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Conductive Hydrogels and Biofilm in Microbial Fuel Cells: Scientific Mapping and Research Evolution (2010–2024)

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This study addresses the challenge of low efficiency and limited scalability in microbial fuel cells (MFCs), particularly regarding electron transfer between microorganisms and electrodes. These limitations hinder their potential as sustainable technologies for clean energy generation while treating wastewater. Conductive hydrogels and hybrid polymers are proposed as promising solutions, as they facilitate the formation of electroactive biofilms and enhance electron conductivity. However, research in this field remains fragmented, with limited methodological standardization and comparability across studies. The methodology involved a bibliometric analysis of scientific publications from 2010 to 2024, sourced from the Scopus database. An advanced search strategy was employed using keywords related to hydrogels, MFCs, conductive polymers, and sustainability. The initial corpus was refined to 360 documents, analyzed using Bibliometrix (in RStudio) and VOSviewer. Key indicators assessed included annual production, average citations, leading authors, co-authorship networks, top journals, and contributing institutions. Results reveal exponential growth in publications since 2015, peaking in 2024. The most influential authors were El-Naggar A.M. and Aziz S.B., recognized for both productivity and impact. Journals such as *Polymers* and *ACS Applied Materials and Interfaces* host the highest number of publications in the field. China and Saudi Arabia stood out for their publication volume, with institutions like King Saud University noted for high levels of international collaboration. Emerging topics include nanomaterial-doped hydrogels, circular economy strategies, and electro fermentation applications. This analysis provides a strategic overview of how functional materials are driving the advancement of MFCs toward clean, sustainable, and entrepreneurially viable energy solutions.

Keywords: conductive hydrogels, biofilm, microbial fuel cells, electron transfer, energy sustainability.

Introduction

The growing energy crisis and the impact of climate change have made the search for sustainable, clean, and efficient energy sources a global priority (Mahto and Das, 2025). In this context, microbial fuel cells (MFCs) have emerged as a promising technology, enabling the direct conversion of chemical energy stored in organic matter into electricity through the use of microorganisms as biological catalysts (Cai et al., 2024). In addition to generating renewable energy, this technology offers a viable pathway for wastewater treatment and the valorization of organic waste (Naaz et al., 2023). However, despite their potential, MFCs face significant technical limitations that restrict their efficiency and scalability (Yan et al., 2021). These challenges include low current density, limited electron transfer between microorganisms and electrodes, and the instability of electroactive biofilms (Luo et al., 2025). This study aims to address these limitations by designing advanced materials that enhance the interaction between microorganisms and electrodes (Erensoy and Cek, 2021).

In particular, conductive hydrogels and hybrid polymers have drawn attention from the scientific community for their ability to foster stable, electroactive biofilm formation and improve extracellular electron transfer (Ouyang et al., 2022). These materials combine biocompatibility, electrical conductivity, and a porous three-dimensional structure, creating an ideal environment for microbial growth and efficient electron flow mediation (Sanaei et al., 2025). Nevertheless, research in this field is still in an early phase, with considerable methodological fragmentation, varied material types and microbial strains, and inconsistent evaluation metrics (Atnafu and Leta, 2021). The historical background reveals a progression from inert, rigid electrodes toward more sophisticated and adaptable materials (Tran et al., 2022). Initially, MFCs used graphite or glassy carbon electrodes, which, while chemically stable, had limited interactions with microorganisms (Liu et al., 2024). Later developments introduced conductive polymer coatings such as polyaniline (PANI), polypyrrole (PPy), and poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT: PSS), which improved surface conductivity and microbial adhesion (Xu et al., 2024). More recently, conductive hydrogels have taken center stage for their ability to mimic the natural microenvironment of biofilms, facilitating nutrient and electron diffusion (Li et al., 2025). These hydrogels can be synthesized from natural polymers (e.g., chitosan or alginate) or synthetic ones (e.g., polyacrylamide or polyethylene glycol (PEG)) and functionalized with conductive nanomaterials such as carbon nanotubes, graphene, or metallic nanoparticles (Cheng et al., 2023). The combination of organic and inorganic components produces hybrid polymers with synergistic properties that boost the electrochemical performance of microbial systems (Ng et al., 2021). Despite the increasing number of publications, knowledge in the field remains scattered. Research is being carried out in highly diverse contexts, with heterogeneous experimental approaches and outcomes that are hard to compare. In this context, bibliometric analysis emerges as a strategic tool to map the state of the art, identify emerging trends, key contributors, knowledge gaps, and interdisciplinary collaboration opportunities (Donthu et al., 2021).

Bibliometrics enables the quantification of scientific output over time, analysis of co-authorship networks, identification of leading journals, and evaluation of publication impact (Lazarides et al., 2023). It also helps identify the most frequently studied materials, microbial strains, and MFC configurations, thus guiding future research (Kumar et al., 2023). Several reasons justify undertaking a bibliometric study in this area. First, it consolidates scattered knowledge and establishes a foundation for new research endeavors (Ülker et al., 2023). Second, it provides a panoramic view, benefiting both early-stage researchers and experienced experts. Additionally, such studies inform funding decisions, technological development, and knowledge transfer strategies. Finally, integrating quantitative analysis with qualitative reflection builds a coherent narrative on the field's evolution and future prospects (Pradana et al., 2023).

