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Short communication

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Invariant energy symmetries and quality dispersal in living matter: bridging energy structure theory (EST) to bionic systems

Abstract

Biological architectures and biomimetic transducers operate far from equilibrium, sustaining highly organized macrostates through persistent energy throughput. Traditional classical and non-equilibrium formulations, anchored strictly within canonical action principles or empirical dissipation functions, frequently struggle to capture the universal structural dynamics that govern living tissues and bionic interfaces across hierarchical scales. Here, we present a conceptual paradigm grounded in Energy Structure Theory (EST) and its governing Energy Structure Equation to elucidate the morphological and thermodynamic resilience of biological systems. By incorporating the emerging principle of energy quality alongside invariant energy symmetries independent of standard action bounds—reminiscent of invariant fundamental energy thresholds—we establish a unified framework connecting cellular mechanobiology to advanced bionic actuation. The formulation demonstrates that biological adaptation is fundamentally an optimization of energy quality preservation against irreversible dispersion. This perspective not only unifies equilibrium and non-equilibrium biological mechanics but also predicts novel architectural principles for self-stabilizing synthetic bio-composites.

Keywords: energy structure theory (EST), energy quality, non-equilibrium biomechanics, invariant energy symmetries, biomimetic systems, biological irreversibility

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Introduction

Living matter constitutes arguably the most intricate thermodynamic architecture in the natural universe. Unlike inert engineering materials that passively succumb to entropic decay, biological systems continuously absorb, redistribute, and structurally store mechanical and chemical free energy.[1–4] From the cooperative unfolding of sarcomeric titin in skeletal muscles to the morphogenetic remodeling of cytoskeletal stress fibers, biomechanical functionality is intrinsically coupled to the nature of energy distribution rather than mere scalar conservation.[1,5–7]

Classical continuum thermodynamics and conventional Lagrangian formulations operating under variational principles often treat mechanical dissipation and living kinetics as perturbation phenomena.[8] However, empirical observations in active matter and biosystems reveal persistent structural patterns that remain invariant across diverse regimes of perturbation and deformation rate.[1,8] To reconcile these observations, Energy Structure Theory (EST) was established as a generalized paradigm to govern the evolutionary trajectories of energy densities across thermodynamic systems.[5] Recent advancements have further formalized the laws of general energy behavior[1] and identified invariant energy symmetries independent of stationary action principles.[8,9] Simultaneously, the foundational definition of an "energy quality" metric has paved the way toward an explicit thermodynamic law of degradation and organizational potency,[3–5] echoing fundamental invariant physical scales.[9]

The conceptual roots of energy-quality preservation in living systems trace back to the thermodynamics of irreversible processes, where the maintenance of organized structure far from equilibrium was established as a hallmark of biological robustness.[10–12] This perspective has been substantially extended in contemporary frameworks, notably the free-energy principle, which formalizes how adaptive organisms resist the tendency toward entropic dispersal by continuously minimizing variational free energy and sustaining internal structural order.[13] Within living tissues, such homeostatic resilience is achieved through dynamic reconfiguration — vascular and extracellular remodeling that redistributes mechanical load and chemical potential to preserve functional energy quality under perturbation,[14] a behavior conceptually mirroring the invariant energy symmetries proposed here. Concurrently, the field of biomimetics has matured from qualitative inspiration into a rigorous engineering discipline, translating principles of biological energy management into synthetic adaptive systems and soft robotic architectures.[15,16] Energy Structure Theory (EST) extends this trajectory by proposing that these diverse biological strategies converge upon a common invariant — the conservation and dispersal of energy quality — thereby offering a unified theoretical scaffold from living mechanobiology to future bionic engineering.

In this Short Communication, we project these theoretical breakthroughs onto the canvas of applied bionics and biomechanics. By eliminating unnecessary mathematical clutter from the discursive narrative, we focus purely on the conceptual architecture of how biological organisms preserve mechanical order, and how modern bionics can emulate these natural invariant symmetries.

Ultimately, this Short Communication challenges the long-standing dogma that biological resilience is merely an epiphenomenon of complex chemical kinetics or empirical viscoelastic damping. By stripping away conventional mathematical friction and distilling the core tenets of Energy Structure Theory, we formulate an uncompromising conceptual blueprint: life persists not by resisting thermodynamics, but by mastering the structural hierarchy of energy itself. For researchers and engineers at the cross-section of applied bionics and biomechanics, the following sections offer a paradigm-shifting roadmap—demonstrating how harnessing invariant energy symmetries can redefine the boundaries of autonomous artificial systems and synthetic biomaterials.

