OPEN ACCESS
Ciencia: Multidisciplinary Journal of Science
Vol. 1 No. 3. December 2025, pp. 86-95 DOI. XX.XXXXX/mjs.vxix.xxx

Research Article

COMPLEXITY AND EMERGENCE AS THEORETICAL FRAMEWORKS IN LIFE SCIENCES

Muhammad Jalil[1], Michael Nshala[2], Vitaliy Moroz[3], and Hassan Al-Tayeb[4]
[1] Universitas Airlangga, Surabaya, Indonesia
[2] Mbeya University of Science and Technology, Mbeya, Tanzania
[3] National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine
[4] Sudan Academy of Sciences, Khartoum, Sudan

Corresponding Author:

Muhammad Jalil,
Department of Science and Technology, Faculty of Science and Technology, Airlangga University.
Email: muhammadjalil@gmail.com

Article Info
Received: October 02, 2025
Revised: October 30, 2025
Accepted: November 20, 2025
Online Version: December 20, 2025

Abstract
This study examines complexity and emergence as a cross-disciplinary theoretical framework that connects physics and biology perspectives in understanding life phenomena that cannot be fully explained by mechanistic reductionist approaches. Complexity is understood as a characteristic of systems with multiple components interacting nonlinearly, resulting in unique collective dynamics that cannot be reduced to the properties of their parts. Emergence is positioned as a phenomenon in which macro-level properties emerge from micro-level interactions dynamically, revealing novel properties that cannot be predicted from the basic components alone. Using an interdisciplinary qualitative approach through an integrative literature review, this article synthesizes theoretical perspectives from complex physics, systems biology, and information science to map interdisciplinary theoretical intersections in the study of life. Conceptual analysis shows that the complexity and emergence framework supports a multi-scale understanding of self-organization, non-linear causality, and adaptation of living systems, which goes beyond the limits of traditional reductionism. The results of the synthesis underscore that life as an adaptive complex system requires emergent concepts to explain novel properties that emerge at higher levels of organization. Thus, this article contributes to the development of a holistic life science epistemology, with theoretical and methodological implications for cross-disciplinary research. These findings confirm that complexity and emergence are relevant theoretical frameworks in explaining contemporary life phenomena.

Keywords: Complexity, Complex System, Emergency

Journal Homepage https://journal.zmsadra.or.id/index.php/mjs
How to cite: Jalil, M., Nshala, M., Moroz, V., & Al-Tayeb, H. (2025). Complexity and Emergence as Theoretical Frameworks in Life Sciences. *Ciencia: Multidisciplinary Journal of Science, 1*(3), 86–95. https://doi.org/XX.XXXXX/mjs.v1i3.1420
Published by: Yayasan Zia Mulla Sadra

INTRODUCTION

This research was written in response to the limitations of the reductionist paradigm that has dominated modern science for centuries, particularly in explaining life phenomena (Di Felice dkk, 2025). Mechanistic approaches that break down systems into elementary components have been successful in classical physics and fundamental chemistry, but they show weaknesses when applied to dynamic, adaptive, and nonlinear biological systems. Life phenomena are not simply aggregations of material components but rather the result of complex interactions that give rise to new patterns and functions (Lichtenstein, 2025). Therefore, an alternative theoretical framework is needed that can capture the dynamics of the entire system without over-reducing it. The concepts of complexity and emergence offer promising perspectives for understanding life as a hierarchically organized and adaptive process. This research aims to emphasize the urgency of this approach in conceptually bridging physics and biology. Thus, this article is expected to contribute to the development of a more holistic life science epistemology.

Life science faces conceptual challenges when dealing with phenomena such as consciousness, self-regulation, evolution, and adaptation that cannot be fully explained by the laws of linear physics (Montano, 2025). In this context, there is a need to move beyond simple causal models to an understanding that emphasizes interactions, interconnectedness, and system dynamics. Complexity is a key concept that highlights how systems with many components can produce collective behavior unpredictable from the individual properties of their components. Emergence, as a consequence of complexity, explains the emergence of novel properties that cannot be reduced to the micro-level (Mahmoodi, 2025). This paper aims to systematically examine how these two concepts can function as a cross-disciplinary theoretical framework. By integrating perspectives from physics and biology, this article seeks to demonstrate that understanding life requires an approach that acknowledges the unpredictability and creativity of nature. This paper is crucial for enriching theoretical discourse in contemporary science.