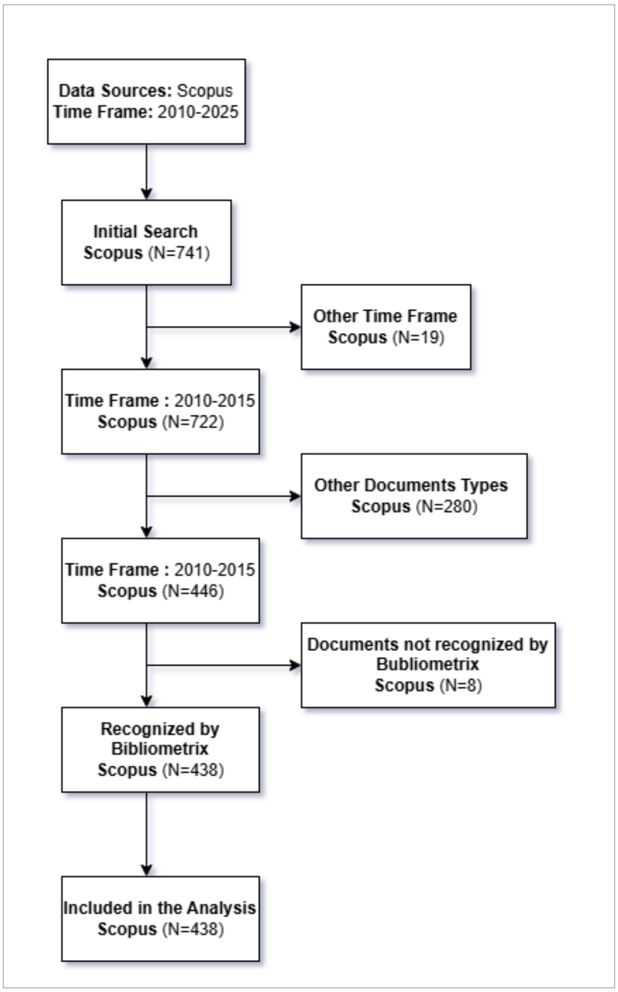
The main objective of this research is to conduct an exhaustive bibliometric analysis of the use of conductive hydrogels and hybrid polymers in MFCs, with emphasis on their role in forming electroactive biofilms and enhancing electron transfer. This study aims to map the scientific development of the field, consolidating knowledge and guiding future research. To achieve this, we address key questions: Q1: What has been the annual evolution of scientific publications on conductive hydrogels and biofilm formation in MFCs between 2010 and 2024? Q2: Who are the most cited and impactful authors in this interdisciplinary line of research? Q3: Which are the most influential articles, in terms of citations, that have shaped the development of materials for MFCs? Q4: Which scientific journals have the highest productivity and citation impact in this field? Q5: Which institutions lead in scientific output and international collaboration? Q6: Which countries have developed the most extensive scientific collaboration networks around hydrogels and biofilms in MFCs? Q7: Which regions of the world exhibit the greatest publication density and impact in advancing sustainable development through bioelectrochemical strategies? Q8: What are the main emerging thematic trends in this area, particularly regarding environmental sustainability, energy efficiency, and functional materials?

The period 2010–2024 was selected to encompass the emergence, consolidation, and recent expansion of the use of conductive hydrogels in MFCs. This period allows us to observe the thematic, technological, and collaborative evolution of the field, from its earliest applications to its interdisciplinary maturity. This study seeks not only to systematize existing knowledge but also to contribute to the consolidation of an interdisciplinary field with high scientific, technological, and social impact potential. By understanding how functional materials such as conductive hydrogels and hybrid polymers can enhance microbial bioelectrochemistry, new avenues are opened for the design of cleaner, more accessible energy technologies tailored to 21st-century challenges. This integrative approach will support decision-making in science and innovation, promote international collaboration, and accelerate the development of energy solutions grounded in sustainability and advanced biotechnology.

Methods

To conduct the bibliometric analysis of scientific production related to conductive hydrogels and biofilm in MFCs, a quantitative approach was adopted, grounded in scientific data mining techniques and network visualization. A systematic search was carried out using the Scopus database, selecting articles published between 2010 and 2024 (December 31st) based on an advanced search strategy that combined relevant thematic descriptors. The following keyword structure was used: (("conductive hydrogel" OR "conductive polymer" OR "hydrogel" OR "gel" OR "polymer") OR ("microbial fuel cell" OR "MFC" OR "biofuel cell" OR "microbial energy" OR "bioenergy") AND ("hybrid polymer" OR "composite polymer" OR "blended polymer" OR "polymer blend") AND ("electrical conductivity" OR "conductivity" OR "electrical properties" OR "ionic conductivity") AND ("sustainability" OR "renewable energy" OR "energy conversion" OR "energy storage")) These terms were connected using Boolean operators to ensure broad and relevant coverage, as outlined in the flowchart in *Fig. 1*.

Fig. 1. *Flowchart of used bibliometric methodology*



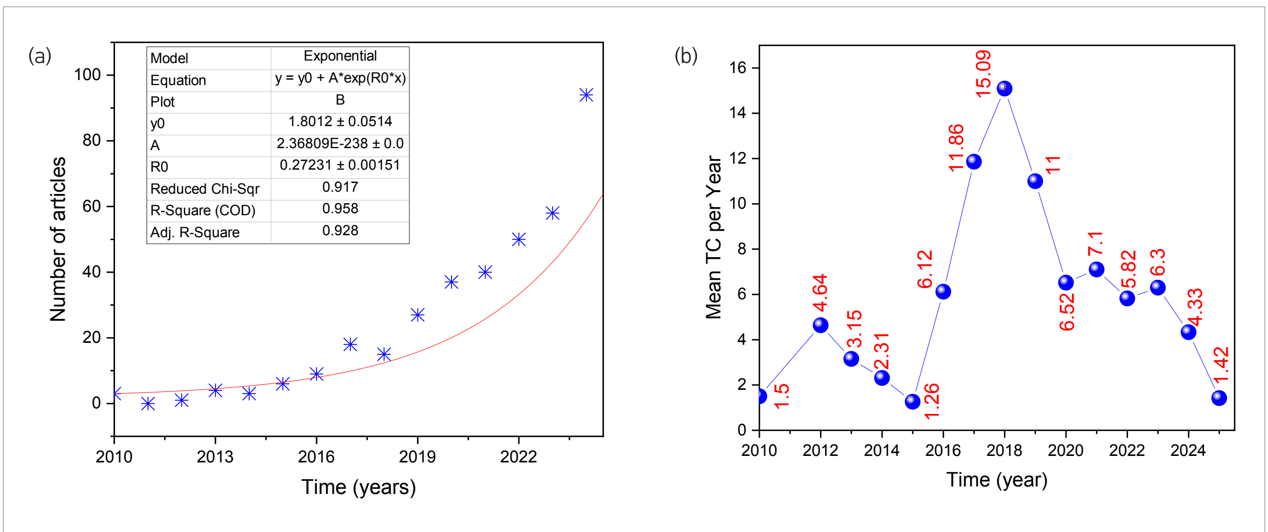
The bibliographic data collected were processed using RStudio software (version 4.3.1) (Equipo Posit, 2025), employing the bibliometrix package along with its graphical interface, biblioshiny (Equipo Posit, 2025). Data collection included searches conducted in databases such as Scopus and Web of Science, applying inclusion criteria that considered articles published between 2000 and 2025 in peer-reviewed journals focusing on topics related to microbial fuel cells (MFCs). Exclusion criteria omitted conference proceedings and non-English publications. These tools enabled the calculation of key indicators, including annual publication output, most influential authors, journals with the highest impact, geographic distribution of articles, and institutional and international co-authorship networks. Additional metrics were also analyzed, such as the h-index, m-index, average citations per document, and collaboration patterns (SCP and MCP). For co-citation, co-authorship, and institutional interaction network analysis, the software VOSviewer (version 1.6.19) was used. This tool generated scientific maps where nodes represent bibliographic entities (authors, institutions, or journals), and links reflect bibliometric relationships. Node size corresponded to the number of occurrences or publications, and colors were used to identify thematic or collaborative clusters. All visualizations produced were complemented by a qualitative analysis of the main emerging scientific trends, framing the results within the context of environmental sustainability, technological innovation in bioelectrochemistry, and the interdisciplinary evolution of knowledge in MFCs. This integrated methodology not only quantified the field's development but also helped identify knowledge gaps, potential synergies among key contributors, and opportunities to guide future research toward cleaner and more efficient energy solutions.

