The annual trend of publications related to SCI pharmacotherapy from 1992 to 2025. The bar chart illustrates the steady growth in research output over the past 33 years. The red dotted line represents the linear fitting curve of the annual publication trend, indicating a consistent increase in global scientific interest. Notably, the annual output peaked in 2025 with 244 publications, demonstrating that pharmacotherapy for SCI remains a rapidly expanding field with high research vitality. SCI = spinal cord injury.

Table 1

Top ten productive countries/institutions/authors in drug therapy for SCI.

Subject	No. of publications	Times cited (without self-citations)	H-index
Country			
The United States	1,221	76,114	125
China	807	26,251	67
Canada	252	24,007	73
Italy	233	22,773	61
England	194	24,483	63
Germany	168	20,453	48
Australia	142	17,791	48
Japan	137	14,808	39
Spain	134	16,372	41
Iran	133	13,075	34
Institution			
University of California System	128	21,780	55
US Department of Veterans Affairs	95	13,249	36
US Veterans' Health Administration	93	12,787	34
University of Toronto	82	14,346	39
University of Miami	82	3,892	32
Harvard University	78	13,556	33
University of London	76	14,080	38
Harvard University Medical Affiliates	71	12,122	31
University of Texas System	70	12,107	35
University of Kentucky	70	13,360	39
Author			
Michael G. Felings	31	2,505	20
Hari S. Sharma	24	574	18
Aruna Sharma	20	395	15
Edward D. Hall	18	1,659	16
Shiqing Feng	17	206	8
Brian K. Kwon	15	1,270	15
James A. St John	15	292	11
Dafin F. Muresanu	15	289	12
Joanna Mika	15	749	12
Salvatore Cuzzocrea	14	604	14

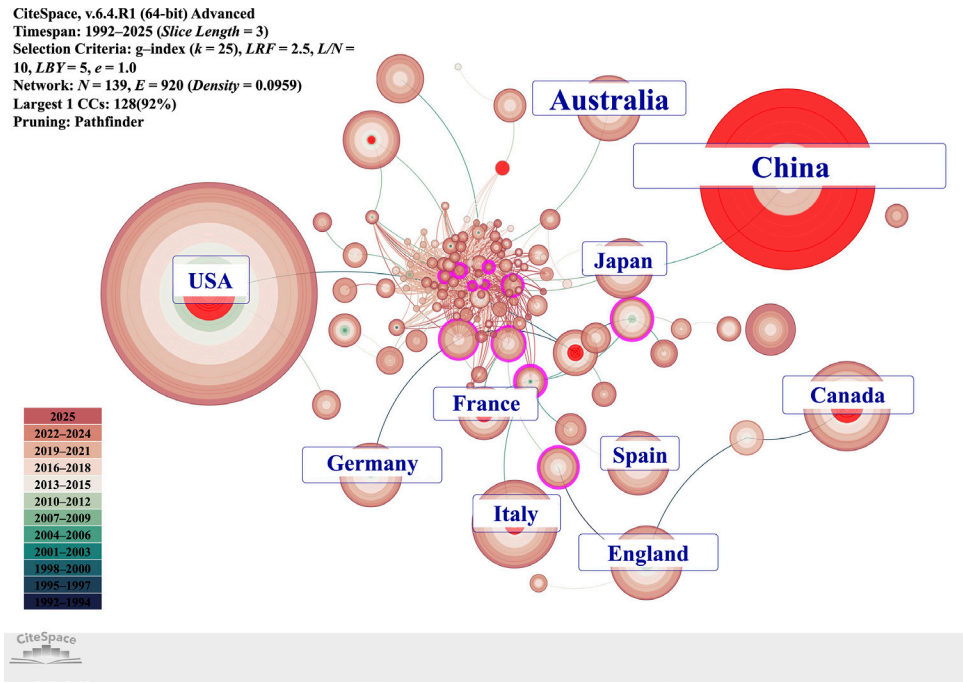


Figure 2. Network visualization of country/region co-authorship in SCI pharmacotherapy research (1992–2025). The size of the node represents the number of publications, and the lines indicate collaborative links. The United States (1,221 papers) and China (807 papers) are the two largest contributors. Notably, the large red rings within the China node indicate an explosive growth in publication output during the most recent period (2022–2025), surpassing other regions in recent activity. SCI = spinal cord injury.