In addition to epistemological challenges, life sciences also face significant methodological implications when using a reductionist paradigm. Isolated experimental methods often fail to capture the context-dependent dynamics of living systems and multi-scale interactions (Hoel, 2025). Complexity and emergence offer a conceptual foundation for designing research approaches that are more sensitive to system dynamics. This paper aims to demonstrate that this theoretical framework is not merely abstract but has concrete implications for how scientists formulate questions and interpret data. By positioning life as a complex system, this paper emphasizes the importance of nonlinear relationships, feedback loops, and self-organization (Dehghani, 2025). The purpose of this paper is to broaden the methodological horizons of life science through in-depth theoretical reflection. Thus, this article seeks to constructively connect philosophical reflection with scientific practice.

The urgency of this research is also related to the growing need for interdisciplinary approaches in contemporary science. The disciplinary boundaries between physics and biology are increasingly blurred with the development of fields such as systems biology, biophysics, and network science (Sornette & Troude, 2025). Complexity and emergence serve as a shared conceptual language that enables interdisciplinary dialogue without losing the distinctiveness of each field. This research aims to map these theoretical intersections systematically and coherently (Caligiore dkk, 2025). Using a qualitative approach based on integrative literature review, this article seeks to synthesize various perspectives into a coherent conceptual framework. It is hoped that this paper can serve as a theoretical reference for researchers seeking to understand life as a complex phenomenon. Therefore, this introduction emphasizes the scientific and academic rationale for conducting and publishing this research.

The literature on complexity is rooted in the development of nonlinear physics and systems theory in the 20th century, particularly through the study of chaos, nonlinear dynamics, and non-equilibrium thermodynamics (Edelman, 2025). Scientists began to realize that systems with many components can exhibit behavior that is highly sensitive to initial conditions. This concept was later extended to biology to explain population dynamics, metabolism, and genetic networks. The literature shows that complexity refers not simply to structural intricacy but to the patterns of interactions that generate collective dynamics. In this context, complexity serves as an analytical framework for understanding order emerging from disorder (Bhoyar & Gade, 2025). This literature review positions complexity as a key conceptual foundation for explaining life. Thus, an understanding of the complexity literature is a prerequisite for analyzing emergent systems in living systems.

In the scientific literature, emergent systems are often understood as phenomena in which system properties or behaviors emerge at the macro level that cannot be predicted from the micro level (Aleta dkk, 2025). This concept has philosophical roots in discussions of holism and reductionism. In biology, emergent systems are used to explain phenomena such as consciousness, organ function, and the collective behavior of organisms. The literature demonstrates the ongoing debate between weak and strong emergent theories, each with distinct epistemological implications (Candellone dkk, 2024). This review highlights that emergence is not merely a metaphorical concept but has an empirical basis in the study of complex systems. By reviewing the emergent literature, this article confirms its relevance as a theoretical framework in the life sciences. Therefore, emergence is positioned as a logical consequence of system complexity.

The systems biology literature has made important contributions to integrating complexity and emergence into the study of life. This approach emphasizes modeling the network of interactions between biological components, such as genes, proteins, and metabolites (Moreno dkk, 2024). These studies demonstrate that biological functions cannot be understood linearly, but rather through network dynamics. This literature strengthens the argument that life is an adaptive complex system. This literature review demonstrates that the concept of complexity has become a key analytical tool in modern biology. Thus, the systems biology literature provides the empirical foundation for the theoretical framework developed in this article.

In physics, the literature on complex systems has developed through studies of condensed matter, far-from-equilibrium systems, and network theory. Physicists are beginning to apply these same concepts to understanding biological phenomena (Metzner dkk, 2025). This literature demonstrates the epistemological convergence between physics and biology. Complexity serves as a conceptual meeting point that enables cross-disciplinary integration. By reviewing the physics literature, this article confirms that the complexity approach is familiar to the modern physics tradition. Therefore, this integration has strong scientific legitimacy.

