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Scientific Advancements in Stem Cell Therapy for Cervical Spinal Cord Injuries-A Bibliometric Perspective

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Abstract

Spinal cord injuries, particularly in the cervical region, pose significant clinical challenges due to their severe neurological impact and limited treatment options. In recent years, stem cell therapy has emerged as a promising approach to promote regeneration and functional recovery. This bibliometric analysis aims to map global research trends related to stem cell therapy, cervical, and spinal cord injuries. Using data from major scientific databases, we examined publication outputs, citation patterns, and collaborative networks. Results show a sharp increase in publications over the past decade, with most of the research originating from the United States, China, and Europe. In the past two decades, the development of stem cells and regenerative medicine, as well as in-depth research on the pathophysiology of spinal cord injury, has brought new hope for its treatment. Keyword co-occurrence and trend analysis reveal a strong focus on neural regeneration, transplantation techniques, and clinical trial development. The cervical spinal cord remains a focal point due to its vulnerability and impact on quality of life. Our findings highlight not only current scientific advancements but also gaps in translational research and international collaboration. This study provides a comprehensive overview of the literature, guiding future directions in regenerative medicine and cervical spinal cord injury treatment using stem cell therapy.

Keywords: Stem Cell Therapy, cervical injuries, Spinal cord, Neural regeneration, Bibliometric analysis

Introduction

Stem cells may replace damaged cells, protect neurons, drive regeneration, and promote tissue healing, they have become a promising therapeutic option for spinal cord injury (SCI) [1]. Cell replacement is one of the main ways that stem cells can support the recovery from SCI. The potency of mesenchymal stem cells (MSCs) to develop into diverse cell forms, like neurons and glial cells, may allow them to replace injured spinal cord cells and restore function. This skill is essential because the intricate neuronal network of the spinal cord needs to replace certain cell types that are lost or destroyed following an injury [2].

By releasing neurotrophic factors, stem cells aid in neuroprotection in addition to cell replacement [3]. These elements lessen inflammation, provide system that is more beneficial to nerve regeneration, and shield remaining neurons from additional harm [4]. Stem cells increase the likelihood of recovery by preventing further neuronal damage and creating an environment that is favourable for healing [5]. By encouraging the development of new nerve fibres, or axons, and remyelination—the creation of protective myelin sheaths around axons—stem cells also contribute to regeneration [6]. Since myelin loss is a typical side effect of SCI and impairs brain-body communication, [7] this procedure is essential for regaining nerve function. Stem cells may be able to repair some of the functional deficits linked to SCI by promoting both axonal development and myelination.

Additionally, stem cells can bridge the gap left by the injury by serving as a scaffold

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for nerve fibre regeneration [8]. This scaffold function supports the restoration of disturbed communication between nerve cells by facilitating the reconnection of damaged neural networks [9]. The chances of a significant recovery are increased by this capacity to give the regenerating spinal cord both structural and functional support. This ability to provide both structural and functional support to the regenerating spinal cord enhances the prospects of meaningful recovery [10].

Regeneration and Repair

The regeneration potential of stem cells, especially mesenchymal stem cells (MSCs) and neural stem cells (NSCs), in the nervous system is becoming more well acknowledged [11]. Important cell types in the central nervous system, such as astrocytes, neurons, and oligodendrocytes, can be produced from NSCs, which are located in particular areas of the brain and spinal cord. NSCs can help restore brain tissue in the event of neurological injury by replacing destroyed neurons [12]. In addition to producing new neurons, NSCs also release growth factors that help tissue repair by enabling the existence and functionality of the surviving neural cells [13]. The type of stem cells and its application is discussed in (Table 1).

However, MSCs, typically found in bone marrow and connective tissues, do not directly develop into neurons but instead contribute to the healing process by promoting axon regeneration [14]. MSCs secrete a variety of bioactive molecules, includes growth factors and cytokines, that help create an environment that is favorable for neural repair and modulate inflammation, which can otherwise exacerbate tissue damage after injury [15]. Both MSCs and NSCs, with their regenerative properties, hold great promise for bridging the gaps caused by neural injuries, facilitating the formation of new neural connections, and promoting the recovery of lost or damaged tissue [16]. When combined, they provide a potential treatment option for conditions that were previously thought to be difficult to manage, such as spinal cord injuries and neurodegenerative diseases [17].