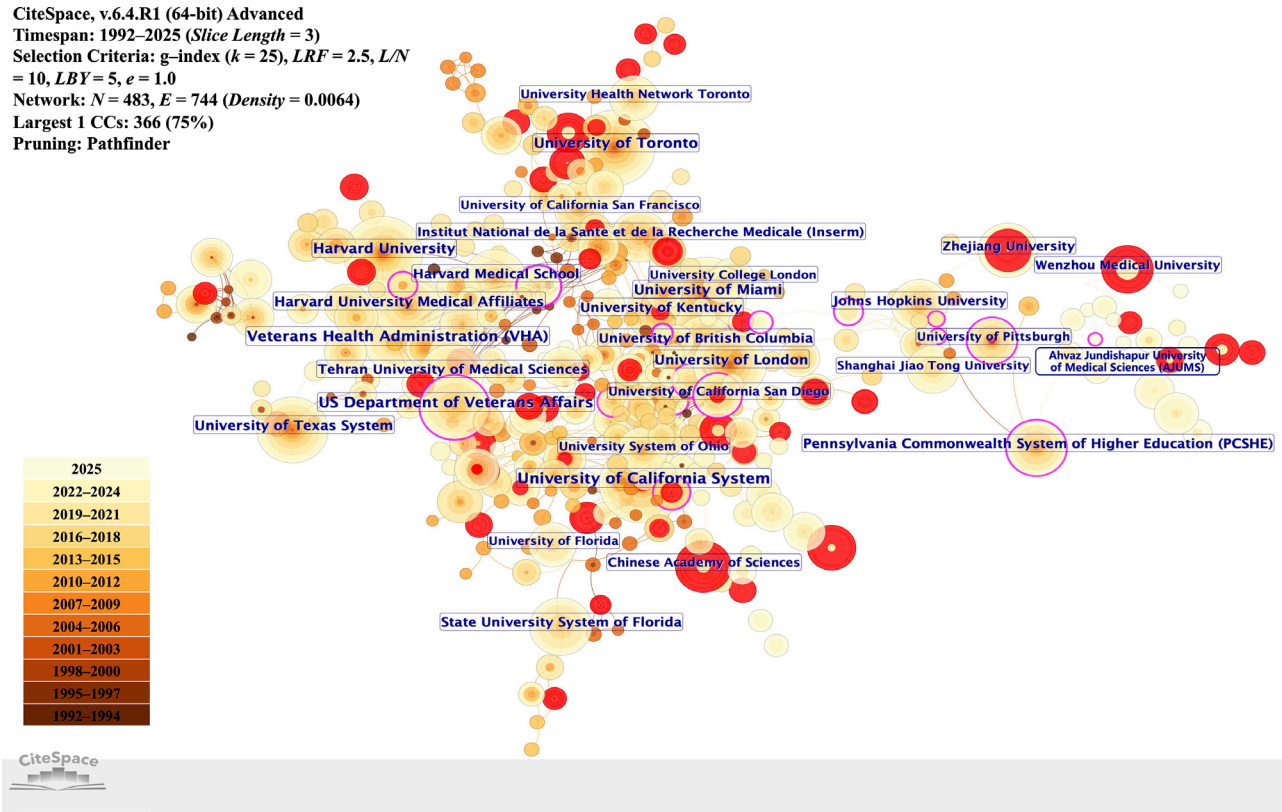


Figure 3. Institutional co-authorship network. The University of California System and Harvard University occupy central positions with high citation impact. In contrast, Chinese institutions such as Zhejiang University and Wenzhou Medical University are marked by prominent red rings, reflecting their rapid emergence and dominance in the field over the last three years. Nodes with purple outer rings represent institutions with high betweenness centrality, acting as key bridges in international collaboration.

Sciences and Wenzhou Medical University, have exhibited an explosive growth in activity during the recent 2022 to 2025 period, as evidenced by prominent red outer rings (Fig. 3).

3.3. Authors with research publications analysis

The top ten authors wrote 184 articles on drug therapy for SCI. Michael G. Feling from the University of Toronto published 31 papers with 2,505 citations. His highest cited article revealed that the primary mechanical trauma initiates a destructive secondary injury cascade—including neuroinflammation, ischemia, and apoptosis—which leads to progressive cell death and the formation of an inhibitory microenvironment composed of glial scars and cystic cavities. Adhering to the "time is spine" clinical paradigm, effective management necessitates rapid diagnosis, early surgical decompression, and hemodynamic stabilization to mitigate secondary damage and optimize long-term functional recovery.[2] The top 10 cited papers and relevant information are listed in Table 2. The immense citation impact of these top articles is driven by two key factors: the enduring clinical reliance on comprehensive reviews regarding neuropathic pain management and SCI pathophysiology, and the explosive academic interest in emerging regenerative paradigms, specifically exosome-mediated therapies and functional biomaterials, which represent the field's cutting-edge direction.

3.5. Analysis of journals and research areas

Since 1992, 3,470 articles have been published in 652 journals. The top ten journals with the most cited counts are listed in Table 3. *Journal of Neurotrauma* received the top cited counts (1,710), followed by the *Experimental Neurology* (1,563) and Proceedings of the National Academy of Sciences of the United States of America (*PNAS*) (1,472). Overall, the identified publications are grouped into 82 research areas. As shown in Table 4, the most representative research area was neurosciences neurology (1,412 records, 35.73% of all articles), followed by pharmacology pharmacy (743, 18.80%), and biochemistry molecular biology (295, 7.46%). In addition, a dual-map overlay of journals was used to analyze the association of subject categories between citing and cited journals. The spline wave from left to right describes the citation path, and this interaction illustrates the linkage of different research areas. Two critical citation paths marked in yellow and pink indicate that articles published in the journals of *Molecular/Biology/Immunology* and *Neurology/Sport/Ophthalmology* are usually cited by articles published in *Molecular/Biology/Genetics journals* (Fig. 4).

