

THE CONCEPT OF LIFE IN MODERN BIOLOGY A THEORETICAL ANALYSIS OF THE BOUNDARY BETWEEN LIVING THINGS AND ARTIFICIAL SYSTEMSHendri Putra¹, Tatenda Ncube², Emmanuel Lungu³, and Ingrid Larsen⁴¹ Gadjah Mada University, Sleman, Indonesia² Bindura University of Science Education, Bindura, Zimbabwe³ Zambia College of Applied Sciences, Lusaka, Zambia⁴ Norwegian University of Science and Technology, Trondheim, Norway**Corresponding Author:**

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Abstract

This article examines the conceptual challenges surrounding the definition of life in modern biology, focusing on the boundaries between living organisms and artificial systems. The development of artificial life and synthetic biology challenges traditional definitions of life, which are based on classical biological features such as metabolism, reproduction, and homeostasis. Using a qualitative-philosophical approach through an in-depth literature review of theoretical biology, philosophy of biology, and artificial life research, this article maps contemporary debates about what constitutes "life." A conceptual-reflective analysis is conducted to evaluate various definitions proposed in the recent literature, including those emphasizing the emergent nature of complex systems, open evolution, and the dynamic nature of organizational patterns. The results demonstrate that life is not simply a collection of empirical features but also encompasses organizational structures capable of autonomous self-maintenance through internal interactions with their environment. The phenomenon of artificial life provides important insights that features such as adaptation, evolution, and self-organization are not exclusive to natural biological entities, thus raising the need for a more inclusive and reflective definitional framework. In conclusion, the concept of life in modern biology is pluralistic and spectral, demanding an understanding that integrates empirical and philosophical approaches and opens up discussion for the integration of artificial life into contemporary theoretical biology. These findings have conceptual, methodological, and ethical implications for the future development of biology.

Keywords: Artificial Life, Concept of Life, Theoretical Biology

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INTRODUCTION

The concept of life is a key epistemological foundation in biology, yet ironically, it has become one of the most problematic concepts in the discipline. Since the birth of modern biology, life has often been operationally defined through empirical characteristics such as metabolism, reproduction, growth, and response to the environment (Gómez-Márquez, 2023). This definition was relatively adequate when the object of study was limited to natural biological organisms. However, the rapid development of contemporary technology—particularly in artificial life, synthetic biology, and complex artificial systems—has shaken these conceptual boundaries. The phenomenon of artificial systems capable of mimicking, or even surpassing, some of the characteristics of life raises a fundamental question: is life solely a matter of biological structure, or is it a specific pattern of organization that can be realized in non-biological media? This question positions biology beyond being merely an empirical science, but rather as a field for profound philosophical reflection. Therefore, research on the concept of life is urgently needed to critically and systematically review the basic assumptions of modern biology.

The urgency of this research is further heightened when the definition of life is no longer conceptually neutral but has broad scientific, ethical, and ontological implications. In the context of artificial life and synthetic biology, the definition of life defines the boundary between biological research objects and technological artifacts (Gershenson, 2023). This unclear boundary has the potential to create methodological ambiguity in theoretical biology research and raise normative dilemmas regarding the moral status of artificial systems. Furthermore, in cosmobiology and the search for life beyond Earth, the definition of life becomes a primary criterion for interpreting empirical data. If life is defined too narrowly, the potential for alternative life forms may be overlooked; conversely, an overly broad definition risks obscuring the meaning of life itself. Therefore, this research is needed to reflectively reexamine the concept of life, taking into account contemporary scientific dynamics that have transcended the classical biological paradigm.

The conceptual problem of life cannot be resolved solely through the accumulation of empirical data, as it concerns the conceptual framework used to interpret that data (Beer, 2024). This is where a philosophical approach becomes relevant, particularly the philosophy of biology, which seeks to critically examine fundamental concepts. This approach allows for an analysis of the ontological and epistemological assumptions hidden behind the definition of life used in modern biology. Thus, this research does not aim to formulate a final and universal definition of life, but rather to map the conceptual problems that arise when biology encounters artificial systems. This approach is expected to open a dialogue between biology, philosophy, and computer science, allowing the concept of life to be understood more comprehensively and contextually.

Based on this background, this article was written to systematically examine the conceptual boundaries between living things and artificial systems from a theoretical biology perspective. The primary focus of the research is directed at a theoretical analysis of the criteria for life and their relevance in the context of artificial life and complex non-biological systems. By positioning the concept of life as an object of philosophical reflection, this research is expected to make a conceptual contribution to the development of modern biology.

