

Innovative Approaches In Nonlinear Pedagogy For Biomathematics Education

Subhash Alha^{1*}, Sangeeta Choudhary², Lata Chanchlani³, Pratibha Manohar⁴, Amit G. Gawde⁵, Prof. Nand Kishor⁶, Eliza B. Ayo⁷

^{1*}Assistant Professor, Maulana Azad National Urdu University, Gachibowli, Hyderabad -500032, Telangana, India Email ID: subhashalha@manuu.edu.in Orcid id: 0000-0002-1686-0174

²Associate Professor, Swami Keshvanand Institute of Technology, Management and Gramothan, Jaipur, Rajasthan, India Email ID: sangeeta11rc@gmail.com Orcid id: 0000-0001-9583-5972

³Assistant Professor, University of Rajasthan, Jaipur, Rajasthan, India Email ID: chanchlani281106@gmail.com Orcid id: 0000-0002-4361-1122

⁴Assistant Professor, SKN College of Agriculture, SKN Agriculture University, Jobner, Jaipur, Rajasthan, India. Email ID: prati_manohar@yahoo.co.in Orcid id: 0000-0001-6565-330X

⁵Head, Mathematics, Patkar-Varde College, Goregaon West, Mumbai University: Mumbai University E-mail id: amitggawde28@gmail.com

⁶Professor, Department of Teacher Education, School of Education, Email ID: nandkishor@cuh.ac.in, Orchid ID 0000-0003-4223-0253

⁷ Head, Computer Education Department, Centro Escolar University, Orcid: 0000-0001-7800-5707
ebayo@ceu.edu.ph

ABSTRACT

This research proposes a nonlinear curriculum framework for biomathematics instruction in which learners engage with feedback-controlled biological systems such as population dynamics, epidemiology, and systems biology. Traditional linear approaches to mathematics education emphasize fixed sequences, standardized procedures, and predictable outcomes, which are insufficient for addressing the recursive, adaptive, and multi-scale reasoning required to understand complex biological processes. In contrast, biomathematical learning is inherently iterative, involving cycles of model construction, interpretation, validation, and revision. Such processes demand pedagogical structures that reflect the nonlinear and dynamic nature of biological systems. Grounded in complexity theory, constructivist learning principles, and systems thinking, this study adopts a conceptual-analytical approach to examine nonlinear learning in biomathematics. Learning is conceptualized as an emergent process shaped by feedback loops, contextual interactions, and evolving cognitive structures rather than as a linear progression from instruction to assessment. The proposed framework identifies four interconnected components of nonlinear learning environments: dynamic learner systems, recursive reflection, interconnected knowledge networks, and adaptive understanding. These components interact through continuous, non-sequential learning cycles that closely resemble authentic biological modeling practices. A schematic model illustrates how learners engage in recursive interactions while working with biological systems characterized by feedback, nonlinearity, and emergence. The framework offers practical guidance for curriculum design, teaching, and assessment in biomathematics and quantitative biology programs, contributing to educational innovation and supporting future empirical research in quantitative life sciences education.

KEYWORDS Biomathematics education, Nonlinear pedagogy, Mathematical modeling in biology, Complexity-based learning, Quantitative biology education.

1. Introduction

Linear paradigms, step-by-step sequence of curriculum, instruction based on fixed algorithms, and assessment that rewards single-path solution have long been the influence of mathematics education. This traditional, linear framing usually assumes that mathematical cognition is hierarchical and predictable. However, as modern theorists are making an increasing case, real mathematical thought is much more dynamic, recursive

and non-sequential (Xenofontos & Appelbaum, 2025). There is often a kind of exploratory reasoning, setbacks, feedback loops and conceptual restructuring that learners often use to arrive at insight, all of which are poorly served by traditional linear pedagogy.

Such linearity has been particularly revealed as a limitation in the way mathematical knowledge is presented and evaluated, both at the primary and advanced level. These restrictions do not only indicate a rigidity in instruction, but also a conceptual misconception of the process of knowledge development and change. According to Xenofontos and Appelbaum (2025), linear designs in math can serve to uphold control, standardization, and predictability and hide all the variability and creativity that mathematical thinking entails. These linearities are not only distorting the cognitive development but also limiting the innovation in the pedagogy.