Table 2

Top ten most cited articles about drug therapy for SCI.

Rank	Title	Corresponding author	Journal	Publication year	Total citation	Average citation per year
1	Pharmacotherapy for neuropathic pain in adults: a systematic review and meta-analysis[12]	Nadine Attal	*The Lancet. Neurology*	2015	2,294	229.4
2	Traumatic spinal cord injury[2]	Michael G. Fehlings	*Nature Reviews*	2017	1,679	209.8
3	Traumatic spinal cord injury: an overview of pathophysiology, models and acute injury mechanisms[13]	Soheila Karimi-Abdolrezaee	*Frontiers in Neurology*	2019	983	163.8
4	Spinal cord injury: pathophysiology, multimolecular interactions, and underlying recovery mechanisms[9]	Yogeswaran Lokanathan	*International Journal of Molecular Sciences*	2020	953	190.6
5	Cell transplantation therapy for spinal cord injury[14]	Wolfram Tetzlaff	*Nature Neuroscience*	2017	729	91.1
6	The biology of regeneration failure and success after spinal cord injury[15]	Jerry Silver	*Physiological Reviews*	2018	672	96.0
7	Spinal cord injury: molecular mechanisms and therapeutic interventions[16]	Liming Cheng	*Signal Transduction and Targeted Therapy*	2023	471	235.5
8	Exosome-shuttled miR-216a-5p from hypoxic preconditioned mesenchymal stem cells repair traumatic spinal cord injury by shifting microglial *M*1/*M*2 polarization[17]	Weihua Cai	*Journal of Neuroinflammation*	2020	468	93.6
9	Inflammation after spinal cord injury: a review of the critical timeline of signaling cues and cellular infiltration[18]	Amgad S. H. Anna	*Journal of Neuroinflammation*	2021	439	109.8
10	Exosomes-loaded electroconductive hydrogel synergistically promotes tissue repair after spinal cord injury via immunoregulation and enhancement of myelinated axon growth[19]	Chengyun Ning	*Advanced Science*	2022	322	107.3

Table 3

The top ten journals with the most cited counts in the field of drug therapy for SCI.

Journal	Cited counts (*n*)	IF (2024)	WoS (2024)
Journal of Neuroscience	1,710	4.0	Q2
Experimental Neurology	1,563	4.2	Q1
PNAS	1,472	9.1	Q1
Brain Research	1,418	2.6	Q3
Journal of Neurotrauma	1,417	3.8	Q1
Nature	1,315	48.5	Q1
Neuroscience	1,299	2.8	Q3
Neuroscience letters	1,180	2.0	Q4
Public Library of Science One	1,178	2.9	Q2
Science	1,167	45.8	Q1

Table 4

The top ten research areas with the most publications in the field of drug therapy for SCI.

Research area	Records (*n*)	Percentage (%)
Neurosciences neurology	1,412	35.73
Pharmacology pharmacy	743	18.80
Biochemistry molecular biology	295	7.46
Cell biology	267	6.76
Research experimental medicine	254	6.43
General internal medicine	228	5.77
Science technology and other topics	221	5.59
Rehabilitation	181	4.58
Chemistry	176	4.45
Materials Science	175	4.43