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Conceptual foundations: energy quality and invariant energy symmetries

In conventional mechanics, energy is treated as a uniform scalar currency governed solely by conservation constraints. Yet, in biological systems, identical enthalpy contents yield drastically divergent functional outcomes depending on their structural organization—a property conceptually rooted in energy quality.[2] Biological tissue does not merely convert energy, it regulates the hierarchy of mechanical potential, chemical gradients, and thermal dissipation to safeguard homeostatic structural integrity.[1–4]

Within the Energy Structure Theory (EST), structural reconfiguration is treated not as a passive consequence of external stress fields, but as a proactive dynamic equilibrium governed by intrinsic energy distributions.[5] When biological materials encounter extreme deformation rates, localized structural remodeling prevents catastrophic fracture by transferring mechanical strain energy into reversible conformational states.[1,8,9] This behavior reveals the existence of invariant energy symmetries that operate autonomously from traditional action principles.[8]

Analogous to the way modern physical principles incorporate invariant fundamental energy thresholds to preserve invariance across observation frames,[9] living materials utilize invariant structural thresholds below which deformation remains intrinsically non-destructive, and above which autonomous self-organization and remodeling are triggered.[1,8]

Analytical formulation and energy quality index

To mathematically operationalize Energy Structure Theory (EST) within living and bionic systems, we define the dimensionless Energy Quality Index (ψ) as the ratio of invariant stored structural energy (E_{inv}) to total input energy under dynamic mechanical perturbation:

$$\psi = \frac{E_{inv}}{E_{inv} + E_{diss}}, \tag{1}$$

Where E_{diss} represents irreversible entropic decay. In biological tissues, mechanoadaptive remodeling acts to maximize ψ by shifting mechanical strain into conformational energy symmetries (local gauge-like invariances), whereas conventional bionic materials experience progressive degradation $((\Delta S > 0, \psi \to 0)$.

Assuming a characteristic stress redistribution time τ, the temporal evolution of structural quality rate obeys:

$$\frac{d\psi}{dt} = -\frac{1}{\tau} / (\psi - \psi_{crit}) + \eta \nabla^2 \psi, \tag{2}$$

Here, ψ_{crit} is the critical threshold for functional stability, and $\eta \nabla^2 \psi$ represents spatial energy redistribution driven by invariant EST symmetries. This formulation bridges theoretical energy conservation with quantifiable metrics for adaptive bionic designs.

Bridging EST to bionic architecture and biomechanical resilience

The operational core of the Energy Structure Equation (EST) unifies localized gradient behaviors with overarching macroscopic thermodynamic laws.[1,5] In living muscle bundles and cartilaginous matrices, energy degradation is systematically constrained by architectural topology.[2–5] This fundamental concept offers critical design blueprints for synthetic bionics:

1. **Autonomous damage arrest:** Traditional synthetic implants suffer from progressive micro-fatigue. By designing bio-composites that embody EST principles, mechanical energy concentrations can be systematically transformed into controlled energy-dissipating modes without loss of primary load-bearing capacity.[1,5]
2. **Quality-driven bionic actuation:** Modern bionic prosthetics often exhibit poor metabolic-equivalent efficiency. Formulating prosthetic actuators around the preservation of energy quality[4] ensures that electrical and mechanical inputs are transduced with minimal irreversible entropic dispersal.[2,4,8]
3. **Multi-scale invariance:** From nanoscale motor proteins to macroscale muscular frameworks, living systems exhibit scale-invariant energy behaviors.[1,5,8] Designing bionic metamaterials that replicate these invariant energy states will enable artificial organs and limbs to interact harmoniously with natural host tissues.

Graphical overview of the EST framework

To make the abstract framework operationally tangible, the following schematic figures translate the Energy Structure Equation into a visual architecture. Figure 1 maps the EST paradigm across hierarchical living systems—from cytoskeletal filaments to complete bionic muscle actuators—illustrating how state energy potentials, non-equilibrium gradient fluxes, and structural configurational terms converge into a single unified balance. Building on this foundation, Figure 2 extends the framework to bionic interfaces, contrasting classical entropic degradation with EST-governed energy quality dynamics and outlining an engineering blueprint for next-generation prostheses. Together, these visual representations bridge the theoretical formalism established above with the practical design principles of applied bionics.

The diagram systematically illustrates:

(a) The multi-scale continuum from cytoskeletal filaments to complete bionic muscle actuators.