The other option is to accept nonlinearity as not something chaotic, but as a better representation of human learning. This change can be attributed to the constructivist theory of education, which suggests that students are active in building knowledge and not passive recipients of knowledge. Kritt and Budwig (2022) highlight that when analyzing the contemporary constructivist thinking, it is essential to go beyond the obsolete simplifications and to revisit the radical essence of constructivism, involving the appreciation of complexity, uncertainty, and agency of learners. In a similar vein, the emergent constructivism proposed by Allen and Bickhard (2022) redefines learning as the process that cannot be reduced to the interaction of isolated inputs and outputs, but rather the outcome of self-organizing and recursive interactions between the learner and the environment.

This re-theory will be in sync with the findings of complexity theory, which has become increasingly popular in the field of education in the last ten years. Instead of perceiving the classroom as a closed linear system with inputs and measurable outputs, complexity theory sees it as a dynamic system of interactions that is characterized by feedback, adaptation, and emergence. The application of the Cynefin framework provided by Gunawardena et al. (2024), is a very interesting example because the educational processes are simple, chaotic, and educators need to differentiate between complicated and complex in the process of teaching and learning.

These views became more urgent in case of disruptions in the world such as the COVID-19 pandemic. Fellus et al. (2025), ponder the ways the crisis has revealed the frailty of the linear assumptions in mathematics education, particularly when routines were shaken and educators were compelled to create learning environments capable of changing with uncertainty and change. They claim that constructs that are complex like interdependence, emergence and co-adaptation provided a superior perspective in how meaningful learning continued in an unpredictable environment.

Similarly, the teacher education is also starting to accept complexity as it redefines the instructional practice Sato et al. (2025), also studied the way that preservice teachers, after being introduced to the complexity theory, started to think of teaching not as a set of preset strategies but as a relational, situated practice that is responsive to the unpredictable needs of students and environments. This dynamism and feedback orientation as opposed to standardization can be seen as a wider change in the thought processes of education.

According to Jacobson et al. (2019), education itself as a complex adaptive system needs to be systematically redefined and that learning should be viewed as a distributed, nonlinear phenomenon with interconnected agents, local rules, and emergent patterns. These systems are complements to the philosophical critique of linear educational models by Morrison (2019) who says they are based on old positivist paradigms that undermine ambiguity, dialogue, and contingency. Rather, Morrison suggests an

alternative vision of education as a non-pipeline but as a multidimensional ecology of knowledge, relationships and change.

Based on these changing theoretical perspectives in education, this paper suggests mathematics education needs to be re-conceived using a nonlinear pedagogical approach. Recursively, contextually, and dynamically such a model would be a more appropriate way of describing how learners approach mathematics. It would also help teachers to create instructional plans that are responsive and not prescriptive and create environments, where complexity is not a problem to be downsized but an asset to be leveraged.

This study aims to develop a theory of nonlinear education which effectively captures the emergent and feedback-driven nature of the mathematical learning process and to explore how complexity-based pedagogical theories can transform the nature of mathematics instruction, curriculum, and teacher cognition.

2. Conceptual Foundations and Thematic Framework for Nonlinear Pedagogy

2.1 Conceptual-Analytical Orientation

This research is based on a conceptual-analytical orientation, which is meant to formulate a theoretical perspective of nonlinear pedagogy in mathematics education. The method emphasizes logical arguments, theoretical abstraction, and conceptual consistency instead of using empirical data gathering or being empirically validated. Such an orientation is especially suitable considering the main theme of the paper: the idea that mathematical and biomathematical modeling epistemology is nonlinear and feedback-based, and ought to be reflected in the pedagogical structures. Through the conceptual approach, the research intends to synthesize and generalize the available theoretical knowledge to formulate a single explanatory model that can be used in explaining the complexity of learning processes.