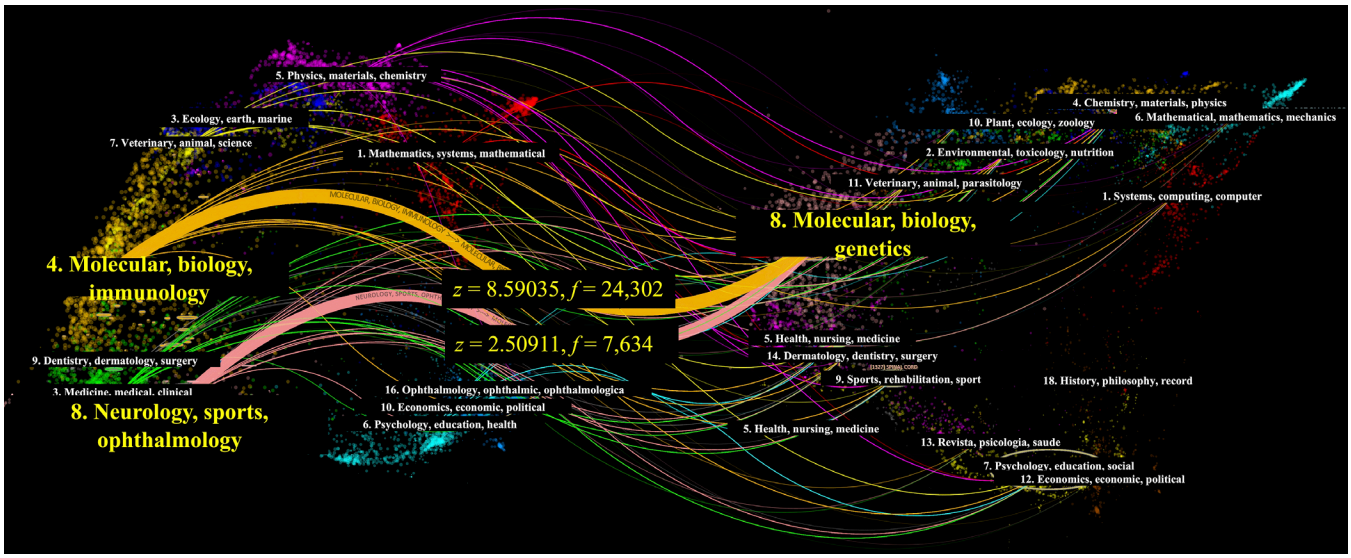


Figure 4. The dual-map overlay of journals related to drug therapy for SCI. The left side represents citing journals (research frontiers), and the right side represents cited journals (knowledge base). The colored paths illustrate the citation trajectory: research published in Molecular/Biology/Immunology journals and Neurology/Sports/Ophthalmology journals primarily cites foundational works in Molecular/Biology/Genetics journals, highlighting the translational nature of the field. SCI = spinal cord injury.

3.6. Citation and co-citation analyses

The co-cited references were then clustered based on indexing terms. As shown in Figure 5, 11 main clusters were found: #0 SCI/neuropathic pain, #1 nerve regeneration/stem cells, #2 neuropathy pain/pharmacological treatment, #3 nerve injury/exosomes, #4 small fiber neuropathy/SCI, #5 biomaterial scaffolds/3d bioprinting, #12 cell therapy/neuroregeneration, #13 chronic pain/microglia, #14 clinical trial/central pattern generator, 15# isoform-specific nicotinamide adenine dinucleotide phosphate hydrogen (NADPH) oxidase inhabitor/morphine, and #18 central neuropathic pain/antioxidant. The *S* value for all the clusters above is over 0.8, indicating that the articles in each cluster have substantial