Table 1: Types of stem cells and roles in SCI

Stem Cell Type	Role in SCI	Reference
Totipotent	Develops into multiple cell type involved in extra-embryonic tissues like placenta	[25]
Pluripotent	Differentiates into any cell type within three germ layers (ectoderm, mesoderm, endoderm) but not extra-embryonic tissues	[26]
Multipotent	Can segregate into a limited range of cell categories within a specific lineage	[27]
Oligopotent	Can differentiate into a few associated cell types	[28]

Neuroprotection

Numerous bioactive substances, such as neurotrophic factors, which are essential for preserving neurons and accelerating healing following spinal cord injury (SCI), can be released by stem cells [1]. These factors, which include brain-derived neurotrophic factor (BDNF), vascular endothelial growth factor (VEGF), and nerve growth factor (NGF) enhance axonal growth, lower inflammation, and alter the glial response. By releasing anti-inflammatory cytokines throughout the acute phase of SCI, stem cells lessen inflammation and prevent further tissue damage. Additionally, they trigger intracellular signaling pathways that support cell survival and inhibit neuronal death. Additionally, stem cells secrete substances that promote axonal regeneration,

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aiding in remyelination and guiding developing axons. Stem cells promote a more conducive environment for regeneration by affecting glial cells, which lessens scar formation that would otherwise prevent axonal renewal [18]. When combined they provide a potential treatment option for conditions that were previously thought to be difficult to manage, such as spinal cord injuries and neurodegenerative diseases. Additionally, stem cells promote angiogenesis, which is essential for neuron survival because it restores blood flow to the injured location [19]. Stem cells are a significant treatment option during the acute phase of SCI because they assist minimize neuronal loss, enhance tissue regeneration, and produce conditions, [20] conducive to long-term recovery**.** In order for neurons to survive, stem cells also promote angiogenesis, which replenishes the damaged area's blood supply

Mechanisms of stem cell therapy in SCI

Axonal regeneration, immunomodulation, neuroprotection, cell replacement, and remyelination are some of the ways that stem cell therapy for spinal cord injury (SCI) functions [21]. Damaged neural circuits can be repaired with the aid of stem cells, including neural stem cells, mesenchymal stem cells (MSCs), or induced pluripotent stem cells, which can differentiate into neurons, oligodendrocytes, and astrocytes. Additionally, they release neurotrophic factors that protect surviving neurons, lower apoptosis, and encourage axonal development, such as BDNF, NGF, and GDNF [22]. Furthermore, by inhibiting detrimental inflammation (e.g., decreasing TNF-α and IL-6 while raising IL-10) and causing microglia/macrophages to adopt a regenerative phenotype, stem cells alter the immune response [23] by releasing matrix metalloproteinases (MMPs) and blocking inhibitory molecules like CSPGs, they help dissolve glial scarring and make the environment more conducive to axon regeneration [24].

Stem cell-derived oligodendrocyte precursors aid in remyelinating axons, hence reestablishing nerve signal transmission [7] VEGF and other angiogenic factors increase blood flow to the site of injury, while exosomes generated from stem cells transport proteins and miRNAs that promote healing [29]. There are still issues to be resolved, though, such as maximizing cell kinds, transport strategies, transplant timing, and lowering hazards like immunological rejection or tumor development. To optimize recovery, future strategies might incorporate stem cells with scaffolds, growth factors, and rehabilitation [30].

Cell replacement and regeneration

By injecting pluripotent or multipotent cells that can differentiate into astrocytes, oligodendrocytes, and neurons stem cell therapy helps with cell replacement and regeneration in spinal cord injuries. These cells have the capability to develop into functioning neurons that create new synaptic connections when transplanted into the site of injury, possibly repairing damaged brain circuits [31]. Their capacity to produce oligodendrocytes, which remyelinate surviving but demyelinated axons and restore appropriate nerve signal conduction, is a crucial component [32]. By activating latent neural stem cells in the ependymal zone of the spinal cord, the treatment also encourages endogenous healing. Significant obstacles still need to be overcome, nevertheless, such as guaranteeing appropriate cell integration into pre-existing neural networks, avoiding aberrant differentiation into tumorigenic or non-neural cells, and obtaining adequate long-term survival of transplanted cells [33]. The goal of current research is to improve results through the use of genetic engineering to increase cell survival and focused differentiation, the combination of stem cells with scaffolds of supportive biomaterials, and the optimization of delivery techniques [34]. Although encouraging, successful regeneration probably calls for further strategies to treat the damaged

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spinal cord microenvironment's inhibitory factors, inflammation, and scarring [35].

Neurotrophic Factor Secretion

By producing a regenerative milieu that promotes neuronal survival and repair, stem cells' strong release of neurotrophic factors gives them powerful therapeutic possessions in spinal cord injury (SCI). Brain-derived neurotrophic factor (BDNF), glial cell line-derived neurotrophic factor (GDNF), nerve growth factor (NGF), and ciliary neurotrophic factor (CNTF) are among the released chemicals that improve recovery through a variety of parallel pathways [36]. Through the activation of growth-associated genes, they stimulate axonal sprouting and elongation while also promoting neuronal survival by upregulating anti-apoptotic pathways in damaged cells [37]. By strengthening the surviving neuronal connections and promoting synaptic plasticity, the variables enable functional rebuilding of circuits. Crucially, they facilitate the activation of endogenous stem cells and direct the development of transplanted stem cells into neural lineages that are functional [38]. By encouraging angiogenesis and decreasing oxidative stress and excitotoxicity, this neurotrophic support also modifies the injury microenvironment. Neurotrophic factor secretion is plays significant and early methods of stem cell therapy, frequently taking place even before cell replacement or integration occurs [39]. These actions work together to assist overcome the inhibitory environment of the wounded spinal cord [40]. To strengthen and extend these positive effects, current research focuses on improving factor delivery using integrated biomaterial techniques or created stem cells.