2.2 Theoretical Synthesis Across Complexity-Informed Traditions

The framework is built in a synthesis exercise that uses various and interconnected scholarship bodies. The complexity theory, constructivist and emergent learning theories, and dynamic systems thinking are core influences in education. These traditions are not perceived as individual or opposing viewpoints, rather they are studied as complimentary lenses that together contribute to a nonlinear view of learning. Complexity theory has been used to provide insights into feedback, emergence, and adaptation; Constructivist views have placed more focus on the agentic role of learners and on the construction of knowledge; and systems thinking has demonstrated relationality, interdependence, and nonlinearity in the educational setting. Combined, these views uphold a pedagogical paradigm that does not follow a linear sequence on instructions, but views learning as a process of evolution, adaptation.

2.3 Analytical Abstraction of Core Nonlinear Constructs

The study will be based on this synthesis by using analytical abstraction to determine the important conceptual constructs shared by nonlinear and complexity-informed educational theories. The following four interrelated constructs become the major ones in the framework: feedback, recursion, emergence, and adaptability. These constructs are not considered as fixed variables or independent mechanisms. Rather, the discussion is based on their dynamic interactions to influence the learning pathways in the education systems. The connections among these constructs are abstracted and structured into a conceptual base of the nonlinear pedagogical framework through logical reasoning and pattern recognition that is conducted among theoretical sources.

2.4 Conceptual Modeling of Nonlinear Learning Processes

A conceptual model of nonlinear learning has been created in order to express and visualize these relationships. Formally, learning is expressed as a recursive nonlinear process where the cognitive state of a learner changes through recurrent processes of interaction with instructional inputs and contextual conditions:

$$x_{k+1} = x_k + \alpha F(x_k, u_k, c_k) \quad (1)$$

Here, x_k denotes the learner's cognitive state at iteration k , u_k represents instructional stimuli, c_k captures contextual influences, and α reflects learner responsiveness. The nonlinear function $F(\cdot)$ encodes feedback, recursion, and adaptation, emphasizing learning as an evolving system rather than a linear sequence.

The model signifies learning as a dynamic system whereby learners, instructional inputs and contextual factors are in a continuous relationship via a process of recursive feedback. The model focuses on pathways of multi-direction, cycles of reflection, and continuous knowledge reconstruction, as opposed to the more linear view of learning as the process of instructional input to measurable outcome. This conceptualization is represented in Figure 1, which shows learner cognition, contextual factors, instructional stimuli and emergent understanding to be part of a cohesive system connected by feedback loops.

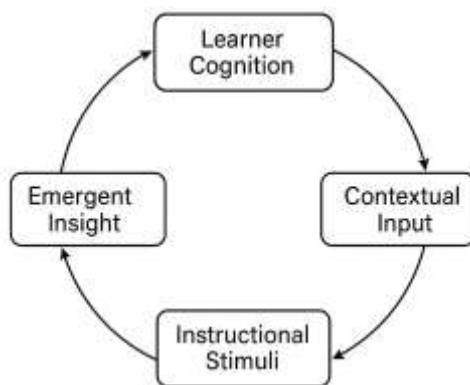


Figure 1. Nonlinear Learning Framework: Recursive Feedback Model in Mathematical Pedagogy

The figure emphasizes that there is a steady stream of influence between components of the system and arrows are used to show recursive interactions and adaptive responses. This graphical interpretation supports the thematic assertion that learning is a dynamic process of repetitive interaction and change and is nonlinear like mathematical and biological systems.

2.5 Sources, Evaluation Criteria, and Theoretical Rigor

There is no empirical data that is used in this study. Rather the framework is enlightened by the secondary theoretical materials such as peer-reviewed journal articles, philosophical review and foundational writings in the fields of education, complexity science and systems theory. Theoretical propositions are produced and developed with the help of these sources and analyzed in terms of internal consistency, conceptual sufficiency, and heuristic worth. The usefulness of the framework does not reside in the statistical extrapolation but its ability to provide an explanation of the complexity of pedagogy, provide interpretive clarity, and produce a direction of future empirical study and instructional change.

3. Emergent Outcomes of a Nonlinear Pedagogical Framework

3.1 Recursive and Emergent Nature of Nonlinear Mathematical Learning

The mathematical learning based on the proposed nonlinear pedagogy model is redefined as a recursive, dynamic and emergent process. Contrasting with the traditional linear models that view education as a fixed and sequential process of transferring knowledge where the instruction process starts and the assessment process ends, nonlinear education focuses on the interaction, feedback, and adaptive learning processes. This model does not perceive understanding as a fixed state but as an ever-changing process, which depends on the cognition of learners, learning context and learning environments.

