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Review

Bioelectromagnetic fields as signaling currents of life

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ABSTRACT

Bioelectromagnetic signaling, a fundamental aspect of biological systems, has gained increasing attention in recent years. This review synthesizes current knowledge and recent advancements in bioelectromagnetic research, covering principles, evidence, and emerging applications. We discuss the generation, reception, and roles of bioelectromagnetic fields in living organisms, focusing on intercellular and organism-level communication. The review also examines therapeutic applications, and technological innovations arising from our understanding of bioelectromagnetic phenomena. Finally, we outline future research directions that promise to deepen our comprehension of life's electromagnetic dimensions and potentially revolutionize medicine and technology.

1. Introduction

Bioelectromagnetic signaling is a captivating area of research that bridges biology and physics, exploring how biological systems communicate and interact through electromagnetic fields and waves.[1] This field has a rich history dating back to the 18th century when Luigi Galvani's discovery of “animal electricity” in 1,791 laid the foundation for future investigation.[2] Over the years, pioneering work by researchers such as Harold Saxton Burr, Robert O. Becker, and Björn Nordenström has significantly advanced our understanding of bioelectromagnetic signaling and its crucial role in biological systems.[3–5]

The importance of this field extends far beyond academic curiosity. As our knowledge of bioelectromagnetic signaling expands, it unveils new possibilities for medical treatments, technological innovations, and insights into fundamental biological processes.[6,7] Recent advancements have shown promising applications in neurodegenerative diseases, cancer therapy, and regenerative medicine.[8–10]

This comprehensive review explores the complex and rapidly evolving field of bioelectromagnetic signaling. We synthesize current knowledge, examine recent advancements, and identify future research directions. The review covers fundamental principles of bioelectromagnetic signaling, evaluates evidence for bioelectromagnetic communication, and discusses the applications and implications of this research. Through this analysis, we hope to stimulate further inquiry and highlight the potential of bioelectromagnetics to revolutionize our understanding of life and health.

2. Methodology

This comprehensive review employed a systematic literature search approach, encompassing a broad historical perspective while focusing on recent advancements in the field of bioelectromagnetic signaling. We conducted extensive searches across major scientific databases, including PubMed, Web of Science, and Scopus, covering literature from the late 18th century through 2024. This wide-ranging temporal scope was chosen to capture both the historical foundations and the cutting-edge developments in the field. Our search strategy utilized combinations of key terms such as “bioelectromagnetic,” “electromagnetic fields,” “cell signaling,” “biophysics,” and “electrophysiology."

In our selection process, we prioritized peer-reviewed articles, with a particular emphasis on high-impact journals and seminal works that have significantly shaped the field. To ensure comprehensive coverage, we also reviewed relevant books and conference proceedings. Our literature selection followed a multi-stage process, beginning with an initial screening based on titles and abstracts to exclude clearly irrelevant works. This was followed by a thorough full-text review of the remaining literature to identify the most relevant and impactful studies. In recognition of the field's rich history, we included several early works of historical significance, such as Luigi Galvani's 1,791 discovery of “animal electricity.” Simultaneously, we placed special emphasis on literature

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published in the last five years (2019–2024) to reflect the most recent research trends and breakthroughs in bioelectromagnetic signaling.

The selected literature underwent critical analysis and synthesis to provide an up-to-date overview of the field. Our aim was to strike a balance between historical context and current research frontiers, presenting a comprehensive narrative of the field's evolution and future prospects. This approach allowed us to trace the development of key concepts over time while highlighting contemporary innovations and emerging areas of study in bioelectromagnetic signaling.