Results and Discussion

Trends in the annual scientific output on conductive hydrogels and biofilms in MFCs

Fig. 2(a) illustrates the temporal evolution of academic production related to conductive hydrogels and biofilms applied to MFCs between 2010 and 2024. According to data extracted from the Scopus database, there is an exponential increase in publication volume, peaking in 2024. This growth trend is modeled using an exponential equation ($y=y_0 + A \cdot e^{R0x}$), with statistically robust parameters (y_0=1.8012 ± 0.0514, A=2.36809 · 10^{-238}, and R_0=0.27231 ± 0.00151). The model achieved a coefficient of determination R^2 = 0.958, an adjusted R^2 of 0.928, and a reduced chi-square value of 0.917 indicating a highly reliable fit. The surge in scientific output aligns with the global momentum toward developing sustainable technologies that integrate biotechnology, materials science, and renewable energy. In particular, the focus on conductive hydrogels as bioactive scaffolds and on optimizing MFC performance via biofilms has attracted growing attention from the scientific

Fig. 2. *(a) Global academic output over time and (b) Average citations per year (2010–2024) from the Scopus database*



community (Zhang et al., 2024). This uptick may also be linked to stricter environmental policies, targeted funding, and increased access to high-resolution analytical tools (Ma et al., 2025). The low A value suggests the field originated with marginal research interest but has been strongly driven by the growth rate R_0, positioning it as an emerging and strategic domain. These trends underscore the dynamism of an interdisciplinary area with substantial potential impact on global sustainability (Xu et al., 2022).

Fig. 2(b) shows the evolution of the average number of citations per year (Mean total citation (TC) per Year) for scientific publications in this field based on Scopus data from 2010 to 2024. A steady rise is observed from 2015 (1.26 citations) to a peak in 2018 with 15.09 citations per year, reflecting a surge of academic interest. This rise coincides with the global shift toward sustainable technologies and renewable energy, where MFCs have drawn attention for their ability to generate electricity from organic waste and bacterial biofilms (Wang et al., 2023a). However, beginning in 2019, a gradual decline in citation averages is evident, dropping sharply by 2024 (1.42), which may reflect field saturation, shifting research priorities, or the emergence of competing technologies. According to Scopus and ScienceDirect, interest in smart materials such as conductive hydrogels remains strong, though it has increasingly diversified toward biomedical and sensor applications (Wang et al., 2023b). This analysis suggests that while the field has reached a degree of maturity, there are still opportunities for innovation especially in integrating advanced materials with bioelectrochemical systems.

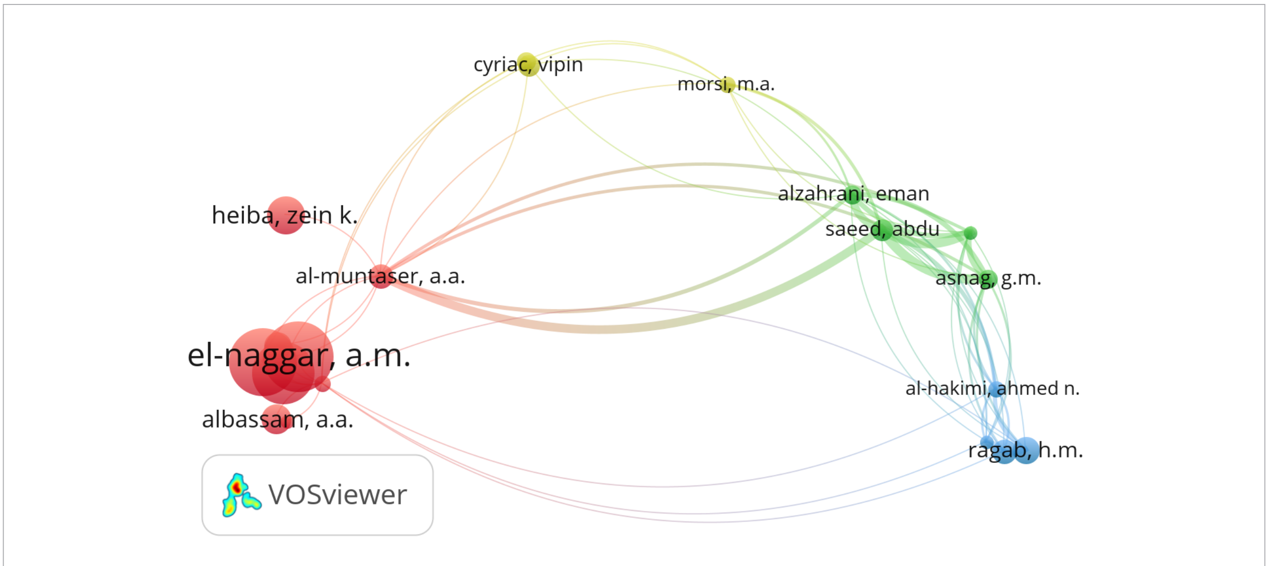
Influential authors and their scientific collaborations

Table 1 highlights the leading authors in the field of conductive hydrogels and biofilms applied to microbial fuel cells (MFCs), revealing a significant evolution in both scientific output and the impact of this research line. Notable figures include El-Naggar, Aziz, and Kamal, who lead in the number of publications (26 and 25 articles, respectively). Aziz, in particular, holds an h-index of 17, reflecting a strong combination of productivity and sustained citation impact. The m-index, which adjusts citation impact based on the number of years since an author's first publication, shows remarkable values of 3.333 for both El-Naggar and Kamal, indicating rapid growth over a short time frame, especially since 2023. This pattern suggests a recent surge of interest in the topic, likely driven by advances in smart materials and the growing demand for sustainable energy solutions. From a technical standpoint, conductive hydrogels have proven to be highly promising materials for improving MFC efficiency by facilitating electron transfer, stabilising biofilms, and serving as scaffolds for microbial immobilisation (Bi et al., 2024). Their porous structure, biocompatibility, and self-assembling capability allow for more efficient interactions between electrogenic microorganisms and electrodes (He et al., 2024). Moreover, the incorporation of conductive polymers such as PANI and PPy, as well as nanomaterials like carbon nanotubes and graphene, has significantly enhanced power density and operational stability in MFCs (Qi et al., 2022). Authors like Kadir M. and