3.2 Core Characteristics of Nonlinearity in Educational Systems

Nonlinearity in education has four characteristics, which include feedback, recursion, emergence, and adaptation. These attributes undermine the predictability of linear teaching strategies and instead conform to models that are informed by complexity and accept uncertainty, diversity, and responsiveness (Hilpert and Marchand, 2018). Learning in nonlinear systems does not occur additively but is transformational; every cognitive interaction changes the future perspective of knowledge (Heyd-Metzuyanim, 2025).

3.3 Dynamic Learner Systems and Feedback-Driven Learning Processes

This model has several conceptual elements that are interconnected at its core. The first one is the concept of Dynamic Learner Systems, according to which learners are regarded as dynamically changing agents that are in open, unstable thought landscapes. They are not static in their development, but they are a result of contextual factors and thoughtful consideration.

The second element, Feedback Loops in Learning, highlights the process of involvement in a circle of activities of learners making sense of the input, implementing strategies, reflecting on outcomes, and adjusting the approach (Panadero and Lipnevich, 2022). These are recursive and frequently nonlinear loops, i.e., learning can tend to loop back to previous understandings in even more complicated fashions than a straight line.

3.4 Interconnected Knowledge Networks in Mathematical Understanding

The third vital element is Interconnected Knowledge Networks where knowledge is not organized hierarchically but rather in the form of a mesh of related nodes. Mathematically, e.g. algebra, geometry and problem solving tend to cross-link each other, not to isolate themselves. Students follow this network through the routes that are conditioned by their backgrounds, experiences, and already formed conceptual frameworks (Ferdiana et al., 2024).

3.5 Emergence and Adaptive Knowledge Reorganization

Lastly, Emergence and Adaptation define the way new insights become a reality owing to interactions that are unpredictable. These understandings are the products of self-organizing systems and the capacity of the learner to adapt, reframe, and reorganize the available knowledge to react to new stimuli (Sutherland et al., 2023). Table 1 summarizes the four defining constructs of nonlinear pedagogy and the roles they play in the process of learning and teaching biomathematics.

Table 1. Core Constructs of Nonlinear Pedagogy and Their Roles in Biomathematics Education

Construct	Description	Role in Learning	Relevance to Biomathematics
Feedback	Iterative response cycles	Self-regulation	Model revision

Recursion	Re-visiting concepts	Deepening insight	Iterative simulations
Emergence	Unpredictable outcomes	Conceptual restructuring	System behavior
Adaptation	Cognitive flexibility	Transfer learning	Parameter sensitivity

3.6 Visualization of the Nonlinear Pedagogical Framework

Figure 2 gives a recursive model of nonlinear mathematical pedagogy to visualize the role of these elements working together. The conceptual nodes in the figure depict the four major components organised in a dynamic flow with multidirectional arrows. The circular structure encourages continuous interaction, where there is no specific entrance or exit, which implies that the learning can start anywhere, and go in different ways depending on the involvement of the learner and the surrounding.

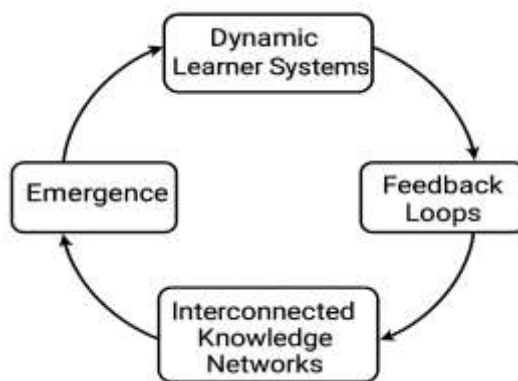


Figure 2. Nonlinear Pedagogical Model in Mathematics Education

The figure is a recursive model of the Dynamic Learner Systems, Feedback Loops, Interconnected Knowledge Networks, and Emergence. The non-linear, repetitive process of knowledge construction and change in complex education systems is marked by curved arrows.