3. Fundamental principles of bioelectromagnetic signaling

3.1. Nature of electromagnetic fields in biology

Bioelectromagnetic phenomena encompass a wide range of electromagnetic interactions within and between living organisms.[11] These fields are characterized by their frequency, intensity, and spatial distribution, each playing a unique role in biological processes.[12] Importantly, bioelectromagnetic phenomena in living systems span a wide range of the electromagnetic spectrum, from static fields to extremely low frequency fields, and extending to higher frequencies including visible light and beyond. Static fields represent the steady-state electric fields that span across cell membranes, as well as the subtle magnetic fields emanating from organs such as the heart and brain.[13] These fields are fundamental to preserving cellular polarity and modulating the distribution of charged molecules, thereby laying the groundwork for cellular homeostasis.[14] ELF fields, ranging from 0 to 300 Hz, synchronize with our body's physiological rhythms. They are integral to neural oscillations, cardiac rhythms, and circadian cycles, acting as coordination signals that facilitate harmonious bodily functions.[15,16] At the higher end of the spectrum, fields extending beyond the ELF range reach into radio frequencies and the optical spectrum.[17] Biophoton emissions exemplify this category, hinting at their involvement in cellular communication and regulatory processes.[18]

3.2. Generation of bioelectromagnetic fields

The mechanisms by which biological systems generate electromagnetic fields are diverse and interconnected. At the cellular level, the movement of ions across membranes creates electrical currents and associated magnetic fields.[19] This ionic ballet is the foundation of the resting membrane potential and the dynamic action potentials that are the lifeblood of neural communication.[20]

Beyond individual cells, the synchronized activity of cellular populations, such as in neural networks, can produce larger-scale electromagnetic fields that ripple through tissues and organs.[21] Some biological materials, like bone and collagen, exhibit piezoelectric properties, the ability to generate an electric charge in response to applied mechanical stress, generating electric fields when subjected to mechanical stress.[22] In the depths of cellular metabolism, the electron transport chain in mitochondria produces weak electromagnetic fields as a byproduct of energy production.[23] The spatial and temporal dynamics of bioelectromagnetic fields add further layers of complexity. From the microscopic electric fields surrounding individual neurons to the macroscopic fields generated by coordinated brain activity, these electromagnetic patterns form a multidimensional landscape of biological information.[24] Temporally, the fields exhibit a rich tapestry of rhythms and fluctuations, from the rapid-fire of neural action potentials to the slower undulations of circadian rhythms.[25]

3.3. Interactions between electromagnetic field and biological systems

The interplay between electromagnetic fields and biological systems involves multiple fundamental mechanisms that produce various biological effects across different frequency ranges. These mechanisms can be categorized into several key areas, each contributing to our understanding of how electromagnetic fields influence living organisms.

At the molecular level, electromagnetic fields may induce conformational changes in proteins, as proposed by Funk et al.[26] This concept opens up new possibilities for understanding how electromagnetic fields regulate cellular functions by potentially affecting enzyme kinetics and signaling pathways. This molecular-level interactions reveal the subtle yet significant ways electromagnetic fields can modulate biological processes.

Cellular-level interactions primarily involve the activation of ion channels. Extremely low frequency electromagnetic fields have been shown to activate voltage-gated calcium channels, ion channels that open in response to changes in cell membrane electrical potential, resulting in rapid increases in intracellular calcium ions. Pall's research suggests that this mechanism may induce physiological changes such as neural activity and muscle contraction, highlighting the direct impact of electromagnetic fields on cellular function.[7,27]

At the tissue level, electromagnetic induction plays a crucial role. Time-varying magnetic fields can generate induced electric fields in conductive tissues, a principle that has been harnessed in transcranial magnetic stimulation (TMS) for neuromodulation.[28] Rossi et al.[29] have emphasized the diverse applications of TMS in both research and clinical settings, ranging from brain function mapping to the treatment of depression, demonstrating the broad potential of this mechanism.