(b) The mathematical synthesis box detailing the generalized Energy Structure Equation, showing the balance between state energy potentials, non-equilibrium gradient fluxes, and structural configurational terms without textbook mathematical baggage.

(c) The operational transition between conservative strain energy and active structural reconfiguration.

As captured schematically in Figure 1, the Energy Structure Theory establishes that biological tissue relies on hierarchical gradient fluxes and non-local configurational potentials to circumvent catastrophic localization under mechanical load. However, the translation of these multi-scale biological symmetries into practical engineering paradigms necessitates an explicit governing criterion for operational stability. While natural systems inherently regulate conformational states to preserve macroscale integrity, synthetic bionic interfaces conventionally suffer from irreversible entropic decay and progressive micro-fatigue.

To bridge this fundamental disparity, the operational principles must be expanded from passive multi-scale representation to active energetic quality control. By coupling invariant energy symmetries with the thermodynamic degradation pathways of energy quality, one can define an analytical criterion for autonomous self-organization.

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Figure 2 formalizes this transition, directly contrasting the classical dissipative run-down of conventional synthetic biomaterials against the active, quality-preserving phase trajectories governed by the Energy Structure Equation, thereby laying out the functional architecture for next-generation bionic transducers.

The diagram features:

(a) The analytical formulations of Energy Quality degradation pathways alongside Invariant Energy Symmetry relations that operate independently of standard action principles.

(b) A comparative phase-space plot depicting classical entropic run-down versus biological quality preservation and structural self-organization.

(c) An engineering blueprint for next-generation bionic prostheses incorporating invariant energy thresholds to arrest mechanical fatigue and optimize metabolic efficiency.

Taken together, Figure 1 and Figure 2 present a coherent and closed-loop thermodynamic paradigm for bio-inspired resilience. Whereas Figure 1 elucidates the spatial and hierarchical continuum—demonstrating how energy structure equilibria distribute applied strain energy across discrete biological domains without localized singular breakdown—Figure 2 establishes the temporal and qualitative governance that dictates dynamic longevity.