3.7 Theoretical Propositions Emerging from the Nonlinear Model

Behind this structure are several theoretical propositions that make this framework different in comparison to linear instruction. To begin with, mathematical learning is carried out in cycles, as opposed to a linear developmental trajectory. Experience, reflection, and adaptation are also the ways by which learners reorganize knowledge at different levels within the network (Montefusco and Angeli, 2024).

Second, the instructional design should facilitate the emergent cognition by incorporating ambiguity, flexibility, and recursive opportunities in learning environments. This model enables learners to investigate, revisit, and restructure their knowledge in an endless way (Yoon et al., 2018).

Third, education experiences nonlinear systems which have fractal-like characteristics with learning tendencies at small scales reflecting longer scale dynamics of the system. These properties facilitate scalable and context-sensitive pedagogies that are flexible and resilient to educational contexts (Koopmans, 2019).

3.8 Synthesis: Implications for Mathematics Pedagogy

Collectively, this nonlinear pedagogical model offers a platform on which the structure, teaching, and meaning of mathematics education can be reconsidered. It suggests a transformation of inflexible models of delivery to adaptive systems that accept

complexity, promote emergent thinking and support dynamic thinking. Table 2 compares the most prominent assumptions of traditional linear pedagogy and the nonlinear one suggested in the proposed framework in terms of their implication to biomathematics education.

Table 2. Comparison of Linear and Nonlinear Pedagogical Assumptions in Mathematics and Biomathematics Education

Dimension	Linear Pedagogy	Nonlinear Pedagogy
Knowledge flow	Sequential	Recursive
Learner role	Passive receiver	Adaptive agent
Assessment	Static outcomes	Developmental trajectories
Curriculum	Hierarchical	Networked
Biomathematics fit	Limited	High

4. Discussion

The suggested nonlinear model of pedagogy is an important theoretical improvement of the old linear instructional models and the background constructivist methods. Even though constructivism focuses on learner agency and active construction of knowledge, it is frequently implicated in linear paradigms that propose a linear progression and progressive scaffolding. On the contrary, the nonlinear framework developed within this paper incorporates the concept of systems thinking in full and defines learning as an emergent and recursive process that is defined by the feedback loops, adaptive reactions, and interdependent knowledge structures. This reconceptualization makes pedagogy more consistent with the way mathematical reasoning evolves in complicated and real-world situations, where there are uncertainty and dynamic interaction.

One of the main implications of this model is in the curriculum design. Traditional mathematics programs are often structured in a hierarchical manner and assume that one needs to master the basics before moving on to the next level. In nonlinear pedagogy, on the contrary, flexible curricular trajectories are endorsed to permit learners to execute concepts in non-linear sequences, influenced by contextual, a priori, and discursive changing learning patterns. This flexibility is consistent with curriculum innovations that focus on connectivity with the aim of co-designing with students and personalized paths (Pepin, 2021). Pattern-based learning, as nonlinear strategies, also facilitate more conceptual interrelationship learning than single-topic learning, as well as integrative knowledge across mathematical fields (Brown, 2023).

The practice of instruction is also redefined on the nonlinear framework. Instead of being the transmitters of the fixed content, educators should act as the facilitators of complexity, facilitating learners in the process of inquiry, reflection, and reconceptualization in the iterative cycles. This dynamic nature reflects the way learners interact with mathematical concepts in the real world in a manner that they revisit, restructure and redefine concepts as they learn and gain knowledge (Zhou, 2024). Such adaptive facilitation acknowledges learning as a responsive process as opposed to an instructional sequence that has been established.

Practices of assessment are also changed. The conventional assessment has been focusing on fixed results and the right answers and ignores the progressive character of knowledge. Nonlinear pedagogy on the other hand favours growth-focused assessment systems that acknowledge individual learning patterns, adaptive problem-solving and transfer of knowledge to different situations. Such strategies are especially applicable to the development of sophisticated thinking skills that entail synthesis, being responsive to uncertainty, and flexibility in strategy (Ramírez-Montoya et al., 2025).