Immunomodulation

By using a complex, multifaceted strategy, stem cell therapy changes the hostile immunological milieu in spinal cord injury (SCI) from an inhibitory to a regenerative site. By inhibiting pro-inflammatory [41] M1 macrophages and microglia and encouraging anti-inflammatory M2 polarization, the transplanted cells actively rebalance the immune response and foster a healing environment. Through paracrine signalling and direct cell-to-cell connections, stem cells release cytokines such as IL-10, TGF-β, and PGE2, which reduce levels of damaging mediators (TNF-α, IL-1β, and IL-6) and suppress destructive inflammation [42]. TNF-α, IL-1β, and IL-6 are among the damaging mediators that are reduced when stem cells release cytokines like TGF-β, IL-10, and PGE2, which suppress destructive inflammation. This immunomodulation is accomplished through direct cell-to-cell contacts and paracrine signalling [43].

Stem cells simultaneously promote regulatory T-cell (T_{reg}) activity and suppress harmful T-cell responses to control adaptive immunity [44]. Additionally, they alter the composition of glial scars and lessen astrogliosis, which inhibits axonal development. In addition to protecting the remaining neural tissue, this thorough immunomodulation facilitates the more efficient operation of other healing processes including neurogenesis and axonal regeneration. By strengthening the surviving neuronal connections and promoting synaptic plasticity, the variables enable functional rebuilding of circuits and the timing seems to be critical because whereas later modification may alleviate chronic inflammation, early action may avoid additional harm [45]. Since successful neuronal repair following SCI depends on controlled immune modulation, researchers are now looking into ways to increase these effects by genetic engineering of stem cells or in combination with other immunomodulatory therapies [46].

Bibliometric analysis

Bibliometric analysis is a measurable research technique used to analyse scientific researches by evaluating its external characteristics like publications, citations, and other bibliographic data [46, 47]. It helps researchers understand research trend and influential authors and journals, and assess the impact and visibility of research outputs. In essence, it's a way to statistically

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analyse publications to gain insights into the structure and development of scientific knowledge. Additionally, it reveals patterns of collaboration and highlights the core journals where influential work is published.

Bibliometric tools also analyse keywords and citation networks, uncovering emerging themes like neural regeneration, mesenchymal stem cells, or induced pluripotent stem cells, while also pointing out gaps in existing research. Overall, bibliometric analysis serves as a powerful tool to understand the scientific landscape, guide future investigations, and support evidence-based decisions in advancing stem cell therapies for cervical spinal cord injuries.

Results

Annual scientific production

Figure 1 depicts "Annual Scientific Production – Stem Cell" plots publication patterns between 2016 and 2024 in Scopus, Web of Science (WOS), and PubMed. Scopus depicts the most frequent and highest volume of output, reaching 14 publications in 2024, with increasing research interest. WOS depicts a wavering pattern but also reaches its peak in 2024, whereas PubMed emphasizes clinical importance with its peak in 2021.

Overall increase in publications, particularly post-2020, signifies growing scientific interest in stem cell therapy for cervical spinal cord injuries, underpinned by improvements in regenerative methods and translational medicine. This increasing trend indicates wider interdisciplinary cooperation and more investment in spinal cord repair. It also indicates that stem cell treatment is gradually heading in the direction of clinical use for cervical spinal injury.

Countries Scientific production

The graphic highlights global contributions to scientific achievements, such as stem cell therapy for cervical spinal cord injury, by displaying three world collaborations that illustrate country-by-country scientific research output from the Scopus, PubMed, and Web of Science (WOS) databases. The maps show that United States is the country with the most scientific publications in all three databases (Fig. 2a Scopus, Fig. 2b PubMed and Fig. 2C WOS) China, United Kingdom, Germany, Japan, and Australia are next in line. The concentration of state-of-the-art research in wealthy nations with sophisticated biomedical infrastructure and financial backing is reflected in this trend. The steady output from