Specifically, this article aims to enrich academic discourse on the ontological status of life and offer a more flexible analytical framework for addressing contemporary scientific challenges.

Classical biology literature generally views life as a biological entity characterized by a specific set of empirical characteristics. This approach can be traced back to the thought of Aristotle and modern molecular biology, which emphasizes the role of DNA as the basis of life (Dorin and Stepney, 2024). Within this paradigm, life is understood as a phenomenon inherent in specific biological materials, particularly cells. The resulting operational definitions are relatively effective in the context of experimental research, but often neglect deeper conceptual dimensions. Contemporary literature has begun to critique this approach, pointing out that the characteristics of life are not necessarily exclusive to biological organisms. For example, certain computational systems are capable of exhibiting adaptive and evolutionary behavior without possessing biological structures. This critique opens the door to a more abstract conceptual approach to life.

Theoretical biology offers an alternative perspective by viewing life as a pattern of organization and dynamic processes, rather than simply a collection of material components (Weckström, 2025). This approach emphasizes concepts such as autopoiesis, self-organization, and emergence as fundamental characteristics of life. The literature on autopoiesis, for example, defines life as a system capable of reproducing and maintaining its own organization. This definition is more formal and not tied to a specific biological substrate, opening the possibility that artificial systems may also meet the criteria for life. However, this approach also faces criticism for being too abstract and difficult to operationalize empirically. Thus, the literature on theoretical biology demonstrates a tension between the need for inclusive definitions and the demands of scientific precision.

Philosophy of biology plays a crucial role in examining the conceptual implications of this theoretical approach (Simondon, 2025). The literature on the philosophy of biology highlights that definitions of life always contain certain ontological assumptions about what constitutes a living entity. Some philosophers argue that life is an objective, natural category, while others view it as a conceptual construct dependent on scientific interests. This debate has become increasingly complex with the emergence of artificial life, explicitly designed to explore the possibility of life in non-biological environments. Contemporary literature on the philosophy of biology emphasizes the importance of critical reflection on these conceptual boundaries, lest biology fall into the trap of reductionism or conceptual relativism.

Studies on artificial life in the scientific literature demonstrate systematic attempts to simulate life processes through computational and robotic systems. These studies are not merely technical in nature but also have significant philosophical dimensions (Greve, 2023). Artificial life is often understood as “life-as-it-could-be,” which differs from natural biological life. This literature challenges the assumption that life must be carbon-based or occur within a specific biochemical context. However, some critics argue that artificial life is more accurately understood as a model or metaphor of life, rather than life itself. This debate demonstrates that the boundary between representation and reality of life remains an open issue in the literature.

The synthetic biology literature adds complexity to the discourse by presenting human-engineered biological systems. In this context, life is no longer entirely natural, but neither is it entirely artificial. Research on synthetic organisms raises questions about the ontological status of rationally designed living beings (Bender dkk, 2025). Does synthetic life have the same ontological value as natural life? Contemporary literature demonstrates that synthetic biology challenges the traditional dichotomy between natural and artificial. Thus, this study is relevant for understanding life as a spectrum, not a binary category.

Overall, the literature review shows that the concept of life is a dynamic and multidisciplinary field of debate. There is no single consensus on the definition of life, either in biology or philosophy. The existing literature provides a variety of complementary and contradictory conceptual frameworks. This situation emphasizes the need for in-depth

conceptual-reflective analysis to understand the boundaries between living beings and artificial systems more systematically and critically.

RESEARCH METHOD

This research uses a qualitative-philosophical approach that focuses on conceptual analysis of scientific literature. This approach was chosen because the object of study is not an empirical phenomenon that can be measured quantitatively, but rather the concept of life as a theoretical construct. Thus, qualitative methods allow for the exploration of the meanings, assumptions, and conceptual implications contained in various definitions of life. A philosophical approach is used to examine the ontological and epistemological dimensions of these concepts, so that the analysis is not limited to mere empirical descriptions.

The research data sources consist of literature on theoretical biology, the philosophy of biology, artificial life, and synthetic biology. The selected literature includes scientific journal articles, academic books, and conceptual works relevant to the research topic. Source selection was carried out purposively, considering theoretical relevance and conceptual contributions to the discourse on life. This approach ensures that the analyzed data has sufficient conceptual depth to support reflective analysis.