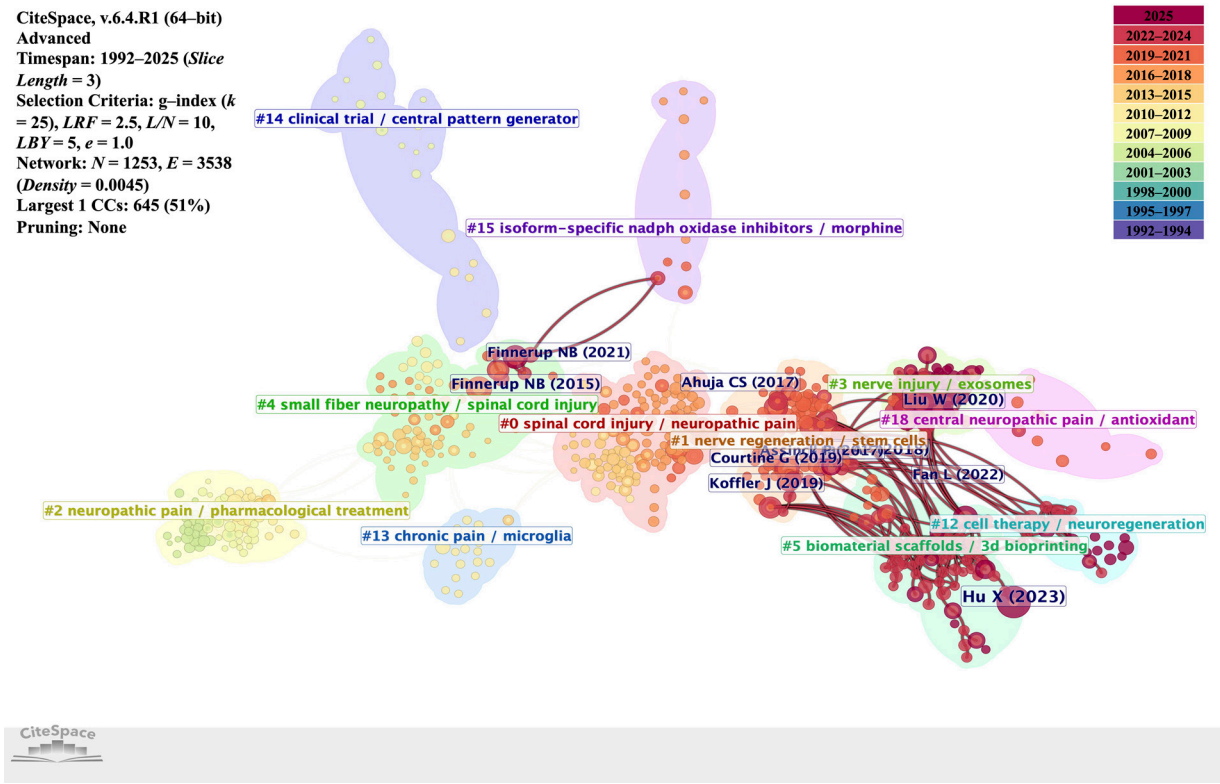


Figure 5. Landscape view of co-citation clusters in SCI pharmacotherapy. The network is divided into distinct clusters labeled by latent semantic indexing (LSI)/log-likelihood ratio (LLR). The shift in research focus is evident: while #0 SCI/neuropathic pain remains a foundational theme, new clusters such as #3 nerve injury/exosomes, #5 biomaterial scaffolds/3d bioprinting, and #15 isoform-specific inhibitors have emerged, indicating a paradigm shift toward nanomedicine, tissue engineering, and precision molecular targeting. LLR = log-likehood ratio; LSI, latent semantic indexing; SCI = spinal cord injury.

homogeneity. The timeline view of all clusters is presented in Figure 6.

3.7. Co-occurrence analysis of keywords

We obtained a total of 679 keywords, of which the five with the highest frequency were SCI (1,670 times), neuropathic pain (461), spinal cord (408), functional recovery (309), and therapy (281). The chronological order is presented from dark to bright yellow (Fig. 7).

We detected the burst of keywords based on CiteSpace's algorithm of burst detection, where the minimum duration of the burst was set to five years. The discontinuous blue lines represent the timeline. The top 20 keywords with the highest burst strength are shown in Figure 8. The most intense keyword was randomized controlled trial (strength = 19.43), followed by drug therapy (14.07) and controlled trial (12.61). The keyword with the longest burst time was intrathecal baclofen, which lasted 25 years from 1993 to 2018. More meaningfully, the keywords "extracellular vesicles" and "microglia" had outbreak citations most recently (2022), indicating increasing research effort into biological therapies and neuroinflammation for SCI conditions.

4. Discussion

In this bibliometric study, the 3,470 literature on drug therapy for SCI published in the WoS database from 1992 to 2025 was analyzed using CiteSpace 6.4.R1 software. A steady linear increase in the total number of publications was observed, consistent with former studies.[20,21] The shifting landscape of research output reflects a transition from a unipolar structure dominated by Western institutions to a more diversified global network. While the United States maintains its historical leadership in citation impact and H-index, China's "explosive growth" from 2022 to 2025 marks a strategic pivot toward intensive investment in regenerative medicine. The explosive growth of publications from Chinese institutions correlates strongly with the rise of clusters related to exosomes and hydrogels, reflecting a strategic pivot toward bioengineering solutions in this region. However, the lower H-index of Chinese entities suggests a potential "quantity–quality gap" that may be bridged through the international collaboration mechanisms identified in our network analysis, where hubs like the University of Toronto and the University of California System act as critical knowledge bridges.

After clustering the selected literature based on the keywords, pain-related clusters occupy 4 of the 12 main