The applicability of this framework is particularly acute in the biomathematics education wherein students combine mathematical reasoning with biological nonlinear, feedback-driven, and multi-scale systems. Linear curricula that focus on rigid procedures are not always able to represent the active nature of biological processes that include population dynamics, epidemiological dispersal, regulatory mechanisms, and ecological exchange (Epstein, 2018). As a matter of fact, the process of learning biomathematics is cyclic, and not cumulative. The fundamental components of the framework, including feedback, interlinked knowledge networks, and emergence, indicate how mathematical models change with a change in assumptions and parameters, and students update their models in response to the density dependence, behavioural feedback, or change in the environment (Sigahi & Sznclwar, 2022).

This correspondence can be observed in the biomathematical applications. The repetition of transitions between formulation, simulation, and interpretation is necessary in teaching ordinary and partial differential equation models in population dynamics, pattern formation and spatial disease spread to reinforce learning in recursive refinement (Haskovec et al., 2015). Epidemiological models are characterised by threshold effects and behavioural feedback, which is why recursive learning structures are pedagogically important (Milgroom, 2023). Nonlinear pedagogy is also demonstrated by systems biology and eco-evolutionary modeling (Des Roches et al., 2021) and is justified by the emergent behavior, which emerges due to multi-scale interactions (Robeva et al., 2020), as well as curriculum and assessment designs that focus on model adaptation and critical thinking (Gugulethu and Irvine, 2025).

The instructional relevance of the framework is illustrated through epidemiological modeling using the Susceptible–Infected–Recovered (SIR) framework (Robeva et al., 2020). In a nonlinear method, students develop the equations of the diffusion, model the dynamics of the disease and explain their emergent behaviour, including equilibria and epidemic peaks. Intuition is questioned by early simulations, which can cause the reassessment of assumptions and parameters in the form of build-test-revise cycles in accordance with the principles of nonlinear modeling (Gan et al., 2020). Feedback loops facilitate self-regulation and adaptive understanding (Morrison and Jacobsen, 2023), whereas emergence emphasizes the way in which patterns of the population are formed based on local interactions (Thomas et al., 2018).

In terms of teacher education, nonlinearity allows teachers to create responsive and inclusive learning experiences that add to the engagement and motivation levels when paired with experiential learning and technology (Pérez-Muñoz et al., 2023). Professional development can also be viewed through the prism of a systems-informed lens as a complex adaptive process (Garner and Kaplan, 2020). The framework is philosophically aligned with transformative learning perspectives, as it puts emergence, uncertainty, and transformation in the first place (Hart et al., 2025). The COVID-19 pandemic also highlighted the restrictions of inflexible systems and the necessity of pedagogies that can react to the disruption in a flexible manner (Azorín, 2020). The empirical comparison indicates that although linear instruction can be helpful at the outset to develop technical accuracy, nonlinear methods allow developing flexibility and a sense of the situation that are crucial to solve real-life problems and lifetime learning (Espoz-Lazo et al., 2025).

5. Implications and Future Research

The suggested model of nonlinear pedagogy provides various opportunities for empirical research and interdisciplinary study. Simulation-based modeling of recursive learning interactions and qualitative classroom research studies on how learners navigate their way through feedback-rich environments could be incorporated in future research. The

methods can justify the way nonlinearity is expressed in actual teaching life and guide the instructional design.

It is necessary to integrate across disciplines. Nonlinear pathways may be customized by artificial intelligence and adaptive learning systems and understanding the way the brain encodes iterative and emergent learning patterns may be achieved through cognitive science. Complex educational ecologies could be mapped via systems modelling and points of leverage to pedagogical change identified.

Theoretically, the framework offers a strong starting point in future research of nonlinear education theory, as it offers a perspective through which the concept of learning can be reintroduced as an adaptive, dynamic process. It challenges educators and researchers to transcend prescriptive models, which encourage innovations that are responsive to the dynamic, interdependent realities of cognition as well as the present-day educational systems.