Fig 1: Publication per year

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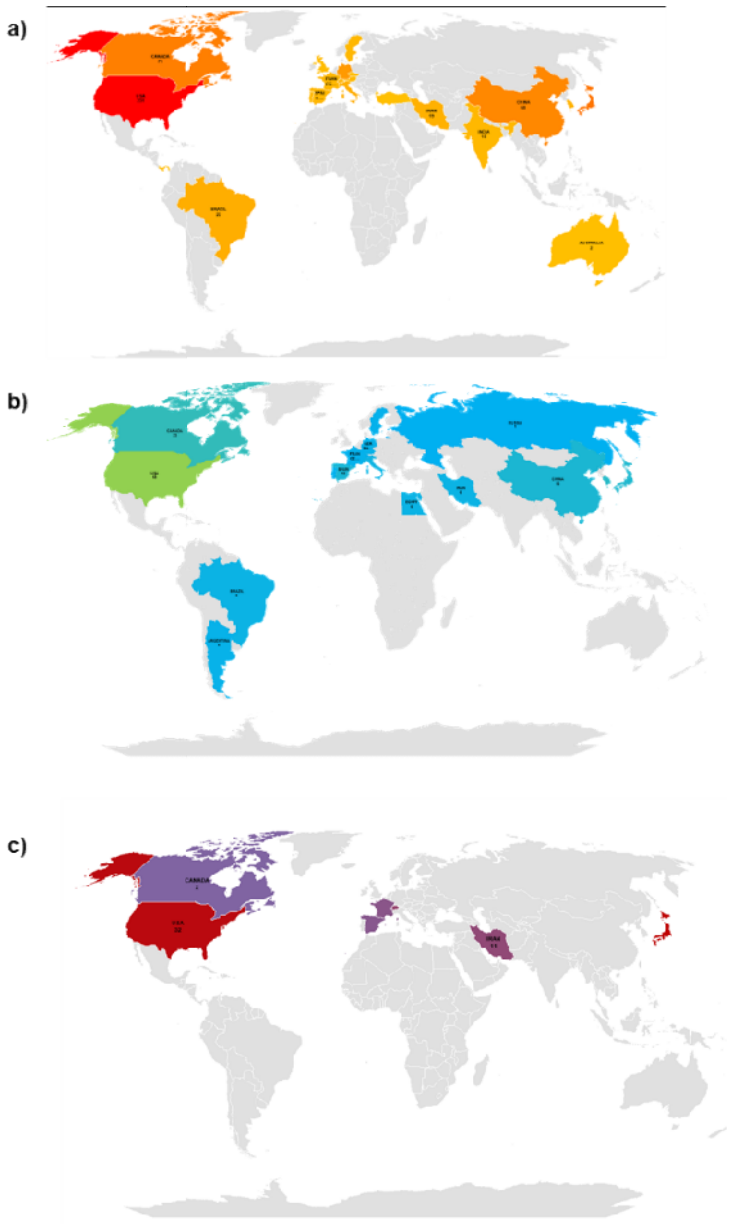

Fig. 2: Country scientific production a) scopus b) WoS c) PubMed

these countries shows how important they are to the advancement of stem cell-based spinal cord restoration treatments. These observations highlight the dynamics of research around the world and highlight areas that are actively advancing stem cell treatments for cervical spinal cord injuries. International partnerships and increased research capacity in developing nations could hasten therapeutic discoveries as the field develops.

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Collaboration networks highlight strong ties between the U.S., China, and Japan, alongside industry partnerships with biotech firms like Asterias Biotherapeutics. Despite progress, challenges remain in translating preclinical studies to clinical applications, with few Phase III trials completed. Future research emphasizes personalized iPSC therapies, exosome-based treatments, and advanced delivery systems like hydrogels. The field's growth underscores the need for interdisciplinary efforts to optimize therapeutic efficacy and functional recovery in cervical SCI patients

Co-authorship

This network map shows the collaboration between key researchers in the field of SCI and stem cell therapy. It highlights two main author clusters. On the left, Klaus Zweckberger leads a closely connected group of researchers, including Andreas Unterberg, Hao Zhang, and Moritz Scherer, who appear to work extensively together, likely on experimental and translational research [48–51]. On the right, Michael G. Fehlings leads another cluster, collaborating with researchers like Anna Badner, James Hong, and Narihito Nagoshi, likely focused more on clinical and therapeutic aspects. The thin link connecting these two clusters suggests occasional collaboration between the two groups, showing a bridge between experimental and clinical research communities. This collaboration network highlights two major groups of researchers actively contributing to spinal cord injury and stem cell therapy research [52–55]. On the left side, Michael G. Fehlings leads a well-connected cluster of international collaborators, including James Hong, Anna Badner, and Narihito Nagoshi, indicating a strong focus on clinical and translational research. This cluster shows diverse interdisciplinary collaboration, with researchers like Mohamad Khazaei and Christopher Ahuja contributing to both experimental and therapeutic aspects. On the right side, Klaus Zweckberger leads a separate group focused on experimental studies, with frequent co-authorships among Thomas Skutella, Hao Zhang, and Moritz Scherer. This cluster appears more tightly connected within itself, indicating consistent teamwork within a focused research domain. The faint links between the two clusters represent occasional collaboration or thematic overlap, suggesting that while the two groups operate somewhat independently, they contribute to a shared goal of advancing treatment for SCI through stem cell research. This network map shows a highly collaborative research group working in the field of spinal cord injury and stem cell therapy. At the center of this map are closely linked researchers such as Fehlings Michael G, Badner, Klaushen and Zweckberger who frequently co-author papers together. The dense web of connections indicates strong teamwork and shared research goals across the group. Researchers also play key roles, suggesting a well-established network with both clinical and experimental expertise. The equal distribution of connections among members reflects an integrated and cooperative team dynamic, contributing significantly to the advancement of spinal cord repair and regeneration studies. This cluster exemplifies a productive and interdisciplinary research environment (Fig. 3).