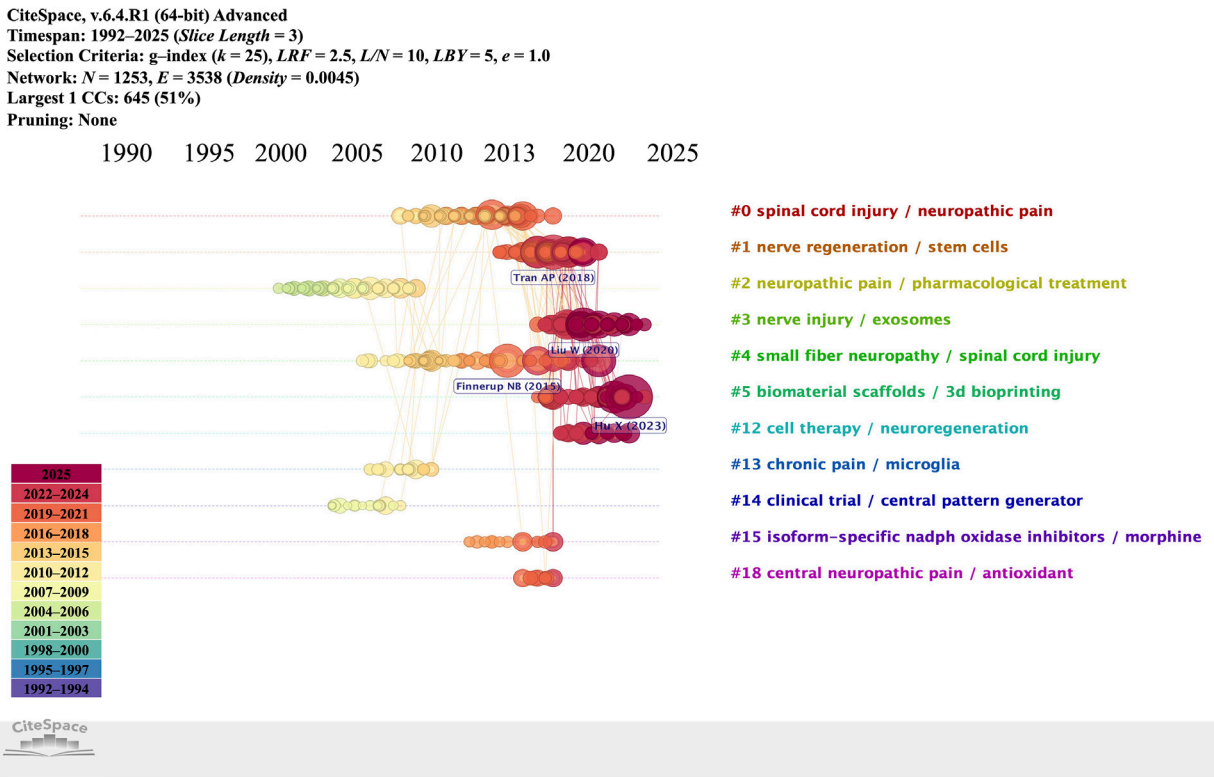


Figure 6. Timeline visualization of co-citation clusters (1992–2025). The horizontal axis represents the year of publication. Clusters are arranged vertically. The progression from cool to warm colors indicates the temporal evolution of research hotspots. Recent high-impact clusters, such as #5 (biomaterial scaffolds) and #12 (cell therapy), are densely populated on the far right (2020–2025), signifying the current frontiers of the field.

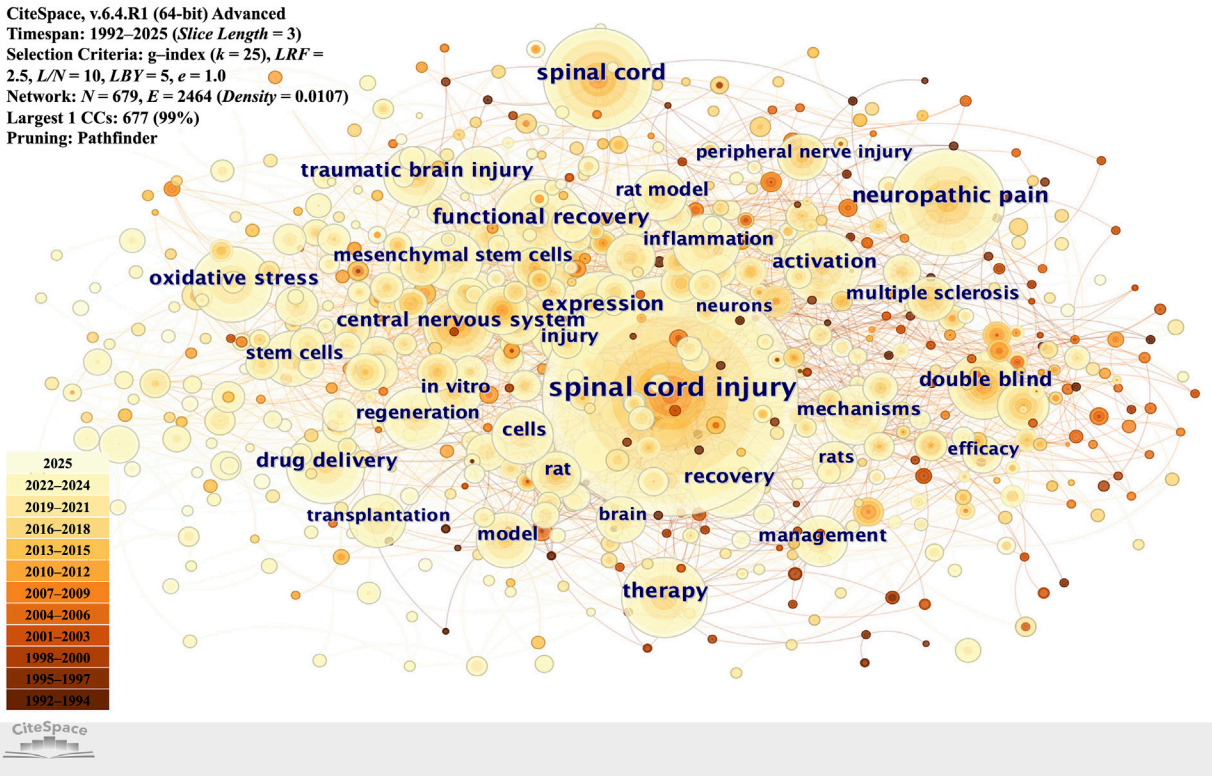


Figure 7. Co-occurrence network of keywords. The size of the node is proportional to the frequency of the keyword. “SCI”, “neuropathic pain”, and “functional recovery” are central keywords. The emergence of mechanism-related keywords like “oxidative stress” and “inflammation” reflects the deepening understanding of secondary injury mechanisms. SCI = spinal cord injury.