6. Conclusion

This paper has dealt with a major weakness of the current mathematics education system, which is still based on linear pedagogical frameworks that are insufficiently responsive to the recursive, adaptive, and feedback-based learning processes demanded by biomathematics. The proposed framework redefines learning as an emergent process by relying on the complexity theory, constructivist principles of learning, and the system thinking that involve nonlinear interactions between learners, mathematical structures, and biological contexts. Instead of viewing knowledge learning as a linear process, the framework focuses on recursive learning, adaptive learning, and the network of knowledge that more appropriately reflects real-life modeling in the life sciences. The work contributes to the research of biomathematics education through providing a pedagogical framework that is consistent to the nonlinear organization of biological systems and mathematical modeling activities. In biomathematics, learners frequently work with population dynamics, epidemiological transmission, and systems biology models that have feedback and threshold effects and emergent behavior. Instructional designs would be based on these attributes as proposed in the framework, which would support learners to build, interpret, revise, and contextualize mathematical models of biological phenomena in an iterative manner. With a correspondence between pedagogy and disciplinary practice, the framework is able to improve conceptual knowledge, quantitative reasoning, and adaptive problem-solving in the teaching of quantitative biology. Pedagogically, the framework promotes flexible curriculums, assessment methods that are feedback-driven and instructional methods that appreciate exploration, reflection and model refinement rather than attaining solutions. It is conceptually an opportunity to re-think biomathematics education as a complex adaptive system as opposed to a linear transmission of content. Future studies can utilize empirical studies to examine the use of nonlinear pedagogic structures in biomathematics classrooms, modeling environments based on technology, and the dynamics of learning among learners in instructional environments that provide feedback. Altogether, this article provides a theoretically based and discipline-consistent way of the education and outreach development in biomathematics.

References

1. Allen, J., & Bickhard, M. (2022). Emergent constructivism: Theoretical and methodological considerations. *Human Development*, 66(4–5), 1–24.
2. Azorín, C. (2020). Beyond COVID-19 supernova: Is another education coming? *Journal of Professional Capital and Community*, 5(3), 381–390.

3. Brown, S. L. (2023). Complexity patterning: A patterns-based design and strategy for transformational education. *Systems Research and Behavioral Science*, 40(5), 808–815.
4. Des Roches, S., Brans, K. I., Lambert, M. R., Rivkin, L. R., Savage, A. M., Schell, C. J., & Alberti, M. (2021). Socio-eco-evolutionary dynamics in cities. *Evolutionary Applications*, 14(1), 248–267.
5. Epstein, J. M. (2018). *Nonlinear dynamics, mathematical biology, and social science*. CRC Press.
6. Espoz-Lazo, S. I., Rahmati-Arani, M., Hinojosa-Torres, C., Farías-Valenzuela, C., & Dehghani Zadeh, J. (2025). Precision or adaptability? Contrasting effects of linear and non-linear pedagogy models in handball instruction. *Frontiers in Sports and Active Living*, 7, Article 1673424.
7. Fellus, O. O., Segal, R., Silverman, B., & Movshovitz-Hadar, N. (2025). Change in mathematics education during a time of crisis: Reflections through the lens of complexity constructs. *European Educational Research Journal*, 24(2).
8. Ferdiana, R., Rahayu, N. W., Adi, A. N., & Kusumawardani, S. S. (2024). Nonlinear learning path: A systematic review. *Turkish Online Journal of Distance Education*, 25(4), 143–161.
9. Gan, M., Guan, Y., Chen, G. Y., & Chen, C. P. (2020). Recursive variable projection algorithm for a class of separable nonlinear models. *IEEE Transactions on Neural Networks and Learning Systems*, 32(11), 4971–4982.
10. Garner, J. K., & Kaplan, A. (2020). A complex systems perspective on policy standards for teacher learning and development. *International Journal of Complexity in Education*, 1(1).
11. Gugulethu, B. P. Z., & Irvine, M. M. (2025). Integrating mathematical modelling of disease transmission into life sciences classrooms: A pedagogical approach. *Journal of Cultural Analysis and Social Change*, 45, 36–42.
12. Gunawardena, M., Bishop, P., & Aviruppola, K. (2024). Personalized learning: The simple, the complicated, the complex and the chaotic. *Teaching and Teacher Education*, 139, Article 104429.
13. Hart, E. J., et al. (2025). Key tips to shift student perspectives through transformative learning in medical education. *BMC Medical Education*, 25, Article 202.
14. Haskovec, J., Markowich, P., & Perthame, B. (2015). Mathematical analysis of a PDE system for biological network formation. *Communications in Partial Differential Equations*, 40(5), 918–956.
15. Heyd-Metzuyanim, E. (2025). Failure to teach/learn mathematics: A complexity-discursive perspective. *Educational Studies in Mathematics*, 119(3), 515–533.
16. Hilpert, J. C., & Marchand, G. C. (2018). Complex systems research in educational psychology: Aligning theory and method. *Educational Psychologist*, 53(3), 185–202.
17. Jacobson, M. J., Levin, J. A., & Kapur, M. (2019). Education as a complex system: Conceptual and methodological implications. *Educational Researcher*, 48(2), 112–119.
18. Joshi, H. R., Lenhart, S., Hota, S., & Agosto, F. (2015). Optimal control of an SIR model with changing behavior through an education campaign. *Electronic Journal of Differential Equations*, 2015(50), 1–14.
19. Koopmans, M. (2019). Fractality and power law distributions: Shifting perspectives in educational research. *Northeast Journal of Complex Systems*, 1, Article 2.
20. Kritt, D., & Budwig, N. (2022). The future of constructivist education. *Human Development*, 66(4–5), 295–309.
21. Milgroom, M. G. (2023). Epidemiology and SIR models. In *Biology of infectious disease: From molecules to ecosystems* (pp. 253–268). Springer.