Light-based interactions, particularly photobiomodulation, represent another important mechanism. Electromagnetic radiation in the visible and near-infrared spectrum can influence cellular function. Hamblin's research has shown that red and near-infrared light can stimulate mitochondrial function and trigger protective cellular mechanisms, illustrating the potential therapeutic applications of specific wavelengths of electromagnetic radiation.[30]

On a more complex level, the radical pair mechanism plays a role in magnetoreception, particularly in avian species.[31] This quantum mechanical effect involves magnetic fields influencing the spin states of radical pairs formed in certain biochemical reactions. Cryptochrome proteins are thought to be the primary magnetoreceptors utilizing this mechanism, providing insight into how organisms can sense and navigate using Earth's magnetic field.[32]

These fundamental mechanisms contribute to various biological processes, from cell signaling to tissue regeneration. Mayrovitz et al. have demonstrated the potential of electromagnetic field therapy in managing various health conditions, including pain relief and tissue regeneration, showcasing the practical applications of these mechanisms in medical treatments.[33]

As our understanding of these fundamental mechanisms continues to deepen, we not only enhance our knowledge of basic biological processes but also pave the way for innovative therapeutic interventions and technological innovations.[34] Future research in this field will need to further elucidate the specific roles of these mechanisms in different biological contexts and explore how they interact to produce complex physiological effects.

Fig. 1 provides a comprehensive visual representation of the bioelectromagnetic signaling process, synthesizing the key concepts discussed in the preceding sections. This diagram elegantly captures the intricate interplay between signal generation, transmission, and reception in biological systems. By illustrating diverse mechanisms such as ion channel activity, mitochondrial processes, and piezoelectric effects in signal generation, the figure underscores the multifaceted nature of bioelectromagnetic field origins. The transmission phase, depicted through electromagnetic field propagation, gap junctions, and photobiomodulation, highlights the various pathways through which these signals traverse biological systems. The reception mechanisms, including voltage-gated ion channels, protein conformational changes, and specialized magnetoreceptive structures, demonstrate the sophisticated ways in which organisms detect and respond to these fields. This figure not only summarizes the fundamental principles of bioelectromagnetic signaling but also serves as a bridge to the subsequent sections on

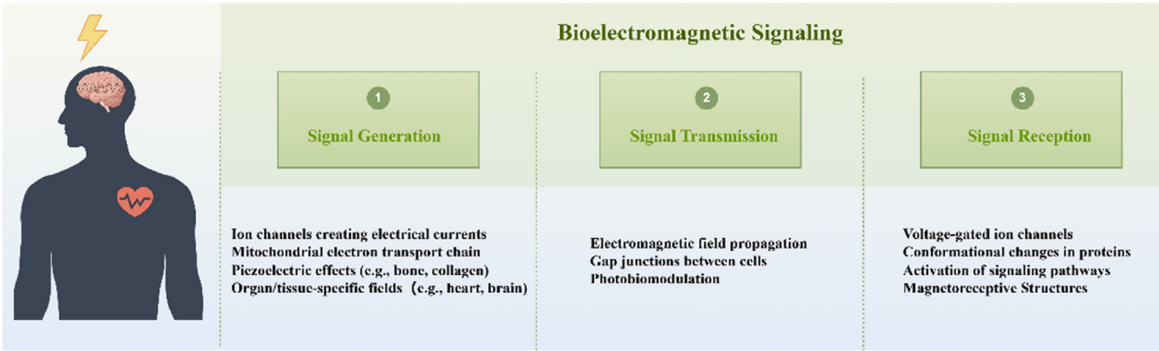

Fig. 1. Mechanisms of bioelectromagnetic signaling generation, transmission, and reception in biological systems.

evidence for bioelectromagnetic communication. It provides a visual framework for understanding the complex and interconnected nature of electromagnetic phenomena in living systems, from the cellular level to organism-wide communication networks.

The diagram succinctly captures the essence of bioelectromagnetic signaling, detailing the generation, transmission, and reception of electromagnetic fields within biological systems. It illustrates the generation of signals through ion channel activity, the mitochondrial electron transport chain, and piezoelectric effects in tissues like bone and collagen. The transmission of these signals is facilitated by electromagnetic field propagation and gap junctions, as well as photobiomodulation. Reception is mediated by voltage-gated ion channels, protein conformational changes, activation of signaling pathways, and magnetoreceptive structures, which are essential for cellular communication and organismal navigation.