Co-Occurrence

This image is a visual representation of how different research topics are connected in the field of stem cell therapy for cervical spinal cord injuries. Each circle represents a frequently used keyword in scientific papers, and the size of the circle shows how often that keyword appears. This visual map shows how key research topics are connected in the field of stem cell therapy for cervical spinal cord injuries. Larger circles like "spinal cord injury", "transplantation", and "therapy" highlight the most studied areas. The coloured groups represent different research themes—green focuses on biological mechanisms, red on clinical applications like trials and safety, blue on

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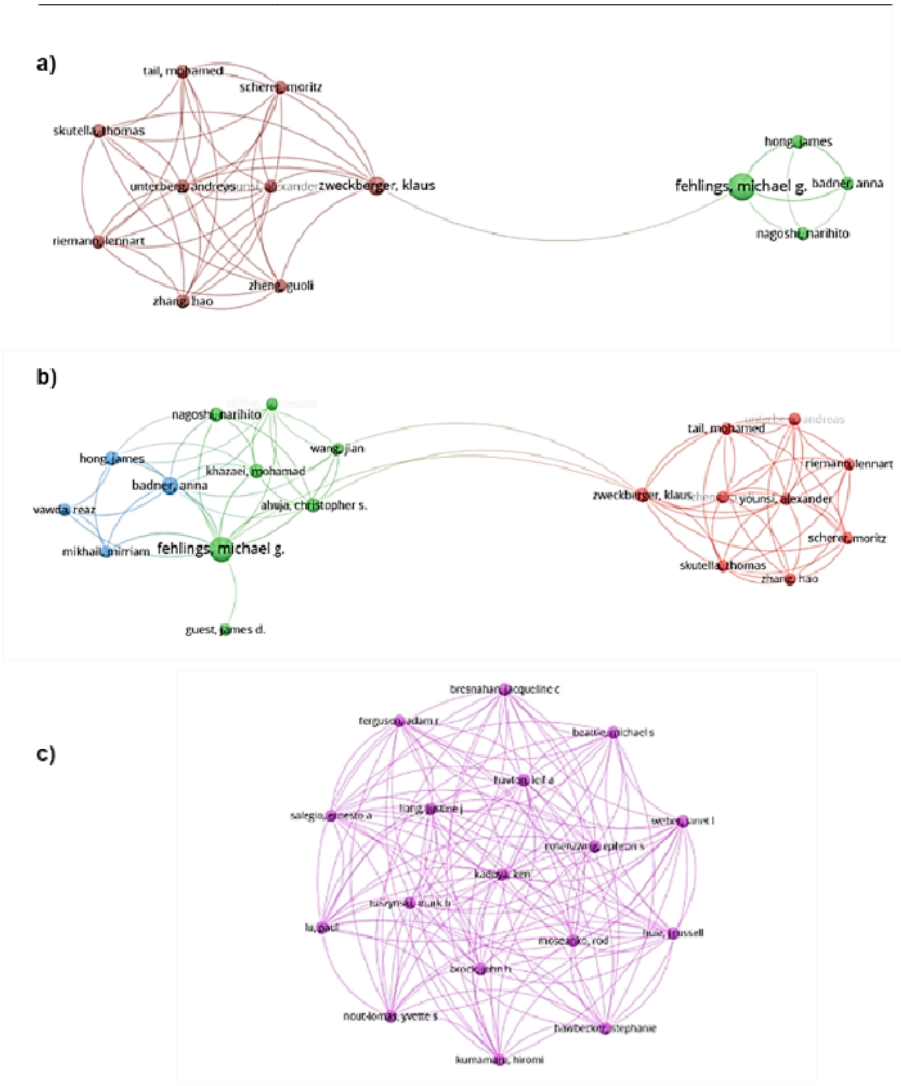

Fig 3: Network visualization of author collaborations over time (a) WoS (b) scopus and (c) PubMed dataset using VOSviewer

recovery and neural regeneration, and yellow on repair outcomes. This network helps us understand how research is evolving and where future efforts can be directed for better treatments. Overall, this map helps paint a clear picture of where the scientific community is focusing its attention. It shows how research efforts are spread across understanding the biology of injuries, developing stem cell treatments, testing them clinically, and working toward meaningful recovery. It also reflects the interconnected nature of this field—progress in one area depends on advancements in others. This kind of analysis helps researchers and clinicians. The larger terms like "spinal cord injury", "nonhuman spinal cord injuries", and "stem cell transplantation" are the most