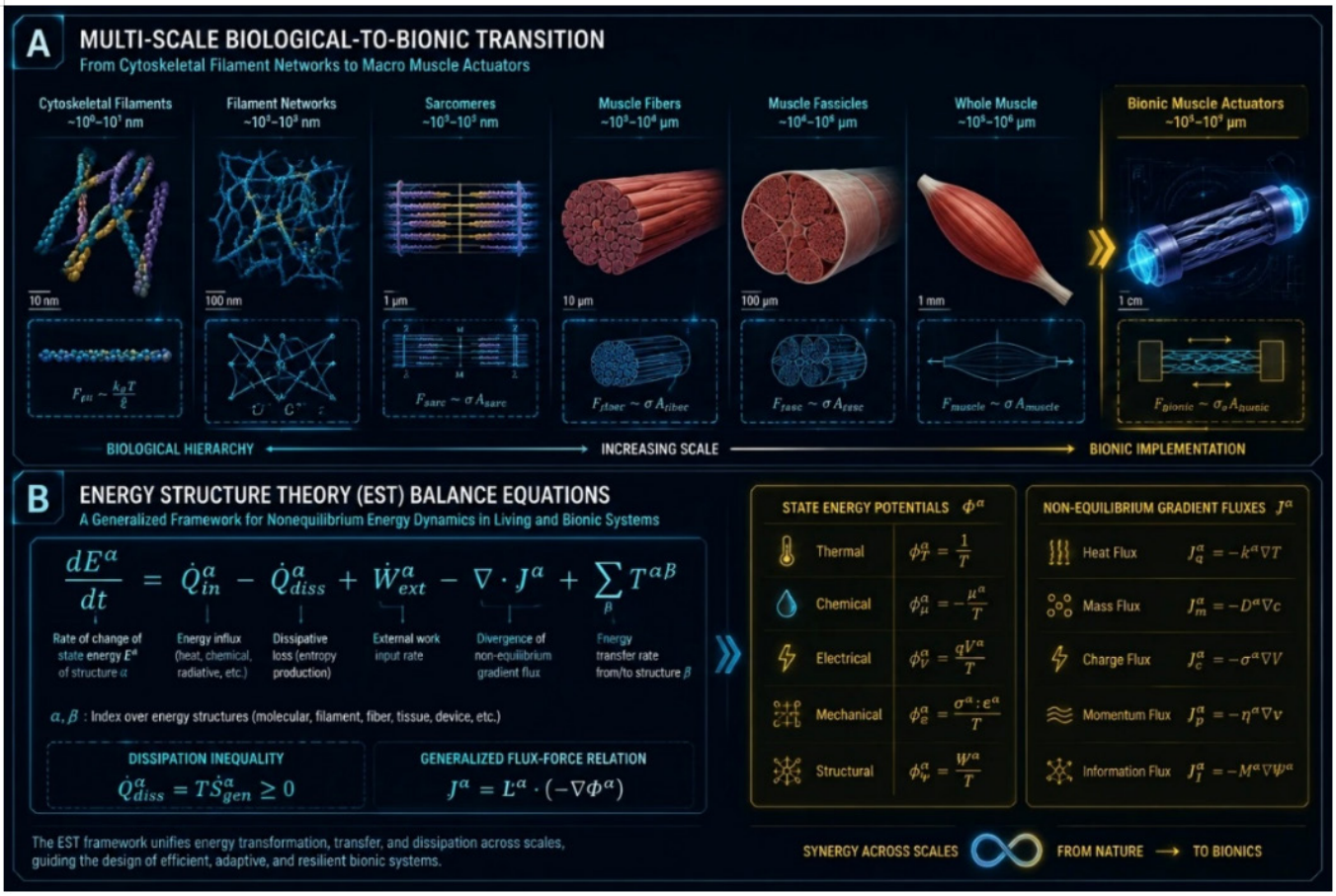


Figure 1 The Energy Structure Theory (EST) Paradigm in Biomechanics: Schematic mapping of the fundamental Energy Structure Equation (EST) across hierarchical living systems.

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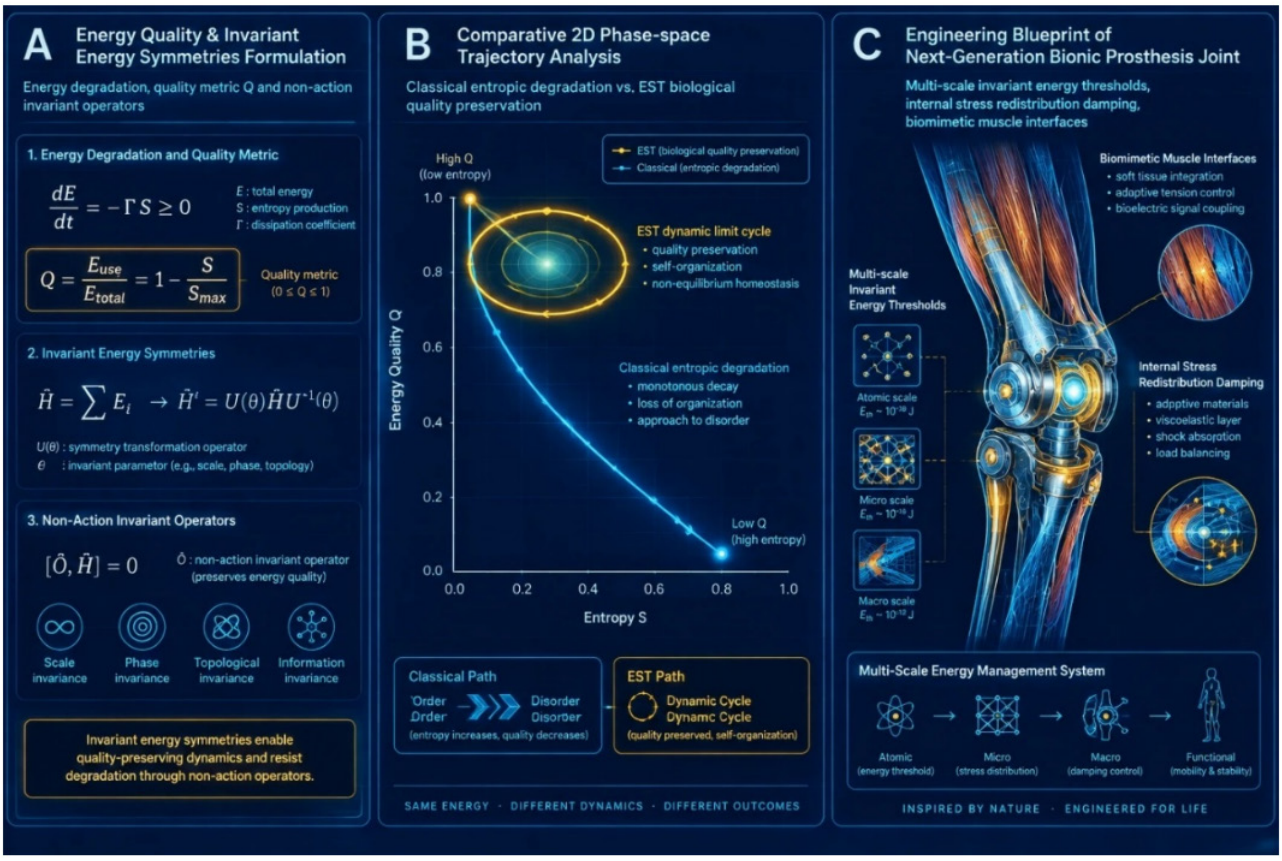