4. Evidence for bioelectromagnetic communication

In essence, bioelectromagnetic signals form an intricate and vital communication and regulatory network within and between living systems. Their diverse functions underscore the fundamental importance of electromagnetic phenomena in biology, ranging from rapid information transfer and physiological regulation to spatial patterning, potential energy transfer, and environmental sensing.

4.1. Reception and transduction of bioelectromagnetic signals

The reception and transduction of bioelectromagnetic signals involve a variety of mechanisms, each finely tuned to detect and respond to specific aspects of electromagnetic fields. This swift information transfer enables organisms to respond quickly to internal and external stimuli, enhancing their adaptive capabilities and overall survival.[35]

Voltage-gated ion channelsserve as molecular gatekeepers, changing their conformation in response to voltage fluctuations and allowing precise control of ion flow and signal propagation.[36] This mechanism forms the basis for the detection and transmission of electrical signals at the cellular level.

In the realm of magnetoreception, some organisms have evolved specialized structures containing magnetite crystals.[37] These tiny biological compasses align with external magnetic fields, providing a mechanism for detecting and responding to Earth's magnetic field. This remarkable ability aids in navigation and spatial orientation for diverse species, from bacteria to birds.[38]

Studies have demonstrated that cells can communicate over long distances through the generation and reception of electromagnetic signals.[39] Some theories in the field of bioenergetics propose that electromagnetic fields may also facilitate energy transfer within biological systems, potentially influencing metabolic processes.While this area requires further research, it opens up exciting possibilities for understanding and potentially manipulating biological energy dynamics.[40]

4.2. Electromagnetic signals in intercellular communication

Growing evidence suggests that bioelectromagnetic signaling plays a crucial role in coordinating cellular activities, complementing traditional chemical signaling pathways.[41]

Costantini et al.[42] demonstrated that extremely low-frequency electromagnetic fields modulate proliferation, differentiation, and extracellular matrix deposition in human dental pulp stem cells, indicating potential applications in regenerative medicine. EMFs may influence calcium signaling pathways, alter membrane properties, and even induce conformational changes in proteins, potentially affecting their function or binding properties.[43]

Scholkmann et al.[44] observed a phenomenon of mitotic synchrony in cell cultures, demonstrating that physically separated cell populations can synchronize their division cycles through electromagnetic interactions. This synchronization persists even when chemical communication is blocked, suggesting a direct electromagnetic mechanism.[45] Moreover, gap junctions, which allow for direct electrical coupling between adjacent cells, may play a role in facilitating the propagation of bioelectromagnetic signals across tissues.[46] However, it's important to note the limitations of this study. The experiments were conducted *in vitro*, and the complex *in vivo* environment may influence these electromagnetic interactions. Additionally, alternative explanations, such as undetected chemical signaling or shared environmental factors, cannot be entirely ruled out. Further research, including *in vivo* studies and more rigorous controls, is needed to fully validate these findings and understand their physiological relevance.

Biophoton emission, the ultra-weak light emitted by all living cells, has been proposed as a potential mechanism for intercellular electromagnetic communication.[47,48] These biophotons, typically in the visible and ultraviolet range, may carry information about cellular metabolic states and could influence neighboring cells.[49]

4.3. Electromagnetic communication between organs and between individuals

Electromagnetic communication at the organism level occurs both within individual organisms (inter-organ communication) and between different individuals (inter-individual communication).