Table 1. *Top authors in conductive hydrogels and biofilm research for MFCs (2010–2024)*

Rank	Author	No. of docs	H-index	M-index	Total citations	First year published
1	El-Naggar A.M.	26	10	3.333	204	2023
2	Aziz S.B.	25	17	2.429	919	2019
3	Kamal A.M.	25	10	3.333	204	2023
4	Mohamed M.B.	23	10	3.333	192	2023
5	Kadir M.F.	22	15	2.143	795	2019
6	Heiba Z.K.	14	7	2.333	111	2023
7	Abdulwahid R.T.	13	10	1.429	525	2019
8	Wang J.	13	8	0.500	405	2010
9	Brza M.A.	12	11	1.571	543	2019
10	Hamsan M.H.	12	9	1.286	449	2019

Fig. 3. *Co-authorship network among key authors in conductive hydrogels and biofilm research in MFCs (2010–2024)*



Brza M. also stand out for their high citation counts (795 and 543, respectively), underscoring the relevance of their contributions to hybrid hydrogel development and electrode modification strategies. In contrast, Wang J., active since 2010, represents a longer research trajectory, although with a lower m-index suggesting an earlier but less intensive contribution in recent years. These findings reveal an expanding scientific community, with a core of emerging researchers pushing the boundaries at the intersection of biotechnology, materials science, and sustainable energy. This growth is further reflected in rising international collaborations and the diversification of applications, ranging from wastewater treatment to biosensors and advanced bioelectrochemical systems (Zhao et al., 2025). The trend points toward a consolidation of the field as a key pathway for the development of clean and efficient technologies.

Fig. 3 displays the co-authorship network generated using VOSviewer for the topic under study. Each node represents an author, with its size corresponding to the number of publications or the overall weight of that author's scientific contribution. The lines connecting the nodes indicate co-authorship relationships, while the colors group authors into collaborative clusters, reflecting scientific communities with shared thematic or institutional links. The node representing El-Naggar stands out as the largest and most central, suggesting he is a highly productive author with an extensive collaboration network. Surrounding him are authors such as Al-Muntaser, Albassam, and Heiba, Zein, forming a consolidated collaborative core. Other noteworthy clusters include one composed of Cyriac, Vipin, and Morsi, which appears to form a distinct but connected subnetwork. This structure implies that the field comprises several interrelated research groups, with certain authors acting as bridges between communities. The density of connections and the distribution of nodes illustrate an active landscape of scientific collaboration, likely driven by the interdisciplinary nature of the topic bringing together materials science, biotechnology, and sustainable energy (Rezaie et al., 2024). Such analysis helps identify key opinion leaders, potential strategic partners, and collaborative dynamics that can inform future academic partnerships or funding decisions. Furthermore, it underscores the importance of fostering collaborative networks to accelerate innovation in clean technologies such as MFCs (Zhang et al., 2023).

Most influential articles in the field

Table 2 presents the ten most highly cited articles, showing the most influential contributions that have shaped this interdisciplinary field. The most cited work is by Zhang (2013), published in ACS nano, with 991 citations. This pioneering article explores the design of conductive hydrogels for flexible electronic devices, laying the groundwork for their application in bioelectrochemical systems such as MFCs (Zhao et al., 2023). It is followed by Zhao et al. (2023) in Advanced Energy

Materials with 615 citations, which delves into the use of conductive polymer hydrogels for energy storage and conversion a key functionality in enhancing MFC efficiency. Ranked third is Lin et al. (2018), whose article in Advanced Materials (511 citations) addresses advanced hydrogel-based materials for bioelectrochemical systems, highlighting their role in improving electron transfer. Palanisamy et al. (2019), in Journal of Cleaner Production with 452 citations, provides a comprehensive review of emerging materials and applications in MFCs, emphasizing the relevance of hydrogels in energy sustainability. Yu and Manthiram (2021), publishing in Energy Storage Materials (378 citations), proposes high-performance hydrogel electrolytes for flexible energy devices, reinforcing the versatility of these materials. Other notable contributions include Forsyth et al. (2019) in Accounts of Chemical Research (324 citations), which examines polymer electrolytes and hydrogels for electrochemical applications. Yang et al. (2023), with 208 citations in Nano-Micro Letters, introduces nitrogen-doped hydrogel composites designed to enhance MFC performance, while Hu et al. (2017) in Materials Science and Engineering R: Reports (201 citations) offers a review of hydrogel-based materials for energy and environmental applications. Collectively, these articles reflect a significant evolution in the use of conductive hydrogels as multifunctional platforms in MFCs, underscoring their role in enhancing energy efficiency, biocompatibility, and the sustainability of these systems (Lin et al., 2018); (Palanisamy et al., 2019). Their high citation counts attest to their scientific impact and status as key references for future research.

Journals with the highest scientific output

Table 3 consolidates the most productive and influential journals in the field, revealing a clear concentration of scientific output within a select group of publications. Polymers leads with 14 articles, an h-index of 13, and a total of 397 citations reflecting both volume and sustained impact since its entry into the topic in 2018. This journal has played a key role in disseminating studies on functionalized hydrogels and their integration into bioelectrochemical systems, with a strong focus on advanced polymer materials. Next are *ACS Applied Materials and Interfaces* and *Journal of Energy Storage*, each with 12 publications. The former, with an m-index of 1,500 and 319 total citations, has been instrumental in publishing research on hybrid hydrogels and their application in bioelectronic interfaces. The

Table 2. *Top 10 most cited Articles in conductive hydrogels and biofilm research for MFCs (2010–2024)*

Author, year	Document title	Journal name	Total citations (TC)
Zhang et al., 2023	Hydrogels for flexible electronics.	ACS nano	991
Zhao et al., 2018	Solid-State Sodium Batteries.	Advanced Energy Materials	615
Lin et al., 2018	A Silica-Aerogel-Reinforced Composite Polymer Electrolyte with High Ionic Conductivity and High Modulus.	Advanced Materials	511
Palanisamy et al., 2019	A comprehensive review on microbial fuel cell technologies: Processes, utilization, and advanced developments in electrodes and membranes.	Journal of Cleaner Production	452
Yu and Manthiram, 2021	A review of composite polymer-ceramic electrolytes for lithium batteries.	Energy Storage Materials	378
Forsyth et al., 2019	Polymer electrolytes and hydrogels for electrochemical applications.	Accounts of Chemical Research	324
Yang et al., 2023	Nitrogen-doped hydrogel composites for enhanced MFC performance.	Nano-Micro Letters	208
Hu et al., 2017	Bioinspired conductive hydrogels for sustainable energy systems.	Science Advances	204
Lund et al., 2018	Electrically conducting fibres for e-textiles: An open playground for conjugated polymers and carbon nanomaterials	Materials Science and Engineering: R: Reports	201