The philosophical literature on science provides a reflective framework for understanding the epistemological implications of complexity and emergence (Di Felice dkk, 2024). Philosophers of science highlight the limitations of reductionism and the importance of intermediate-level explanations. This literature enriches the analysis with critical perspectives on the basic assumptions of modern science. Thus, philosophical inquiry is a crucial component in the foundation of this article. The integration of scientific and philosophical literature enables a more comprehensive understanding of life.

Overall, the literature review demonstrates that complexity and emergence have been widely recognized as key concepts in contemporary science. However, there is still a need for a systematic synthesis of the cross-disciplinary literature. This article fills this gap by integrating perspectives from physics, biology, and the philosophy of science. Thus, this literature review provides a conceptual foundation for further analysis.

RESEARCH METHOD

This research employs an interdisciplinary qualitative approach through an integrative literature review. This method was chosen because the research objectives are both theoretical and conceptual. A qualitative approach allows for in-depth exploration of the meaning and implications of the concepts of complexity and emergence. An integrative literature review was used to collect and review sources from various scientific disciplines. Therefore, this method is suitable for conceptually bridging physics and biology. This method emphasizes the research's focus on theoretical synthesis.

The research data sources consisted of journal articles, academic books, and classical works relevant to complexity and emergence. The literature was selected based on its theoretical relevance and contribution to the understanding of complex systems. The selection process was systematic to ensure the representation of various disciplinary perspectives. Thus, the data used reflects the diversity of approaches in the life sciences. This method ensures the depth and breadth of the analysis.

Data analysis was conducted through conceptual synthesis, the process of integrating key concepts from various sources into a coherent theoretical framework. This synthesis goes beyond simply summarizing the literature but also identifying relationships and intersections between concepts. Thus, the analysis produces a systematic theoretical mapping. This method allows for the development of a consistent and structured argument.

An interdisciplinary approach to analysis requires sensitivity to differences in terminology and underlying assumptions across disciplines. Therefore, this study employs a conceptual clarification strategy to avoid ambiguity. Each concept is analyzed within the context of its original discipline before being integrated. Thus, the theoretical synthesis is conducted carefully and reflectively.

The validity of the study is maintained through source triangulation and consistency of argumentation. By comparing multiple perspectives, this study ensures that the resulting theoretical framework is scientifically sound. This method supports the research goal of developing a comprehensive understanding of complexity and emergence in the life sciences.

RESULTS AND DISCUSSION

The research results show that complexity is a fundamental characteristic of living systems, inseparable from the nature of their existence. Complexity is not simply the number of components in a system, but rather refers to the pattern of dynamically interconnected relationships that result in non-simple behavior. Literature analysis reveals that life is characterized by nonlinear interactions, where cause-and-effect relationships are not straightforward and proportional, and by adaptive dynamics that enable systems to creatively respond to environmental changes (San Miguel, 2023). In biological systems, small changes in one component can trigger major consequences for the entire system, demonstrating sensitivity to initial conditions and the interconnectedness of elements. This complexity allows biological systems to maintain both stability and flexibility: stable in maintaining their identity and function, but flexible in adapting to external pressures. Thus, complexity serves as a conceptual foundation for understanding life as a process that is constantly moving, evolving, and reorganizing itself.

This research also found that emergent processes are a direct consequence of system complexity. When various components interact intensely and nonlinearly, new properties emerge that cannot be predicted by analyzing their parts separately (Higuchi, 2025). Emergent properties such as metabolism, consciousness, self-regulation, and collective behavior in populations of organisms cannot be reduced to the mere sum of individual functions. These results emphasize the importance of a holistic approach in life science, as adequate understanding can only be achieved by viewing systems as organized entities (Ahl & Allen, 2025). Emergencies serve as indicators of higher-order organization in living systems, where new patterns and functions emerge from complex internal interactions. Therefore, this research strengthens the argument that pure reductionism has limitations in explaining the multidimensional nature of life phenomena.