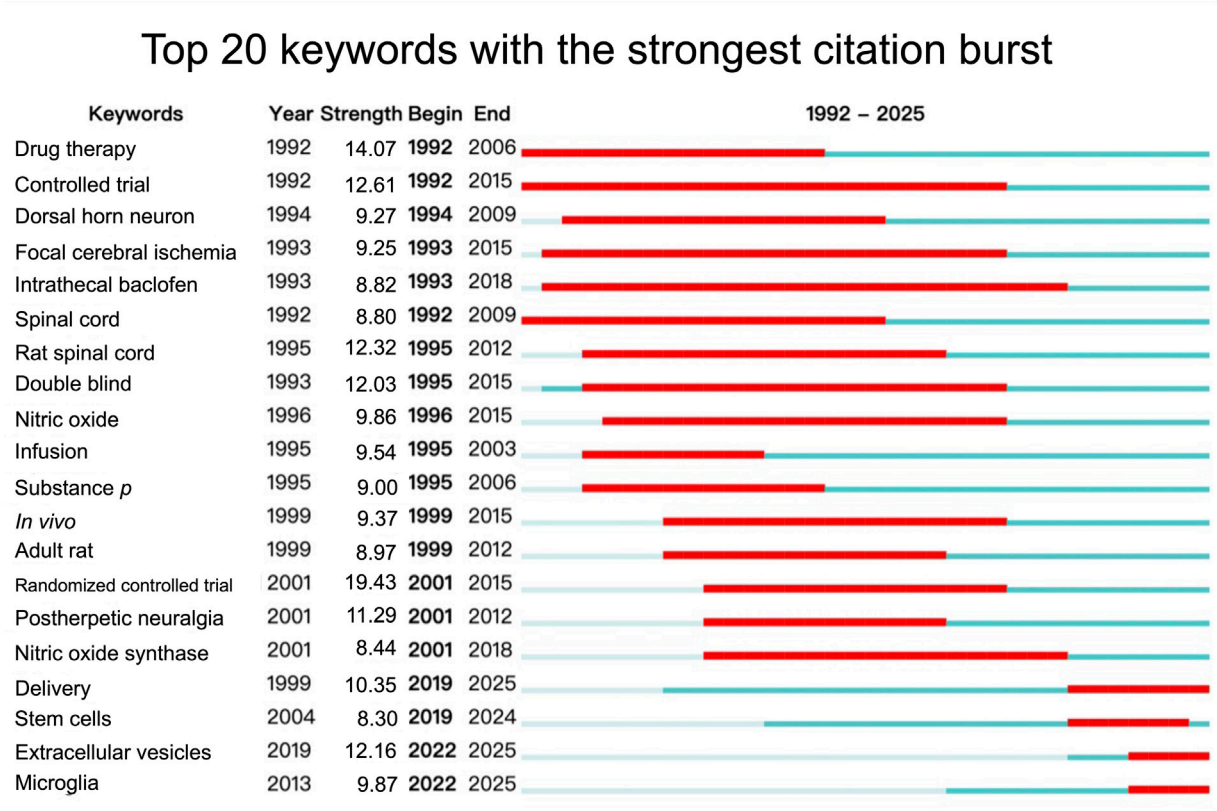


Figure 8. Top 20 keywords with the strongest citation bursts. Red bars indicate the duration of the burst, representing periods of intense scientific attention. While "controlled trial" and "drug therapy" were prominent in the early years, "extracellular vesicles", "delivery", and "microglia" show the most recent citation bursts (continuing through 2025), highlighting the current transition toward biological therapies and immunomodulation.

clusters. It can be seen from the timeline map that pain-related research has formed the base theme of drug therapy in SCI patients since the 1990s. Ahuja CS et al.[2] claimed that about 40% of SCI patients will experience pain at or below the injured segment, all those results indicating one goal of drug therapy for SCI is improving the quality of life of patients.

In 2010, Attal et al.[22] and Finnerup et al.[23] systematically summarized the evidence of treating neuropathic pain with tricyclic antidepressants, serotonin noradrenaline reuptake inhibitors, gabapentin, pregabalin, and opioids. The author believes that the current drug treatment is mainly to relieve the patient's pain.[23] High-dose MP therapy is widely used to control inflammation in the acute phase of SCI. However, it may cause significant side effects such as gastrointestinal tract bleeding,[24] aseptic necrosis of the femoral head,[25] and the neuroprotective effect is not widely accepted. The effect of MP in treating SCI remains under debate.[26–29] This method remains in use because no other drug has successfully replaced MP therapy's effect.

Beyond symptom control, the diagram of drug therapy in SCI has shifted into neuroregeneration. Our citation analysis showed strong links between nerve regeneration, cell therapy, and biomaterial scaffolds clusters.