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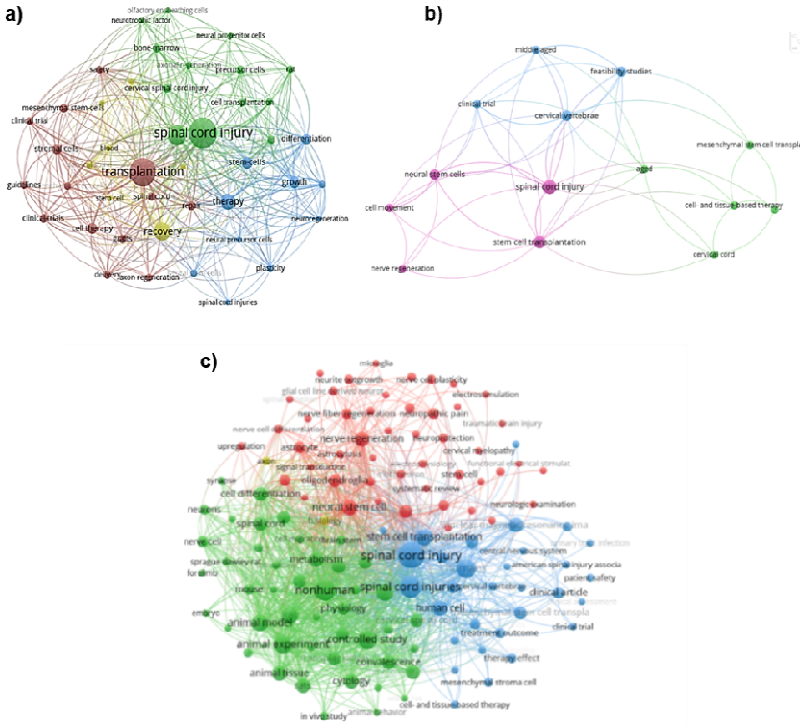

Fig. 4: Co-occurrence network of major key terms (a) WoS (b) PubMed (c) Scopus

frequently studied (Fig. 4). The green cluster focuses on animal studies and experimental models, including terms like "animal model", "mouse", and "controlled study", reflecting preclinical research. The red cluster centres around nerve regeneration and biological processes, with keywords like "neural stem cell", "astrocytes", and "nerve regeneration", showing interest in how stem cells aid nerve repair. The blue cluster highlights clinical and human-cantered research, featuring terms like "clinical trial", "treatment outcome", and "mesenchymal stromal cell".

Together, this map reveals how the field bridges basic animal research, biological understanding, and clinical application to advance stem cell therapy for spinal cord injuries. This network map presents a simplified and focused view of research themes related to stem cell therapy for spinal cord injury. At the centre, "spinal cord injury" and "stem cell transplantation" are the core topics, connecting various related areas. The purple cluster includes terms like "neural stem cells", "nerve regeneration", and "cell movement", indicating studies on how stem cells contribute to nerve repair. The blue cluster features terms like "clinical trial", "feasibility studies", and "cervical vertebrae", reflecting the translation of research into clinical practice, particularly in middle-aged patients. The green cluster connects terms like "mesenchymal stem cell transplantation", "cell- and tissue-based therapy", and "cervical cord", emphasizing therapeutic approaches tailored for aged individuals. Overall, the map shows a balanced focus between basic research, clinical application, and age-specific therapy approaches in the context of spinal cord injury.

Tree Map

The tree map analysis provides information regarding the frequency of

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occurrence of the query keywords searched for the current study and also related terms in author's approach on stem cell therapy. The core developmental themes on spinal cord injury and stem cell applications are highlight in the three tree maps (Fig 5).

The terms "spinal cord injury," "stem cells," "regeneration," and "neuroprotection" are commonly used in Fig. 5a (WoS), suggesting a heavy emphasis on biological repair and recovery techniques. Terms like "stem cell transplantation," "cervical spinal cord," "animal model," and "mesenchymal stem cells" are highlighted in Fig. 5b (Scopus), which reflects translational and experimental approaches