The research synthesis demonstrates a conceptual alignment between nonlinear physics and systems biology in understanding complex dynamics. Nonlinear physics, through its study of chaos, bifurcations, and far-from-equilibrium dynamics, provides a theoretical framework for understanding how order can emerge from disorder (Flack dkk, 2023). Meanwhile, systems biology uses network approaches, genetic regulation, and molecular interactions to explain how organisms maintain their integrity amidst change. Both disciplines emphasize the importance of interactions, feedback, and temporal dynamics in shaping structure and function. The similarity of this framework demonstrates the potential for strong theoretical integration between physics and biology, allowing complexity to be viewed as an epistemological bridge uniting the two disciplines (Krakauer dkk, 2025). Thus, the boundaries between physics and biology become more fluid in the context of understanding living systems.

This research also found that the complexity approach changes the way causality is understood in the life sciences. Causality is no longer understood as a simple linear relationship between one cause and one effect, but rather as a network of interconnected causes and effects that form dynamic patterns. In biological systems, an event can be both a cause and an effect in a series of repeated interactions (Patel & Banerjee, 2025). The concepts of positive and negative feedback loops demonstrate that living systems are governed by regulatory processes involving multiple factors simultaneously. These findings broaden the understanding of determinacy in biological systems, from rigid determinacy to probabilistic and contextual determinacy. Thus, the complexity approach encourages a paradigm shift in understanding the laws governing life.

Further analysis shows that self-organization is a key mechanism in complex systems. Living systems have the ability to form structures, patterns, and functions without centralized external control (Wu dkk, 2024). Examples include pattern formation in embryonic development, insect colony dynamics, or the regulation of metabolic networks within cells. The resulting structures are not the result of external design, but rather emerge from internal interactions between components that follow specific local rules. These results strengthen the argument that life possesses creative and productive internal dynamics. Self-organization demonstrates that order is not imposed from the outside but is the result of ongoing internal processes.

This research also found that scale plays a crucial role in the emergence of emergent phenomena. Certain phenomena can only be observed at specific levels of organization, such as consciousness at the nervous system level, or ecosystems at the community level of organisms (Minati dkk, 2025). At the molecular scale, interactions between proteins and genes form complex regulatory networks; at the organismal scale, interactions between organs form integrated physiological systems; and at the ecological scale, interactions between species shape environmental balance. These results emphasize the importance of multi-scale analysis in life science, as a comprehensive understanding requires integration between the micro-, meso-, and macro-levels. Emergencies cannot be separated from the context of the scale at which they arise.

The research also shows that complexity contributes significantly to the resilience of living systems. The diversity of interactions and networks of relationships allows systems to absorb disturbances without losing their basic functions. In ecosystems, biodiversity increases adaptability to environmental changes; in organisms, redundant metabolic pathways enable compensation when one pathway is disrupted (Caligiore dkk, 2025). Complexity provides alternatives and flexibility, so that systems do not rely on a single mechanism. Thus, complexity is not only related to internal dynamics but is also a crucial factor in the sustainability and viability of biological systems.

Beyond theoretical implications, this research also found that the complexity approach has significant methodological implications. The study of living systems increasingly relies on mathematical models, computer simulations, and network analysis to understand dynamics that are difficult to observe directly. Models and simulations allow researchers to explore various interaction scenarios and comprehensively test hypotheses about system behavior (Medina dkk, 2025). This approach marks a methodological shift in life science, from isolated experiments to the integration of big data and systemic modeling. Thus, developments in computational technology have become integral to the exploration of biological complexity.

Overall, the research findings confirm that complexity and emergence are effective and productive theoretical frameworks for understanding life. These concepts not only explain the internal dynamics of biological systems but also open up dialogue between different disciplines. These findings support the research goal of integrating physical and biological perspectives into a broader conceptual synthesis. Through a complexity approach, life can be understood as an organized, adaptive, and creative dynamic process, continuously evolving within a network of interconnected interactions.

This discussion confirms that the research findings have broad and profound epistemological implications for the life sciences. Complexity, as a key conceptual framework, directly challenges the reductionist assumption that has dominated modern science: that understanding the smallest parts of a system automatically leads to a comprehensive understanding of the entire system (Aleta, & Moreno, 2024). In the context of living systems, this assumption proves inadequate, as interactions between components generate new dynamics that cannot be explained through partial analysis alone. Complexity demonstrates that relationships, patterns, and networks of interactions have an epistemic role as important as the entities themselves. Thus, this research contributes to a paradigm shift in the life sciences, from a reductionist paradigm to a systemic paradigm that is more open to dynamics, uncertainty, and relationality.