Current pharmacotherapy has evolved from broad-spectrum antiinflammatory suppression (e.g., MP) to precision microenvironment reprogramming.[30] As highlighted by Hellenbrand et al.,[18] the inflammatory response follows a critical timeline, suggesting that therapeutic interventions must align with specific cellular infiltration phases. This shift is evidenced by the citation burst of keywords "microglia" and "macrophage polarization". Recent high-impact studies, such as Liu et al.,[17] demonstrate that rather than merely suppressing inflammation, the goal is to orchestrate the M1-to-M2 phenotypic shift. Their work on hypoxic preconditioned mesenchymal stem cell-derived exosomes (HExos) revealed that targeting the TLR4/NF-κB axis can effectively resolve neuroinflammation while preserving reparative immune functions. This marks a transition towards "smart" immunotherapies that leverage specific molecular cargos to modulate rather than ablate the immune response.

A pivotal evolution in the 2022 to 2025 period is the integration of electroconductive biomaterials with bioactive nanocarriers, representing a shift from structural support to functional synergy.[31] While earlier scaffolds primarily served as physical bridges, recent innovations, such as the electroconductive hydrogels developed by Fan et al.,[19] mimic the electrical properties of native neural tissue to stimulate axonal regrowth via the PTEN/PI3K/AKT/mTOR pathway. Crucially, these advanced scaffolds are now being utilized as reservoirs for exosomes (Cluster #3), creating a dual-action system that simultaneously

modulates the immune microenvironment and provides physical guidance for myelinated axon growth. This convergence of Cluster #5 (biomaterial scaffolds) and Cluster #3 (exosomes) signifies that future pharmacotherapy will likely rely on implantable, multi-functional platforms rather than systemic drug administration alone. Furthermore, the emergence of Cluster #15 (isoform-specific inhibitors) suggests that small-molecule drug discovery is moving toward higher specificity. Unlike broad antioxidants used in the past, targeting specific enzymatic isoforms (e.g., NADPH oxidase subtypes) may offer a way to mitigate oxidative stress without disrupting essential physiological signaling.

5. Limitations

This study has distinct limitations. First, relying solely on the WoS database may introduce database bias, potentially excluding relevant non-English publications, influential clinical trial reports indexed elsewhere. Second, the clustering analysis is inherently interpretative; while it identifies major trends, it may oversimplify the complex, multifactorial nature of certain transitional research areas. Finally, citation metrics inevitably lag behind the most recent discoveries and often favor positive outcomes, potentially underrepresenting studies with negative results or papers published in late 2025.

6. Conclusions

Based on the trajectory of citation bursts and cluster evolution identified in this study, we propose three evidence-based research priorities that will likely define the next decade of SCI pharmacotherapy:

6.1. The rise of "cell-free" and "smart" nanomedicine

Our analysis reveals a decisive shift from direct stem cell transplantation (Cluster #1) to exosome-based therapies (Cluster #3). While stem cells offer regenerative potential, they face hurdles regarding survival rates and tumorigenicity. Future research should prioritize engineered exosomes as superior alternatives. As demonstrated by the high-impact work of Liu et al.,[17] exosomes derived from hypoxic preconditioned mesenchymal stem cells show enhanced cargo (e.g., miR-216a-5p) capable of precisely modulating microglial polarization. Future strategies should focus on modifying these nanocarriers to cross the blood-spinal cord barrier more efficiently and deliver specific miRNA cargos that target neuroinflammatory checkpoints.

6.2. Integration of electroconductive biomaterials

The emergence of Cluster #5 (*biomaterial scaffolds*) highlights a critical gap in traditional pharmacotherapy: the lack of physical guidance and electrical signaling for regenerating axons. Drugs alone cannot bridge the lesion cavity. The future lies in combinatorial bio-hybrid systems. As evidenced by Fan et al.,[19] the next generation of therapeutics will likely be electroconductive hydrogels loaded with bioactive factors (e.g., exosomes). These "smart" scaffolds perform a dual function: providing a mechanical bridge with electrical properties matching native spinal cord tissue to stimulate axonal regrowth , while simultaneously releasing immunomodulatory agents to resolve the glial scar.

6.3. Addressing the "acute-chronic" translational gap

A persistent disconnect exists between preclinical success and clinical failure. Our keyword analysis shows a heavy focus on "neuroprotection" (acute phase), yet the clinical reality involves patients in the chronic phase with established glial scars. As noted by Hu et al.,[16] future clinical trials must move beyond broad-spectrum antiinflammatories. Research priority is shifting toward therapies that can remodel the chronic scar tissue and promote neural circuit reconstruction (intermediate neural networks) rather than solely focusing on acute neuroprotection.[32] Furthermore, given the heterogeneity of human SCI, future pharmacotherapy should incorporate biomarkers to stratify patients for precise therapeutic windows, as the inflammatory timeline varies significantly between individuals.

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Ethical statement

Not applicable.

Conflicts of interest

The authors declare that there are no conflicts of interest.

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Data availability statement

All data are available in our research; we shall share our data through the email of the corresponding author upon reasonable request.

Author contributions

YH, BH, XJQ—conceived the study.
DS, WSL, YQX, XNZ, YHY, PY—performed material preparation, data collection, and statistical analysis.
DS, WSL, YQX—wrote the original draft which was edited by YH, BH, XJQ, and PY.
All authors commented on previous versions of the manuscript, as well as, read and approved the final manuscript.

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