Table 3. *Most Productive and Impactful Journals in Conductive Hydrogels and MFC Biofilm Research (2010–2024)*

Journal	h-index	m-index	Total citations (TC)	No. of papers (NP)	First year published
Polymers	13	1.444	397	14	2018
ACS Applied Materials and Interfaces	12	1.500	319	12	2020
Journal of Energy Storage	11	1.833	273	12	2019
Ceramics International	11	1.571	260	11	2019
AIP Conference Proceedings	5	0.625	49	10	2017
Journal of Materials Science: Materials in Electronics	10	1.429	189	9	2018
ACS Applied Energy Materials	10	1.667	214	8	2020
Chemical Engineering Journal	9	1.800	201	8	2019
Electrochimica Acta	9	1.286	164	8	2018
Ionics	8	1.143	140	8	2019

latter, with the highest m-index in the table (1.833), reflects accelerated growth since 2019, driven by studies on energy storage in hydrogel-based systems, such as those by Yu and Manthiram (2021), exploring high-performance hydrogel electrolytes. Ceramics International also stands out with 11 articles and 260 citations, establishing itself as a platform for research on functional ceramic materials in hydrogel-modified electrodes (Yu et al., 2021). Meanwhile, AIP Conference Proceedings, although with lower impact (49 citations and an h-index of 5), has served as a dissemination channel for emerging work and interdisciplinary collaborations, particularly in international conference contexts. Journals such as ACS Applied Energy Materials, Chemical Engineering Journal, and Electrochimica Acta each with 8 publications strike a balance between productivity and quality. For instance, Chemical Engineering Journal reports an m-index of 1,800 and 201 citations, indicating a high yearly impact since its first publication in 2019. Ionics and Journal of Materials Science: Materials in Electronics round out the ranking, both contributing significantly to the development of membranes and functional electrodes for MFCs. These journals not only account for the majority of scientific output in the area but also reflect the thematic evolution of the field from a materials-centered perspective to one increasingly aligned with sustainable energy applications. Their analysis helps identify strategic publication venues for researchers seeking visibility and impact in this emerging research domain (Moradian et al., 2022).

The visualization generated with VOSviewer, shown in *Fig. 4*, represents a co-citation network among key scientific journals in the field. Notably, journals such as *Journal of Energy Storage*, Ionics, Electrochimica Acta, and Ceramics International form a dense co-citation core. These publications have been instrumental in disseminating research on functional materials, electron transfer, and electrode design for microbial fuel cells (MFCs). For instance, Electrochimica Acta has published numerous studies on electrode modification using conductive hydrogels and its impact on electrochemical efficiency. Ionics, in turn, has played a crucial role in characterizing ionic membranes and their integration with microbial biofilms (Kamali et al., 2025). The presence of Polymers in the network, although somewhat peripheral, highlights its role in publishing research on the synthesis and functionalization of hydrogels with electrical and biocompatible properties. According to a recent study, hydrogels based on polymers such as PANI and PPy have demonstrated improvements in microbial adhesion and electron transfer within MFCs. Similarly, Solid State Ionics and Ceramics International reflect growing interest in ceramic materials and hybrid composites that combine structural and conductive properties (Wang et al., 2023). This bibliometric network not only reveals the most influential journals but also clarifies how research clusters thematically around materials science, bioelectrochemistry, and energy sustainability. The interconnection among these publications suggests an active, multidisciplinary scientific community, where technological collaboration across materials science, biotechnology, and electrochemical engineering is essential for advancing MFCs as a clean and efficient energy technology (Truong et al., 2021).

Fig. 4. *Scientific journal network based on co-citation analysis*

Most active institutions and scientific collaborations

Table 4 provides a comprehensive overview of the most productive institutions and countries in the field, highlighting both their publication volume and patterns of scientific collaboration. King Saud University (Saudi Arabia) leads with 88 articles, 95.5% of which involve international collaboration (MCP), reflecting an institutional strategy focused on global research engagement. The university has played a key role in the development of advanced polymeric materials and their integration into bioelectrochemical systems, particularly in partnership with institutions across Asia and Europe. Next is the University of Sulaimani (Iraq), with 66 publications and an impressive 83.3% rate of international collaboration remarkable given the region's geopolitical context. Its research has focused on synthesizing hybrid hydrogels and applying them to modified electrodes for MFCs (He et al., 2024). Universiti Teknologi Petronas (Malaysia) and Ain Shams University (Egypt) also show strong productivity 37 and 36 publications, respectively with international collaboration rates exceeding 59%. These institutions have made substantial contributions to the design of conductive membranes and the characterization of electroactive biofilms. In contrast, Chinese institutions like Huazhong University of Science and Technology and the University of Chinese Academy of Sciences also exhibit high productivity (30 and 27 articles, respectively), but with relatively low rates of international publications (13.3% and 14.8%),

Table 4. *Most productive institutions and their countries with collaboration metrics (2010–2024)*

Rank	Institution name	Articles of institution	Country	Articles of countries	SCP	MCP	MCP %
1	King Saud University	88	Saudi Arabia	25	4	84	95.50
2	University of Sulaimani	66	Iraq	30	11	55	83.30
3	Universiti Teknologi Petronas	37	Malaysia	22	15	22	59.50
4	Ain Shams University	36	Egypt	26	7	29	80.60
5	Huazhong University of Science and Technology	30	China	94	26	4	13.30
6	King Abdulaziz University	29	Saudi Arabia	25	4	25	86.20
7	University of Malaya	28	Malaysia	22	15	13	46.40
8	University of Chinese Academy of Sciences	27	China	94	23	4	14.80
9	Manipal Institute of Technology	22	India	95	17	5	22.70
10	School of Advanced Sciences (Vellore Institute of Technology)	20	India	95	17	3	15.00

suggesting a more nationally focused collaboration strategy. However, China leads in total publication output (94 articles), reflecting its increasing investment in sustainable technologies. India also stands out with institutions like Manipal Institute of Technology and Vellore Institute of Technology contributing a combined total of 42 articles, although with lower international engagement (MCP < 23%). These data reflect a global trend toward scientific cooperation in the realm of energy sustainability. The most impactful institutions are not only prolific publishers, but also active participants in international networks enhancing knowledge transfer and driving technological innovation (Fu et al., 2025). According to recent studies, international collaboration in MFC research has accelerated the development of materials such as nanomaterial-doped hydrogels (e.g., graphene, carbon nanotubes), which significantly improve electron transfer efficiency and biofilm stability (Ratheesh et al., 2021).