Within organisms, electromagnetic signals play a crucial role in coordinating activities between different organs. MCCraty and colleagues demonstrated that the human heart generates a significant electromagnetic field that can be detected several feet away from the body.[50] McCraty et al.[51] proposed that this cardiac electromagnetic field may carry emotional information and influence other organs and physiological processes. Advanced imaging techniques such as magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI) have revealed complex patterns of electromagnetic activity in the human brain associated with various cognitive processes and mental states.[52,53]

Bioelectromagnetic fields exert a profound influence on biological systems at various scales, from neuronal firing patterns to embryonic development. They help maintain homeostasis, coordinate cellular activities, and ensure the proper functioning of organs and organ systems.[41,54] These fields also guide cellular organization and tissue formation during embryogenesis, organogenesis, and wound healing by establishing bioelectric gradients and patterns.[55,56]

Inter-individual electromagnetic communication has been observed in various species. Studies using "separated" biological systems have shown that introducing a stimulus to one sample can elicit a response in another, even in the absence of chemical communication.[57] In the animal kingdom, several examples of inter-individual electromagnetic communication have been documented. Birds, for instance, exhibit magnetoreception, which allows them to perceive and orient themselves using the Earth's magnetic field during long-distance migrations.[58] Honeybees use Earth's electromagnetic fields for navigation and communication within the hive, with disruptions to the local electromagnetic environment impairing their waggle dance communication and foraging efficiency.[59] Certain fish species, such as the electric eel, possess an electric sense that enables them to detect weak electric fields in water, aiding in prey location, predator avoidance, and social communication.[60,61]

Even in the plant world, recent studies have revealed that trees are capable of communicating with one another through the transmission of electrical signals over considerable distances, potentially coordinating responses to environmental stresses.[62,63] These remarkable abilities highlight the sophisticated ways in which living organisms have evolved to utilize electromagnetic phenomena for survival and interaction with their environment.[64]

This comprehensive body of evidence underscores the pervasive and essential nature of bioelectromagnetic communication in living systems, from the cellular level to inter-individual interactions, opening new avenues for research and potential applications in various fields of biology and medicine.

5. Therapeutic applications and technological innovations in bioelectromagnetic signaling

5.1. Technological applications

The expanding knowledge of bioelectromagnetic signaling has led to numerous therapeutic applications and technological innovations with significant implications for human health. Electromagnetic stimulation techniques have emerged as promising approaches for various neurological and musculoskeletal disorders.

Transcranial magnetic stimulation (TMS) has shown promise in treating mental health disorders, particularly depression. Lefaucheur et al. have demonstrated that TMS, a non-invasive method of modulating brain activity through electromagnetic fields, can effectively alleviate symptoms of depression and potentially other neurological conditions. This approach offers a novel, non-pharmacological intervention for patients who may not respond well to traditional treatments.[65] Pulsed electromagnetic field (PEMF) therapy has shown potential in addressing musculoskeletal issues. Markov's work has indicated that PEMF can accelerate bone healing processes and reduce pain associated with various orthopedic conditions.[66] This suggests a broader applicability of electromagnetic therapies beyond neurological disorders, extending into the realm of physical rehabilitation and pain management.

Emerging research suggests potential applications of electromagnetic therapies in regenerative medicine, particularly in guiding stem cell differentiation and tissue repair processes. These findings open up exciting possibilities for enhancing the body's natural healing mechanisms and potentially revolutionizing treatment approaches in fields such as orthopedics and wound care.[11] The rapidly evolving field of bioelectronic medicine represents a promising frontier in bioelectromagnetic research. It aims to develop implantable devices capable of modulating neural activity to treat a range of conditions, from chronic pain to autoimmune diseases.[67,68] These devices could offer more precise, targeted interventions than traditional pharmacological approaches, potentially revolutionizing treatment for previously intractable conditions.[69,70] In oncology, tumor treating fields (TTFields), a technique that uses alternating electric fields to disrupt cancer cell division, has already shown promise in the treatment of glioblastoma and is being investigated for other cancer types.[71]

This innovative approach could potentially offer a more targeted and less toxic alternative to conventional cancer therapies, although further research is needed to fully understand and harness this phenomenon.[72]