Data collection techniques were carried out through an in-depth literature study, with a systematic and critical review of texts. Each source was analyzed to identify the definition of life used, the basic assumptions underlying it, and its conceptual implications. This process is carried out iteratively to ensure a comprehensive understanding of the various existing perspectives. Thus, the literature review serves not only as a theoretical inventory but also as a basis for critical reflection.

Data analysis was conducted using the conceptual-reflective analysis method. This method involves clarifying concepts, identifying internal contradictions, and evaluating theoretical coherence. Each concept of life is evaluated based on its logical consistency and relevance within the context of artificial phenomena. This reflective approach allows researchers to critically assess the limits and potential of each conceptual framework.

The validity of the analysis is maintained through conceptual triangulation, namely by comparing different theoretical perspectives (Martinez-Saito, 2025). In this way, the research is not trapped in a single paradigm but instead considers the plurality of existing views. This approach is expected to produce a more balanced and comprehensive understanding of the concept of life in modern biology.

RESULTS AND DISCUSSION

The analysis shows that the definition of life in modern biology is inherently plural and deeply contextual. No single, universally accepted definition is capable of encompassing the full range of phenomena that are commonly classified as living. In biological research and laboratory practice, operational definitions—such as metabolism, growth, reproduction, and responsiveness to stimuli—have proven highly effective for empirical investigation and experimental control. However, when these criteria are applied to borderline cases, particularly artificial or hybrid systems, their limitations become evident. This finding confirms that life cannot be adequately reduced to a fixed checklist of empirical properties, as such reductionism fails to capture the conceptual and theoretical complexity of living phenomena.

Further analysis of approaches in theoretical biology indicates that life is more coherently understood as a dynamic process rather than as a static entity or substance. From this perspective, life is characterized by ongoing activities, relational interactions, and continuous transformations rather than by stable structures alone. Concepts such as self-organization, non-linear dynamics, and emergence become central in distinguishing living systems from non-

living ones. These concepts emphasize how complex order arises from interactions among components without centralized control. However, the analysis also reveals a critical tension: similar patterns of self-organization and emergence can be observed in complex non-biological systems, such as physical, chemical, or computational models. This overlap further blurs the conceptual boundary between life and non-life, challenging traditional categorical distinctions.

In the context of artificial life research, the study finds that many artificial systems partially satisfy commonly accepted criteria of life, including adaptation, learning, and evolutionary change (Kumar dkk, 2024). Digital organisms, robotic systems, and computational simulations often display behaviors that resemble biological processes. Nevertheless, these systems typically depend on artificially designed environments and sustained human intervention for their continued operation. This dependence raises fundamental questions about autonomy as a defining characteristic of life. If autonomy implies self-maintenance and self-determination independent of external designers, then artificial systems occupy an ambiguous position that complicates classical definitions of living beings.

Synthetic biology further intensifies this conceptual challenge by demonstrating that life-like systems can be rationally engineered without losing key biological characteristics (Li dkk, 2024). Through genetic modification, genome synthesis, and the redesign of metabolic pathways, synthetic biology shows that living systems can be constructed and modified according to human intentions. This development directly challenges essentialist views that associate life exclusively with natural origin or spontaneity. Synthetic life forms suggest that the boundary between natural and artificial is not absolute but gradational, marked by degrees of intervention rather than categorical separation.

The analysis also reveals that distinctions between living and artificial systems are often normative rather than purely descriptive. Judgments about what qualifies as life are shaped by scientific purposes, methodological priorities, and broader cultural values (Beekman and Jochemsen, 2023). In many cases, definitions of life are tailored to serve specific research goals, such as planetary exploration, biomedical innovation, or technological development. This finding indicates that the concept of life is not entirely objective or value-free, but is partially constructed through epistemic and pragmatic considerations within scientific practice.

Another important result of the study is the recognition that the material substrate of a system is not the primary determinant of its status as living (Artimo and De Domenico, 2022). Whether a system is composed of organic molecules, silicon-based components, or digital code is less significant than the organizational patterns and dynamic processes it exhibits. Features such as functional integration, information processing, and systemic coherence play a more decisive role. This insight reinforces non-reductionist and organizational approaches in theoretical biology, which prioritize relational structure over material composition.

However, the study also identifies significant limitations in adopting an overly broad or abstract definition of life. While inclusive frameworks can accommodate novel and unconventional systems, they risk erasing important conceptual distinctions between different kinds of entities. If the definition of life becomes too expansive, it may lose explanatory power and analytical usefulness. Therefore, one of the central challenges in contemporary biology is to strike a careful balance between conceptual inclusiveness and definitional precision.