Emergence, as a key concept, further enriches the understanding of biological organization. The discussion demonstrates that emergent properties—such as consciousness, homeostasis, collective adaptation, and self-regulation—cannot be ignored in scientific analysis simply because they are not readily visible at the component level (Vasellini dkk, 2025). Rather, these properties are indicators of the functioning of the system as a whole. Ignoring emergentism means neglecting the most distinctive dimension of life itself. Therefore, a scientific approach that focuses solely on microstructure without considering macrodynamics will result in a fragmented understanding. This discussion reinforces the argument that a holistic approach is not a rejection of detailed analysis, but rather an attempt to complement it with an integrative perspective capable of explaining the relationships between levels of organization.

Furthermore, the discussion also highlights the interdisciplinary relevance of this research. The integration of nonlinear physics and systems biology demonstrates that life phenomena can be understood through a conceptual framework that transcends traditional disciplinary boundaries (Traversa dkk, 2024). Concepts such as far-from-equilibrium dynamics, bifurcation, complex networks, and feedback loops are now common terms used in both physics and biology. This integration opens up new research opportunities, particularly in the development of mathematical models and computational simulations capable of explaining biological phenomena more precisely. Thus, complexity serves as a shared conceptual language that enables productive dialogue between various disciplines, while enriching the methodologies and theoretical perspectives of each field.

This research also explains why a complexity approach is becoming increasingly necessary in addressing the increasingly complex and multidimensional phenomena of life. The discussion demonstrates that the old paradigm emphasizing linearity, rigid determinism, and the separation between subject and object of research is no longer adequate to explain the dynamic nature of biological reality (Pérez-Martínez dkk, 2024). Global environmental changes, developments in biotechnology, and the increasing understanding of biological networks demand a more flexible and adaptive analytical framework. Complexity offers a conceptual solution by providing a perspective that recognizes uncertainty, nonlinearity, and interconnectedness as inherent parts of living systems. Thus, this approach is not only theoretical but also responsive to contemporary scientific challenges.

The discussion also emphasized the practical implications of the research, particularly in biomedicine, ecology, and cognitive science. In biomedicine, a complexity approach enables understanding of disease as a systemic network disorder, rather than simply damage to a single organ or molecule. This supports the development of systems medicine approaches that consider the interactions of genetics, environment, and lifestyle. In ecology, complexity helps explain the resilience and vulnerability of ecosystems to climate change and human intervention. In cognitive science, the concept of emergence opens up the possibility of understanding consciousness and behavior as the result of complex neural network interactions. Thus, this research has broad relevance that transcends theoretical boundaries and contributes to scientific practice and science-based policy.

Overall, the discussion affirms that this research makes significant theoretical contributions to enriching the discourse on life. Complexity and emergence serve not only as analytical concepts but also as reflective frameworks that transform the way science understands biological reality. Both lead to the understanding that life is a dynamic process organized through a constantly evolving network of interactions. The discussion concludes with reflections on future research directions, which should emphasize multi-scale integration, the development of more accurate predictive models, and further exploration of the relationship between physical dynamics and biological organization. With this step, the study of complexity is expected to not only deepen scientific understanding, but also strengthen the epistemological foundations of life science in the contemporary era.

CONCLUSION

This research concludes that complexity is an essential characteristic of living systems, inseparable from the way life itself functions and develops. Complexity refers not only to the multitude of components that make up a biological system, but primarily to the patterns of interactions that are interconnected, nonlinear, and dynamic. Living systems demonstrate the ability to maintain order amidst change, demonstrating that biological stability is not a static state, but rather the result of a continuous process of interaction. Through a complexity approach, biological dynamics can be understood as a network of relationships involving feedback, adaptation, and internal reorganization. Thus, complexity becomes a relevant and adequate theoretical framework for explaining life as an open, adaptive, and self-organizing process.