5.2. Technological implications and innovations

Advanced understanding of bioelectromagnetic signals is driving the development of highly sensitive biosensors for medical diagnostics and environmental monitoring.[73] Recent innovations have further enhanced our ability to detect and measure bioelectromagnetic signals.[74] The development of optically pumped magnetometers (OPMs) has enabled the creation of wearable magnetoencephalography (MEG) systems, allowing for more naturalistic studies of brain activity.[75] Additionally, advances in nanoscale sensing technologies, such as nitrogen-vacancy (NV) centers in diamond, have pushed the limits of spatial resolution and sensitivity in bioelectromagnetic field detection.[76]

A significant development is the use of ultra-sensitive electric field sensors based on graphene field-effect transistors (GFETs). These sensors have demonstrated the ability to detect extremely weak electric fields generated by individual neurons, opening up new possibilities for studying neural activity at the cellular level.[77] A highly sensitive superconducting quantum interference device (SQUID) magnetometer, capable of detecting ultra-weak magnetic fields generated by cellular processes, has been developed.[78]

In drug delivery, researchers are developing nanoparticles that can be guided by external magnetic fields to deliver drugs precisely to target tissues. This marriage of electromagnetic control and nanoscale engineering promises to enhance the efficacy of treatments while minimizing side effects, potentially transforming drug delivery in the treatment of various diseases.[79] Progress in decoding brain electromagnetic signals is facilitating more sophisticated brain-computer interfaces, holding potential for restoring communication and mobility to individuals with neurological impairments and enhancing human cognitive capabilities.[80] Additionally, the study of natural bioelectromagnetic phenomena is inspiring biomimetic technologies.

From communication technology to energy harvesting, researchers are looking to nature's ingenious use of electromagnetic signals to develop more efficient and sustainable technological solutions. This bioinspired approach could lead to significant advancements in fields such as wireless communication, energy production, and environmental sensing.[81]

Table 1 provides a comprehensive overview of the diverse applications of bioelectromagnetic signaling in medical and technological fields. This table synthesizes the current state of research and practical implementations, showcasing the broad impact of bioelectromagnetic principles across various domains.

6. Future directions in bioelectromagnetic signaling research

The field of bioelectromagnetic signaling stands at the forefront of scientific discovery, offering profound insights into the fundamental nature of life and biological organization. As we continue to unravel the complexities of these silent currents, we find ourselves on the cusp of potential paradigm shifts that could revolutionize our understanding of biology, medicine, and technology.

A critical avenue of research lies in the development of more sensitive tools for detecting and measuring weak bioelectromagnetic fields. These advancements will enable us to probe deeper into the subtle electromagnetic interactions that occur within and between living organisms,

Table 1
Therapeutic applications/innovation of bioelectromagnetic signaling.

Application/Innovation	Description
Transcranial Magnetic Stimulation (TMS)	Used to treat mental health disorders, particularly depression, by modulating brain activity through electromagnetic fields.
Pulsed Electromagnetic Field (PEMF) therapy	Shows potential in addressing musculoskeletal issues, accelerating bone healing processes, and reducing pain associated with orthopedic conditions.
Electromagnetic therapies in regenerative medicine	Guiding stem cell differentiation and tissue repair processes, enhancing the body's natural healing mechanisms.
Implantable Devices	Modulate neural activity for conditions like chronic pain and autoimmune diseases.
Tumor Treating Fields (TTFields)	Using alternating electric fields to disrupt cancer cell division, showing promise in the treatment of glioblastoma.
Biosensors for medical diagnostics	Advanced biosensors for detecting and measuring bioelectromagnetic signals, enhancing medical diagnostics and environmental monitoring.
Optically Pumped Magnetometers (OPMs)	Development of wearable magnetoencephalography (MEG) systems for more naturalistic studies of brain activity.
Nanoscale sensing technologies	Advances in technologies like nitrogen-vacancy (NV) centers in diamond for high-resolution bioelectromagnetic field detection.
Graphene field-effect transistors (GFETs)	Used for detecting extremely weak electric fields generated by individual neurons.
Superconducting Quantum Interference Device (SQUID) magnetometers	For detecting ultra-weak magnetic fields generated by cellular processes.
Magnetic drug delivery	Development of nanoparticles guided by external magnetic fields for precise drug delivery to target tissues.
Brain-computer interfaces	Decoding brain electromagnetic signals to facilitate more sophisticated brain-computer interfaces.
Biomimetic Technologies	Developments in wireless communication, energy production, and environmental sensing.