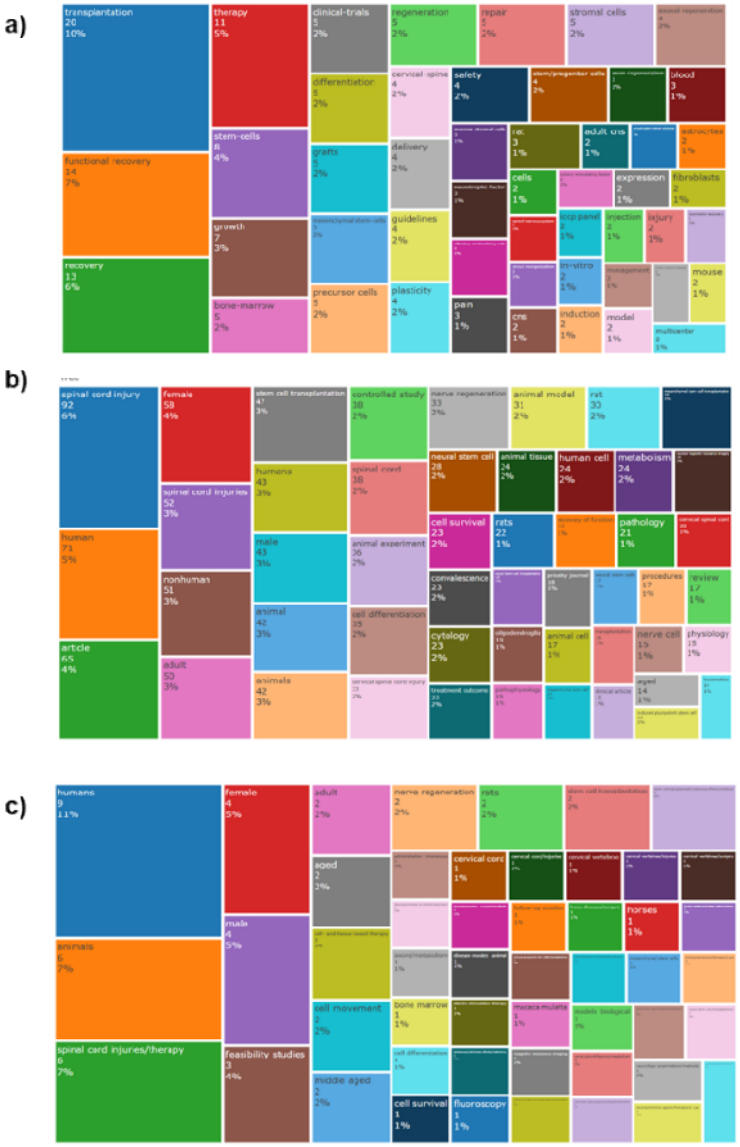

Fig 5: Tree map of terms by author reported in publication from (a) WoS (b) Scopus (c) PubMed

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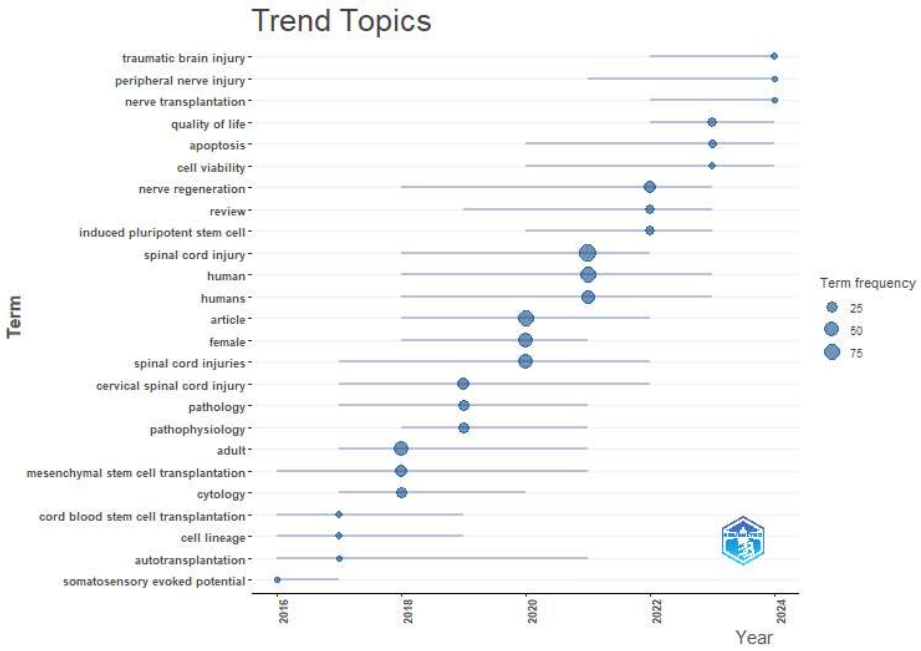

Fig 6: Topics blooming with time period based on author's keywords

meant to restore motor and sensory function. Keywords like "functional recovery," "neural stem cells," "injury model," and "neuroinflammation" are displayed in Fig. 5c (PubMed), indicating a focus on inflammatory modulation, therapeutic results, and mechanistic understanding. When taken as a whole, these visualizations propose a throughout summary of the main subjects and future directions of the area. It demonstrate the interdisciplinary character of urrent research, which includes neurology, bioengineering, cellular therapies, and clinical translation, with the goal of developing novel stem cell-based interventions to address the difficulties associated with cervical spinal cord injury.