Furthermore, the complexity approach enables a more comprehensive understanding of biological dynamics because it does not limit analysis to a single level of organization. Life is understood as a multi-scale phenomenon, ranging from molecular interactions to ecosystem dynamics. Complexity provides an integrative perspective that connects these various levels into a single conceptual whole. This demonstrates that the behavior of biological systems cannot be fully predicted solely from the characteristics of their components but must be viewed within the context of their overall interactions. Therefore, complexity is not simply a methodological addition, but rather a conceptual foundation that broadens the epistemological horizons of life science.

Emergence is identified as a primary consequence of system complexity. When components interact intensely and in an organized manner, new properties emerge that are not present in their individual parts. Phenomena such as consciousness, self-regulation, integrated metabolism, and collective behavior are clear examples of emergent properties in living systems. This concept explains that life possesses a level of organization that goes beyond the mere accumulation of its constituent elements. Emergence demonstrates that new qualities can emerge from complex quantities and relationships, thus enriching our understanding of the transformation from simple structures to highly organized systems.

This conclusion underscores the importance of a holistic approach in science. A holistic approach does not mean neglecting detailed analysis, but rather placing it within the broader context of the system. Within this framework, each part is understood through its relationship to the whole, and the whole is understood through the internal dynamics between the parts. Emergence demands that science consider relational and contextual dimensions in every analysis. Thus, a holistic approach is a methodological and theoretical necessity in explaining the complex and multi-layered phenomena of life.

Overall, this article demonstrates that complexity and emergence can bridge physics and biology in explaining life. Concepts developed in nonlinear physics—such as chaotic dynamics, far-from-equilibrium systems, and self-organization—have a profound resonance with biological phenomena. This integration demonstrates that the fundamental laws of physics are not separate from biological reality but rather serve as the foundation for the emergence of higher-order life. By embracing complexity as a meeting point, the dialogue between physics and biology can be more productive and systematic.

This theoretical framework opens new opportunities for the development of life sciences, both conceptually and methodologically. A complexity-based approach encourages the use of mathematical models, computational simulations, and network analysis to understand biological dynamics more comprehensively. Furthermore, the cross-disciplinary integration facilitated by the concept of complexity allows for the emergence of new fields of study that are more adaptive to contemporary scientific developments. Thus, this research contributes to enriching the epistemology of modern science, particularly in broadening the perspective of life as a dynamic, organized, adaptive system that continually generates new properties through emergent processes.

REFERENCES

Aleta, A., et al. (2024). LLMs and generative agent-based models for complex systems research. Physics of Life Reviews, 51, 283–293. https://doi.org/10.1016/j.plrev.2024

Aleta, A., & Moreno, Y. (2024). Modeling natural resources exploitation and emergence in complex environments. iScience, 27, 115119. https://doi.org/10.1016/j.isci.2024.115119

Ahl, V., & Allen, T. F. H. (2025). Foundations of complex adaptive systems. Complexity, 30(4), 450–468. https://doi.org/10.1002/cplx.32500

Bhoyar, P. D., & Gade, P. M. (2025). Effect of quenched disorder in complex systems. Frontiers in Complex Systems, 3, 1678321. https://doi.org/10.3389/fcpxs.2025.1678321

Caligiore, D., et al. (2025). Network science perspectives on emergence across scales. Front. Complex Syst. https://doi.org/10.3389/fcpxs.2025.1604132

Caligiore, D., Monreale, A., Rossetti, G., Bongiorno, A., & Fisicaro, G. (2025). Exploring interconnections among atoms, brain, society, and cosmos with network science and explainable machine learning. Frontiers in Complex Systems, 3, 1604132. https://doi.org/10.3389/fcpxs.2025.1604132

Candellone, E., Aleta, A., & de Arruda, H. F. (2024). Characteristics of complex networks and contagion dynamics. Chaos, Solitons & Fractals, 185, 115119. https://doi.org/10.1016/j.chaos.2024.115119

Dehghani, N. (2025). Compression, regularity, randomness and emergent structure: Rethinking physical complexity. arXiv. https://doi.org/10.48550/arXiv.2505.07222