potentially uncovering hitherto unknown mechanisms of biological communication and regulation. The exploration of quantum effects in bioelectromagnetic phenomena represents an exciting frontier. As our understanding of quantum biology grows, we may discover that quantum processes play a more significant role in life's electromagnetic symphony than previously thought, potentially bridging the gap between the microscopic and macroscopic worlds of biological function.

An equally crucial area of investigation is the intricate interplay between chemical and electromagnetic signaling in biological systems. By elucidating how these two modes of communication interact and complement each other, we can gain a more holistic understanding of biological processes and potentially develop more effective therapeutic interventions. The advancement of therapeutic applications based on bioelectromagnetic principles holds immense potential for improving human health. From refined electromagnetic stimulation techniques to sophisticated bioelectronic devices, these approaches could offer new hope for treating a wide range of conditions, particularly those that have proven resistant to conventional therapies.[82,83] Recent developments in optogenetics and magnetogenetics are opening up new avenues for non-invasive neuromodulation with unprecedented spatial and temporal precision.[84,85] As we harness the power of bioelectromagnetic signaling, it is imperative that we also examine the potential long-term effects of environmental electromagnetic fields on health and ecosystems. This research is crucial not only for safeguarding public health and environmental integrity but also for informing responsible development and application of electromagnetic technologies.

These future research directions are interconnected, each informing and building upon the others. Advances in this field will depend on the combined efforts of biologists, physicists, engineers, and medical professionals, each bringing their unique expertise to bear on complex problems.As the field progresses, it will be important to address the ethical implications of bioelectromagnetic research and applications, particularly in areas such as neuromodulation and bioelectronic implants.

7. Conclusion

This review has explored the fundamental role of bioelectromagnetic signaling in biological systems, from the cellular level to inter-organism communication. We have examined the nature and generation of bioelectromagnetic fields, their reception and transduction mechanisms, and their diverse functions in living organisms. The evidence presented underscores the importance of these "silent currents" in coordinating cellular activities, guiding developmental processes, and facilitating communication within and between organisms.

As we continue to unravel the complexities of bioelectromagnetic signaling, we stand on the brink of potential paradigm shifts in our understanding of life processes. Future research in this field promises to yield not only deeper insights into fundamental biological mechanisms but also innovative solutions to pressing medical and technological challenges. Firstly, in the realm of non-invasive medical treatments, therapies based on bioelectromagnetic principles could revolutionize the management of certain diseases. For instance, precise modulation of electromagnetic fields in specific tissues may lead to novel treatments for neurodegenerative disorders or chronic pain, potentially offering greater efficacy and fewer side effects than traditional pharmacological approaches. Secondly, research into bioelectromagnetic signaling may usher in new paradigms for understanding cellular communication. Deeper insights into how cells communicate 'remotely' via electromagnetic fields could unveil previously unknown physiological regulatory mechanisms, opening new avenues for research into complex diseases such as cancer and autoimmune disorders. Lastly, in diagnostics, more refined techniques for measuring bioelectromagnetic fields may enable earlier detection of diseases, particularly in the nervous and cardiovascular systems.

The study of bioelectromagnetic signaling represents a vibrant intersection of biology, physics, and engineering. As we move forward, interdisciplinary collaboration will be crucial in addressing the complex questions that lie ahead and in realizing the full potential of this fascinating field.

CRediT authorship contribution statement

Haiying Wang: Writing – original draft. **Weijin Zou:** Writing – original draft. **Yi Cao:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

Prof. Yi Cao, on behalf of all authors, hereby declare that we have no financial or personal relationships with other individuals or organizations that could potentially influence or bias the content of this review.

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