Trend Topics

Key trending phrases such as growth, differentiation, regeneration, stem cells, and transplantation in Fig. 6 show a long-standing and increasing focus on cellular treatments and biological healing mechanisms. The rising phrase frequencies over time point to a growing corpus of work devoted to improving treatment approaches**.**

A smaller selection of terms, including humans, animals, and spinal cord injury/therapy, are shown in (Fig. 6), which represents model-based and therapeutically relevant studies that frequently concentrate on translational research from preclinical to human applications. This represents therapeutically relevant and model-based studies that frequently concentrate on translational research from preclinical to human applications. Topics such as mesenchymal stem cell transplantation, induced pluripotent stem cells, cervical spinal cord, neuro regeneration, and quality of life are all covered in greater. These demonstrate the promise of new treatments to improve patient outcomes and functional rehabilitation, as well as their technological sophistication. When taken as a whole, these trend analyses show how research is gradually moving toward more sophisticated and customized

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stem cell treatments, emphasizing significant turning points and increasing interest in using cutting-edge regenerative techniques to treat cervical spinal cord injuries.

Conclusion

Although there is preclinical potential for stem cell therapy for cervical SCI, lack of clear proof makes human applications extremely difficult. Small sample sizes, less stringent designs, and a lack of prospective registration, control groups, or blinding are just a few of the methodological flaws that have plagued clinical trials up to this point, all of which reduce the validity of the results [56]. Technical issues, such as unanswered questions about the best time to treat, the best kind and source of cells, guaranteeing endurance of transplanted cells, and figuring out the best dosages and delivery methods, further impede development [57]. There are still ethical issues, especially with embryonic stem cells, but adult substitutes like mesenchymal stem cells have drawbacks of their own, such as less scalability and differentiation capability [58]. Stem cell therapy is emerging as a highly promising approach on addressing the complicated troubles of cervical spinal cord injuries have significantly expanded the potential for restoring lost function and improving patient outcomes [59]. While there are still hurdles to overcome in terms of safety, long-term efficacy, and clinical translation, the progress made so far offers real hope for regenerative treatments that were once considered impossible [60]. Continuous interdisciplinary research and well-designed medical trials will be key to turning this hope into routine clinical reality studies indicating negative side effects associated with stem cell transplantation have raised serious concerns about safety, highlighting the necessity of a thorough risk-benefit analysis [61]. At the same time, more and more study is being done to determine how stem cells might help with healing by regulating inflammation, encouraging axonal regeneration, and creating new brain connections [62]. Strong, well-planned studies, the clearing of ethical and technical obstacles, and a deeper understanding of mechanisms to convert preclinical potential into safe, efficient treatments are all need to meet these challenges. Strong, well planned studies, the clearing of ethical and technical obstacles, and a deeper understanding of mechanisms to convert preclinical potential into safe, efficient treatments are all need to meet these challenges [63]. Addressing these challenges demands robust, well-designed trials, resolution of technical and ethical hurdles, and deeper mechanistic insights to translate preclinical potential into safe, effective therapies [64].

Future Scope

Looking ahead to the future, stem cell therapy for cervical SCI seems very promising, since emerging innovations may guide it. Induced pluripotent stem cells also offer potential for personalized, immune-compatible treatments made through the patient's own cells [65]. These advancements transform medicine by how they lower the risk that is rejection along with the ethical concerns [35]. At the same time, researchers increasingly combine stem cells and biomaterials in addition to 3D [66] bioprinted scaffolds, which creates supportive environments that can improve cell survival and promote axonal regrowth, while they adapt to the anatomical complexity of the cervical spinal cord. Combination therapies with integration of stem cells and gene editing or electrical stimulation as well as neurotrophic factors are also being explored for the maximization of functional recovery, especially when considering the severe motor impairments that are caused by cervical injuries [67]. Finally, as clinical trials move into late-stage phases (Phase II/III), we can expect more strong data on standardized protocols, efficacy, with safety—setting the stage for broader clinical adoption plus the inclusion of patients with chronic, not just acute, spinal cord injuries [68]. Stem cell-based interventions may become a core component in regenerative medicine. These developments do collectively suggest this future for cervical SCI [69].

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With their ability to provide structural support and biochemical cues to direct brain regeneration and enhance stem cell survival at the lesion site, improved biomaterials and 3D bioprinted scaffolds will also play a bigger role [70]. Addressing chronic-stage injuries, which have traditionally been left out of clinical trials, is another important area of development; future treatments are anticipated to target both acute and chronic spinal cord damage [71]. Furthermore, personalized treatment routines based on real-time imaging, biomarker profiling, and machine learning predictions can soon be a reality thanks to the development of AI-assisted diagnostics and precision medicine [72]. When taken as a whole, these advancements imply that in the years to come, stem cell therapies will not only increase therapeutic effectiveness but also increase their accessibility and suitability for patients with cervical spinal cord injuries all over the world [73].

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