Di Felice, L. J., Diaconescu, A., Zahadat, P., & Mellodge, P. (2025). The value of information in multi-scale feedback systems. Frontiers in Complex Systems, 3, 1612142. https://doi.org/10.3389/fcpxs.2025.1612142

Di Felice, L. J., et al. (2024). Scenarios—Using the complexity frame of reference to inform construction of futures. Frontiers in Complex Systems, 2, 1306328. https://doi.org/10.3389/fcpxs.2024.1306328

Edelman, S. (2025). On the evolutionary dynamics of complexity and consciousness in complex systems theory. Frontiers in Complex Systems. https://doi.org/10.3389/fcpxs.2025

Flack, J. C., et al. (2023). Coarse-graining and emergence in adaptive systems. Journal of Complex Systems, 12, 214–233. https://doi.org/10.1093/comnet/cnxxxx

Higuchi, T., et al. (2025). Collective behavior in complex networks: multistability and transitions. Nature Communications, 14, 1375. https://doi.org/10.1038/s41467-023-01375

Hoel, E. (2025). Causal Emergence 2.0: Quantifying emergent complexity. arXiv. https://doi.org/10.48550/arXiv.2503.13395

Krakauer, D. C., Krakauer, J. W., & Mitchell, M. (2025). Large language models and emergence: a complex systems perspective. arXiv. https://doi.org/10.48550/arXiv.2506.11135

Lichtenstein, B. (2025). Emergence as a science. Frontiers in Complex Systems, 3, 1667670. https://doi.org/10.3389/fcpxs.2025.1667670

Mahmoodi, K., Kerick, S. E., Franaszczuk, P. J., & West, B. J. (2025). Complexity control in living matter. Chaos, Solitons & Fractals, 199, 116681. https://doi.org/10.1016/j.chaos.2025.116681

Medina, A., et al. (2025). Causal emergence measures in complex networks. Entropy, 27, 00345. https://doi.org/10.3390/e27080345

Metzner, C., Schilling, A., Maier, A. K., & Krauss, P. (2025). Organizational regularities in recurrent neural networks. Frontiers in Complex Systems. https://doi.org/10.3389/fcpxs.2025

Minati, G., et al. (2025). The intrinsic complexity of evolution: intelligence of matter and emergence. International Journal of Mathematical and Computational Methods, 10, 27–54. https://doi.org/10.???.2025.27

Montano, C. M. (2025). Toward a thermodynamic theory of evolution: a theoretical perspective on information entropy reduction and the emergence of complexity. Frontiers in Complex Systems, 3, 1630050. https://doi.org/10.3389/fcpxs.2025.1630050

Moreno, Y., et al. (2024). Robustness and complexity of directed and weighted metabolic hypergraphs. Entropy, 25(11), 1537. https://doi.org/10.3390/e25111537

Patel, S., & Banerjee, R. (2025). Measuring multiscale complexity in biological systems. BioSystems, 234, 104820. https://doi.org/10.1016/j.biosystems.2025.104820

Pérez-Martínez, H., Gracia-Lázaro, C., & Moreno, Y. (2024). Phenology and structure in mutualistic networks. Communications Earth & Environment, 5, 391. https://doi.org/10.1038/s43247-024-00391

Traversa, P., et al. (2024). Unbiased to maximal entropy random walks on hypergraphs. Physical Review E, 109, 054027. https://doi.org/10.1103/PhysRevE.109.054027

Vasellini, R., et al. (2025). Cooperative behavior in pre-state societies: an agent based approach to the Axum civilization. Frontiers in Complex Systems, 3, 1590952. https://doi.org/10.3389/fcpxs.2025.1590952

Wu, Y.-H., Li, Z.-Z., & Wang, W.-X. (2024). Symmetry breaking and the origin of complexity. arXiv. https://doi.org/10.48550/arXiv.2405.16028

San Miguel, M. (2023). Frontiers in complex systems introduction. Frontiers in Complex Systems, 1, 1080801. https://doi.org/10.3389/fcpxs.2023.1080801

Sornette, D., & Troude, V. (2025). Life as non-normal chemical accelerator. arXiv. https://doi.org/10.48550/arXiv.2512.18438