22. Montefusco, A., & Angeli, F. (2024). Turning complexity into a delight to the mind: An integrative framework for teaching and learning complex reasoning. *Management Learning*, 56(4).
23. Morrison, K. (2019). Educational philosophy and the challenge of complexity theory. *Educational Philosophy and Theory*, 51(5), 453–466.
24. Morrison, L., & Jacobsen, M. (2023). The role of feedback in building teaching presence and student self-regulation in online learning. *Social Sciences & Humanities Open*, 7(1), 100503.
25. Panadero, E., & Lipnevich, A. A. (2022). A review of feedback models and typologies: Towards an integrative model of feedback elements. *Educational Research Review*, 35, Article 100416.
26. Pepin, B. (2021). Connectivity in support of student co-design of innovative mathematics curriculum trajectories. *ZDM – Mathematics Education*, 53(6), 1221–1232.
27. Pérez-Muñoz, S., Melo, A. C., Huete García, S., & Rodríguez-Cayetano, A. (2023). Nonlinear pedagogy effect and value of the city and new technologies as a didactic resource in the training of future teachers. *Education Sciences*, 13(7), Article 672.
28. Ramírez-Montoya, M. S., Portuguese-Castro, M., & Mendoza-Urdiales, R. (2025). Redefining education: Educational trajectories for complex thinking skills. *Humanities and Social Sciences Communications*, 12, Article 958.
29. Robeva, R. S., Jungck, J. R., & Gross, L. J. (2020). Changing the nature of quantitative biology education: Data science as a driver. *Bulletin of Mathematical Biology*, 82(10), Article 127.
30. Sato, M., Ma, T., & Abbiss, J. (2025). Using complexity theory to understand teaching: Re-framing perspectives from preservice teachers. *Teaching and Teacher Education*, 156, Article 104905.
31. Sigahi, T. F., & Sznclwar, L. I. (2022). Exploring applications of complexity theory in engineering education research: A systematic literature review. *Journal of Engineering Education*, 111(1), 232–260.
32. Sutherland, L., Markauskaite, L., & Cruickshank, L. (2023). A complex systems framework for examining the impact of school-based professional learning initiatives: Emerging agentic practices in a collaborative curriculum redesign. *Professional Development in Education*, 49(6), 1087–1102.
33. Thomas, M., Clack, L., & Plaspohl, S. (2018). Blending pedagogical approaches in public health education: the ADOPT model. *Pedagogy in health promotion*, 4(3), 227–233.
34. Xenofontos, C., & Appelbaum, P. (2025). Conceived linearities in mathematics education and how to disrupt them. *Research in Mathematics Education*. Advance online publication.
35. Yoon, S. A., Goh, S. E., & Park, M. (2018). Teaching and learning about complex systems in K–12 science education: A review of empirical studies (1995–2015). *Review of Educational Research*, 88(2), 285–325.
36. Zhou, P. (2024). Make lectures match how we learn: The nonlinear teaching approach to economics. *Education Sciences*, 14(5), Article 509.