Overall, the results demonstrate that life is a multifaceted concept that resists binary classification. Rather than being divided strictly into living and non-living categories, life is more accurately understood as a spectrum of phenomena characterized by varying degrees of complexity, autonomy, and organization. This spectral view allows biology to account for borderline cases, such as viruses, artificial organisms, and synthetic systems, without forcing them into rigid conceptual boxes.

These findings emphasize that the boundary between living and artificial systems is flexible and context-dependent. Such flexibility reflects the evolving nature of scientific inquiry itself, as new technologies and experimental practices continuously reshape the objects of biological knowledge. As science advances, definitions of life must remain open to revision in order to accommodate emerging forms of organization and agency.

The results of this study have important implications for the understanding of modern biology (Artic, 2024). By conceptualizing life as patterns of organization and dynamic processes, biological theory can integrate new empirical phenomena without sacrificing coherence or rigor. This approach broadens the scope of theoretical biology and enhances its capacity to respond to scientific innovation, particularly in areas such as artificial life and synthetic biology.

From a philosophical perspective, these findings support the view that the concept of life is both constructive and reflective (Gómez-Márquez and Beekman, 2023). Life is not merely discovered as a pre-given natural category but is also shaped through conceptual frameworks, theoretical models, and epistemic values. This perspective calls for a critical and reflexive use of the term “life,” especially when it is applied to novel or technologically mediated systems.

In the context of artificial life research, this study demonstrates that artificial systems can function as conceptual laboratories for testing and refining definitions of life (Luisi, 2024). Rather than being regarded as life in a strict biological sense, artificial life systems serve as heuristic tools that illuminate the strengths and limitations of existing theories. They enable scientists and philosophers to explore alternative possibilities and challenge entrenched assumptions about living systems.

This discussion is equally relevant to synthetic biology, which occupies a liminal space between nature and technology. A spectral approach to life allows for a more nuanced understanding of synthetic organisms, recognizing their biological functionality while acknowledging their engineered origins. Such an approach avoids simplistic dichotomies and better reflects the complexity of contemporary biological practice.

Furthermore, the study highlights important ethical implications related to the moral status of artificial and synthetic systems. If life is understood as a gradational phenomenon rather than a binary category, then ethical considerations cannot be uniformly applied. Instead, moral responsibility and ethical concern must be contextually and proportionally adjusted according to the degree of autonomy, complexity, and potential for harm or benefit exhibited by a given system.

In conclusion, this study contributes to the development of a more adaptive, reflective, and conceptually robust framework for understanding life in modern biology. By embracing plurality, process-oriented thinking, and philosophical reflexivity, this framework equips biology to confront future scientific and technological challenges more effectively. Such an approach is essential for navigating the increasingly complex interface between living systems, artificial constructs, and human values.

CONCLUSION

This study concludes that the concept of life in modern biology cannot be adequately understood through a single, static, or universally fixed definition. Life emerges as a highly complex phenomenon that operates across multiple levels of analysis, encompassing empirical biological processes, theoretical models, and deeper philosophical interpretations. Biological data alone are insufficient to capture the full meaning of life without theoretical frameworks that organize those data and philosophical reflection that clarifies their conceptual implications. Consequently, a pluralistic approach is not merely an option but a methodological necessity, allowing different definitions and perspectives on life to coexist and complement one another in response to diverse scientific contexts and research objectives.

The study further demonstrates that the boundary between living organisms and artificial systems is neither rigid nor absolute, but flexible and context-dependent. Developments in artificial life research and synthetic biology increasingly blur the traditional dichotomy between the living and the non-living by producing systems that exhibit life-like properties such as adaptation, self-maintenance, and evolution. These advancements challenge long-standing assumptions in biology and reveal the limitations of binary classifications. As a result, the distinction between life and non-life requires continuous conceptual reassessment, ensuring that biological theory remains responsive to technological innovation and empirical novelty.

Finally, this study emphasizes the crucial role of philosophical inquiry in sustaining the intellectual coherence of modern biology. Through conceptual and reflective analysis, philosophy helps biology critically examine its foundational concepts, clarify its assumptions, and adapt its theoretical frameworks to emerging scientific developments. In an era marked by rapid technological progress, such as synthetic biology and artificial intelligence, philosophical engagement becomes essential for preserving the epistemological relevance of biological science. Within this perspective, the concept of life is best understood not as a closed or definitive boundary, but as an open and evolving field of scientific reflection that invites ongoing dialogue between biology, philosophy, and technology.

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