Fig. 5 illustrates the scientific collaboration network among institutions researching conductive hydrogels and biofilms in microbial fuel cells. Prominent institutions such as the University of Sulaimani, King Saud University, Ain Shams University, and the University of Malaya form dense collaboration clusters, indicating a strong presence within international scientific networks. Inter-institutional collaboration has been crucial for advancing MFC technologies, particularly in the development of hybrid materials like hydrogels doped with nanomaterials (e.g., graphene, carbon nanotubes, and metal oxides), which enhance electron transfer and biofilm stability (Bashir et al., 2021). These properties are essential for boosting the energy efficiency and operational durability of MFCs, especially in applications such as wastewater treatment and renewable energy generation (Sanaei et al., 2025). According to a recent study, hydrogels enable improved microbial immobilization and a more efficient interface between electrogenic microorganisms and electrodes (Li et al., 2022); (You et al., 2023). Institutions such as Universiti Teknologi Petronas and the University of Malaya have made significant contributions to synthesizing hydrogels with tunable mechanical and electrical properties, while King Saud University and KAUST have led research on integrating these materials into bioelectrochemical systems. Conversely, Chinese institutions such as Huazhong University of Science and Technology and the University of Chinese Academy of Sciences exhibit high research output but lower levels of international collaboration, suggesting a more nationally oriented approach. However, China remains the global leader in total publications in this field. This network also highlights the growing role of institutions from the Middle East and Southeast Asia as key players in sustainable technology research. Collaboration across these regions is accelerating the development of bioelectrochemical solutions aligned with the Sustainable Development Goals, particularly those related to clean energy (SDG 7) and water sanitation (SDG 6).

Fig. 5. *Institutions y-level scientific collaborations (MFCs and Hydrogels)*

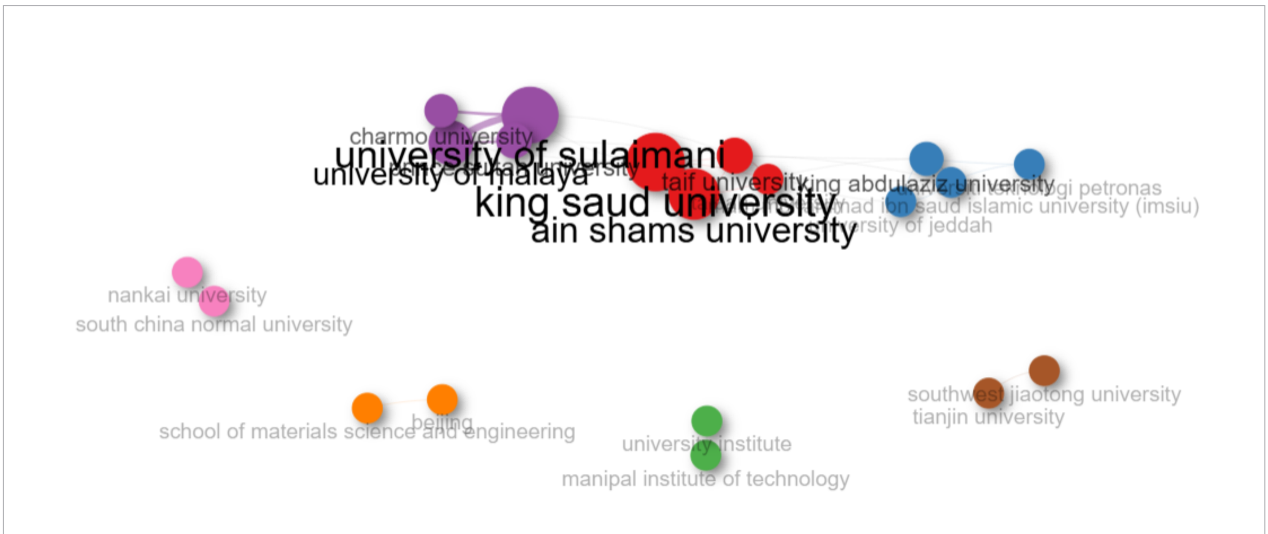
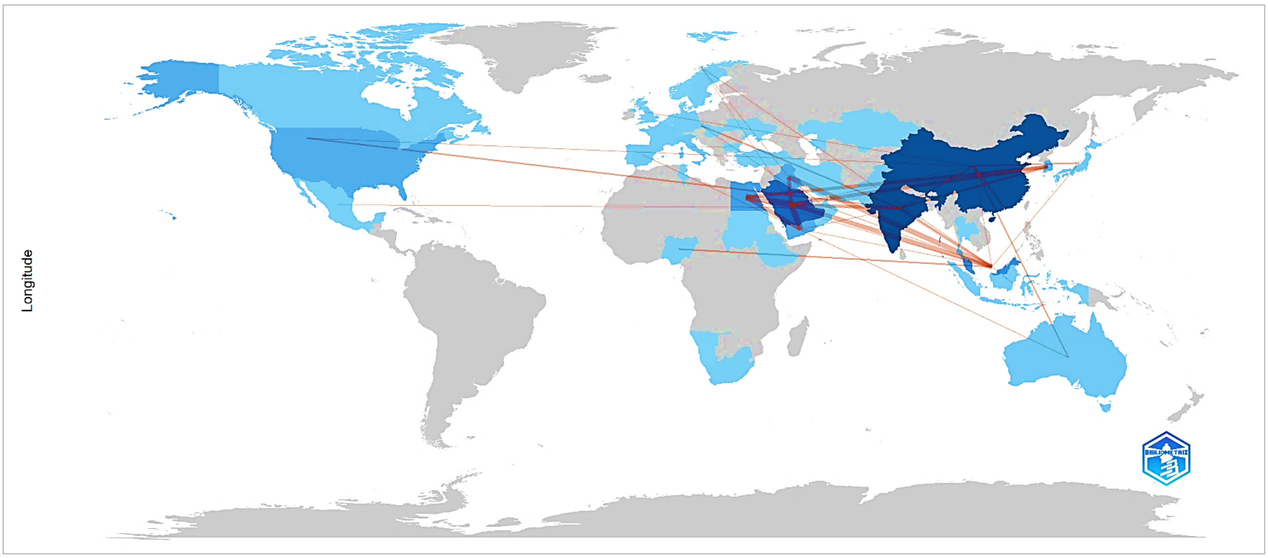


Fig. 6 presents a global map of scientific collaborations between countries. Each country is color-coded according to the intensity of its international partnerships, and the connecting lines represent bilateral co-authorship links. This type of visualization helps identify the central hubs of global scientific cooperation and the flow of knowledge between regions (Cheng et al., 2024). According to the international collaboration data, Saudi Arabia leads with 130 partnerships, positioning itself as a central node in the global network. This leadership is partly driven by institutions such as King Saud University and KAUST, which have established strategic alliances with countries like Egypt (39 collaborations), Yemen (30), Malaysia (18), and India (7). The network reflects an active policy of scientific internationalization fueled by investments in sustainable and clean energy technologies. India ranks second with 61 collaborations, underscoring its role as a bridge between Asia, the Middle East, and Europe. Its strongest ties are with Malaysia (7), South Korea (6), and the United States (3), demonstrating a multidirectional cooperation strategy. China, with 39 collaborations, maintains a more diversified but less dense network, with notable links to Japan, Australia, Germany, and the United Kingdom. While China's publication strategy is more nationally focused, its international presence continues to grow. Malaysia (38 collaborations) and Egypt (27) also emerge as key players, especially along the Asia–Africa axis. Malaysia maintains strong ties with Iraq (21), Yemen (2), and Japan (2), while Egypt collaborates extensively with South Korea (10) and Yemen (15), reinforcing its strategic role in North Africa and the Middle East. Other countries with noteworthy networks include Iraq (20), South Korea (15), Germany (12), and the United States (9), each fostering connections across Asia, Europe, and Africa. The inclusion of countries such as Nigeria, Norway, Tunisia, and Sudan points to a growing representation of traditionally underrepresented regions in global scientific research. Overall, the map depicts an increasingly interconnected ecosystem of scientific collaboration, where South–South alliances (such as Saudi Arabia–Egypt or India–Malaysia) are becoming just as significant as traditional North–South partnerships.

Fig. 6. *Countries' collaboration world map*



Bioelectrochemical strategies for sustainable development and research trends

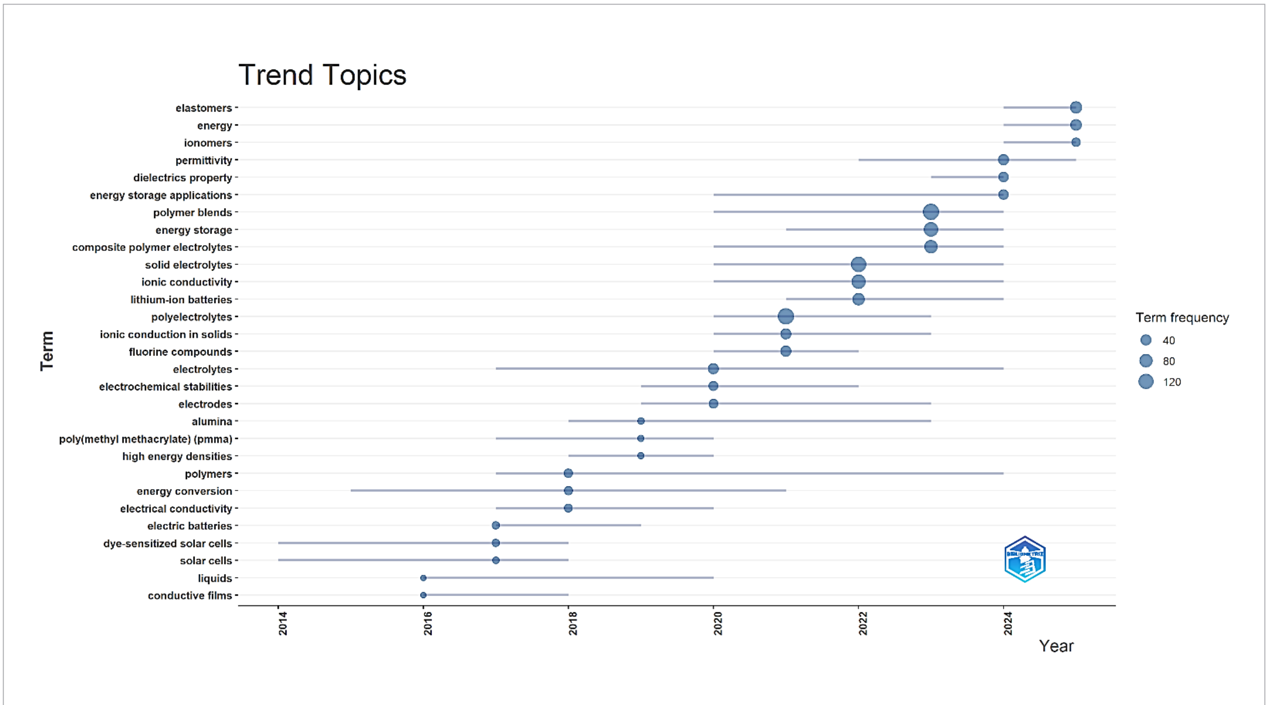
Bioelectrochemical strategies have emerged as a promising avenue for sustainable development, particularly in the context of clean technologies such as MFCs. These systems harness the ability of certain microorganisms to transfer electrons through electroactive biofilms to electrodes, generating electricity from organic waste (Saraf et al., 2025). Conductive hydrogels have taken center stage as key materials for enhancing MFC efficiency by facilitating microbial adhesion, electron transfer, and structural stability of the system (Ji et al., 2025). From 2010 to 2024, scientific mapping reveals steady growth in research on hydrogels and biofilms in

MFCs, with an increasing focus on environmental sustainability. According to Frontiers in Microbiology, bioelectrochemical systems (BESs) have been applied not only for energy generation but also for bioremediation, chemical synthesis, and CO_2 capture (Javed et al., 2025). In this context, hydrogels doped with nanomaterials such as graphene, carbon nanotubes, or polyaniline have significantly improved conductivity and biocompatibility, enabling a more efficient interface between microorganisms and electrodes (He et al., 2025).

Moreover, derivative technologies like electrofermentation have expanded the scope of BESs, allowing for the production of biofuels and value-added compounds from organic waste under redox-controlled conditions using electrodes (Yuyang et al., 2025). These strategies not only optimize energy conversion but also contribute to the circular economy and the reduction of greenhouse gas emissions (Lee et al., 2025). Bibliometric analysis also shows a rise in international collaborations especially among institutions in Asia and the Middle East which has driven innovation in the design of electrodes, reactors, and functional materials. The integration of smart hydrogels capable of responding to chemical or electrical stimuli represents an emerging frontier in MFC engineering, with potential applications in environmental sensors, wastewater treatment, and distributed energy generation (Jin et al., 2025). Bioelectrochemical strategies based on conductive hydrogels and biofilms represent not only a technological solution to energy and environmental challenges but also reflect a broader scientific evolution geared toward sustainability (Domadiya et al., 2025). Their future development will depend on further material optimization, deeper understanding of electron transfer mechanisms, and scaling up for real-world applications.

Fig. 7 illustrates the evolution of key terms associated with the field. Each horizontal line represents a topic, while circles of varying sizes indicate the frequency of that term in the literature. This visualization allows researchers to identify not only the time period during which each term was most relevant, but also its relative prominence, based on the diameter of the bubbles (Xiao et al., 2025). In the earlier years (2014–2016), concepts related to electrical properties and fundamental materials stand out such as "electrical conductivity," "polymers," and "electrolytes." These terms reflect the foundational stage of polymer electrochemistry, when the research community was laying the groundwork for the design of conductive hydrogels and films. The early presence of "liquids" suggests initial exploration of hybrid liquid–solid systems.

Fig. 7. *Thematic trends in conductive hydrogels and biofilm in MFCs*



Between 2016 and 2020, there is a noticeable shift toward more application-specific topics related to energy storage and conversion. Terms like "energy storage", "lithium-ion batteries", "solid electrolytes" and "composite polymer electrolytes" gain relevance. At the same time, "ionic conductivity" emerges with notably large bubbles, highlighting a growing focus on optimizing ion mobility within polymer matrices. Other terms such as "energy conversion" and "high energy densities" also appear, reflecting rising interest in compact, high-performance systems. In the most recent period (2020–2024), cutting-edge topics begin to surface, including "dye-sensitized solar cells," "solar cells," and "energy storage applications." The emergence of "polymer blends" and "ionomers" indicates efforts to combine phases for enhanced mechanical and electrical properties. Additionally, the appearance of terms like "dielectrics property" and "permittivity" points to more sophisticated measurement approaches for advanced applications in flexible electronics and clean energy devices. Altogether, *Fig. 7* reveals a thematic progression from fundamental material characterization to the integration of hydrogels and biofilms in sustainable energy technologies (Simić et al., 2025). The transition from general to specialized terminology highlights the field's maturation and the diversification of its applications (Simić et al., 2025). This temporal mapping provides researchers with a roadmap to identify saturated areas, uncover gaps (e.g., electrosynthesis or integrated sensors), and guide future research directions toward emerging challenges in bioelectrochemistry and the circular economy (Doineau et al., 2025).

Scientific trends in conductive hydrogels and biofilm research in microbial fuel cells (2010–2024)

Between 2010 and 2024, the scientific landscape surrounding conductive hydrogels and biofilm formation in MFCs has undergone a marked transformation, characterized by exponential growth in publication volume and increasing interdisciplinary integration. Early research focused on rigid, inert electrode materials with limited microbial interaction. Over time, the field shifted toward the development of biocompatible, porous, and electrically conductive hydrogels capable of enhancing extracellular electron transfer and stabilizing electroactive biofilms.

This evolution has been driven by the convergence of materials science, biotechnology, and environmental engineering, with conductive hydrogels emerging as multifunctional platforms for improving MFC performance. Hybrid polymers doped with nanomaterials such as graphene, carbon nanotubes, and metallic nanoparticles have demonstrated superior conductivity, microbial adhesion, and structural flexibility. These advances have enabled more efficient energy conversion from organic waste, positioning MFCs as viable technologies for sustainable energy generation and wastewater treatment.

Thematic trends identified through bibliometric mapping reveal a diversification of research topics, including electrofermentation, circular economy strategies, and bioelectrochemical sensors. Keyword co-occurrence and cluster analysis highlight four dominant thematic areas: (1) functional materials for electron transfer, (2) biofilm engineering and microbial immobilization, (3) energy sustainability and conversion efficiency, and (4) environmental applications of MFCs. Geographically, the field has expanded through robust international collaboration, with China, Saudi Arabia, and Southeast Asian countries leading in publication output and institutional partnerships. Journals such as *Polymers*, *ACS Applied Materials and Interfaces*, and *Journal of Energy Storage* have emerged as core publication venues, confirmed through Bradford's law analysis.

Citation dynamics indicate that impact is not solely driven by thematic relevance but also by structural factors such as publication proliferation and citation lag. Therefore, productivity metrics were complemented with normalized indicators (h-index, m-index, average citations per year), and the top 1–5% of authors were identified using percentile-based thresholds in Bibliometrix. Overall, the field exhibits signs of thematic consolidation and technological maturity, with conductive hydrogels positioned as key enablers of next-generation bioelectrochemical systems. These trends underscore the strategic importance of integrating advanced materials into microbial platforms to address global challenges in energy, water, and sustainability.

Conclusions

Based on the bibliometric analysis conducted, the conclusions highlight a significant evolution in research on conductive hydrogels and their role in enhancing electron transfer in microbial fuel cells (MFCs), as well as their potential application in sustainable development and technology entrepreneurship. Regarding the annual evolution of scientific publications (Q1), findings confirm exponential growth since 2010, peaking in 2025. This trend reflects a sustained increase in interest in integrating materials science, biotechnology, and sustainable energy. The strong statistical robustness of the growth model confirms that the field has progressed from being marginal to emerging as a key driver of sustainable innovation. As for the most influential authors (Q2), figures such as El-Naggar A.M. and Aziz S.B. stand out, with high h- and m-index values. This suggests not only productivity but also cumulative impact. Their leadership is supported by collaborative co-authorship networks, as reflected in the relationship map generated with VOSviewer, which displays active clusters of densely interconnected nodes. This cohesion reinforces the importance of scientific alliances in accelerating innovation. In terms of the most cited articles (Q3), publications such as those by Zhang et al. (2024) and Zhao C. (2023) have been foundational in establishing the use of hydrogels in bioelectrochemical systems. These works offer conceptual and technological frameworks that have been widely replicated and refined. The most productive journals (Q4), such as *Polymers* and *ACS Applied Materials and Interfaces*, have served as key technical dissemination platforms in this interdisciplinary field. Their importance is reinforced by co-citation networks, which reveal a coherent thematic structure across materials science, applied electrochemistry, and biotechnology.

Regarding leading institutions (Q5), King Saud University and the University of Sulaimani are identified as key hubs, with high rates of international collaboration. This was confirmed through the MCP (Multiple Country Publications) analysis, showing that international cooperation not only boosts scientific productivity but also enhances technology transfer. At the country level (Q6 and Q7), China, India, Saudi Arabia, and Egypt lead not only in publication volume but also in their central roles within collaborative networks. *Fig. 6* demonstrates that global research on hydrogels in MFCs is highly interconnected, with South–South partnerships emerging as effective pathways for advancing energy sustainability. Finally, emerging thematic trends (Q8) span from the functionalization of hydrogels with nanomaterials (e.g., graphene and PANI) to their application in circular economy strategies. New lines of research are also evident, including electrofermentation and the integration of hybrid systems for environmental remediation and energy production. This bibliometric study provides a strategic and consolidated perspective on a research field that merges advanced materials, biotechnology, and sustainability laying the groundwork for future innovation and entrepreneurship rooted in bioelectrochemistry.

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