Figure 2 Invariant Energy Symmetries and the Principle of Energy Quality in Bionic Interfaces: Structural schematic contrasting classical degradation with EST-governed energy quality dynamics in natural tissue versus advanced bionic systems.

The central takeaway emerging from this combined visual synthesis is that biological and successful bionic robustness does not arise from sheer mechanical stiffness or unconstrained passive dissipation, rather, it is dictated by the structural preservation of energy quality along invariant thermodynamic trajectories. By anchoring bionic design to the invariant energy thresholds detailed across these figures, synthetic actuators and load-bearing bio-composites can autonomously redirect destructive energetic concentrations into benign, reversible configurational states. Consequently, this unified representation shifts modern biomechanics away from empirical phenomenology and establishes an actionable, energy-structured blueprint for self-stabilizing synthetic life interfaces.

Concluding outlook and predictive horizons

The integration of Energy Structure Theory (EST) with the principle of energy quality transcends descriptive biomechanics, establishing a predictive framework for next-generation biomimetic engineering. We foresee that the synthesis of invariant energy symmetries with living tissue dynamics will unlock:

1) Self-adaptive bio-metamaterials capable of autonomous internal stress redistribution prior to macroscopic strain localization.
2) Neuromorphic bionic actuators that mimic the metabolic energy-quality conservation observed in living myofibrils.
3) Non-destructive, energy-based diagnostic modalities for early detection of degenerative musculoskeletal diseases based on localized energy quality decay rather than mere anatomical degeneration.

In conclusion, life does not defy thermodynamics, rather, it manifests the most elegant realization of energy structure dynamics. Embodying these invariant energy principles within synthetic systems represents the defining frontier of modern applied bionics.

Translating EST principles into actionable bionic architectures requires addressing three critical future avenues:

1) **Active bio-metamaterials:** Synthesizing soft materials embedded with autonomous energy-redistribution loops that mimic biological strain-mode conversion.
2) **Multi-scale EST sensing arrays:** Developing sensor networks inspired by invariant cellular symmetries to track localized energy-quality metrics in real time.
3) **Experimental validation protocols:** Establishing standard testing methodologies to quantify the Energy Quality Index (ψ) across biological-synthetic interfaces under cyclic loading.

Overcoming these frontiers will shift bionics from passive fatigue-resisting structures to fully autonomic, life-mimetic systems capable of sustained operational homeostasis.

Conclusions

This Short Communication establishes a conceptual bridge between fundamental thermodynamics and applied bionics by

framing biological resilience through the lenses of Energy Structure Theory (EST), energy quality preservation, and invariant energy symmetries. Rather than modeling living architectures through empirical damping parameters or classical unconstrained dissipation, we demonstrated that biological systems sustain dynamic integrity by structurally channeling energy fluxes across hierarchical scales - from macromolecular assemblies to functional tissues.

The core conclusions of this perspective are twofold:

1. **Thermodynamic unification:** Biological non-equilibrium persistence is fundamentally governed by an optimization of energy quality mediated by non-action invariant symmetries, ensuring that mechanical strain is redirected into reversible conformational modes rather than localized catastrophic degradation.
2. **Engineering paradigm shift:** Embodying the governing Energy Structure Equation within synthetic bio-composites shifts the paradigm of bionic engineering from passive fatigue endurance toward proactive, self-stabilizing energy redistribution.

While the theoretical framework unifies equilibrium and non-equilibrium mechanics, its translation into practical bionics serves as an actionable hypothesis for next-generation bio-metamaterials, metabolic-efficient prostheses, and non-destructive diagnostic tools. Ultimately, decoding the structural laws of biological energy dynamics provides the indispensable foundation for engineering artificial systems that truly emulate the longevity, adaptability, and thermodynamic sophistication of living matter.

Looking forward, translating EST principles into actionable bionic architectures requires addressing three primary frontiers: (i) synthesis of active bio-metamaterials embedded with autonomous energy-redistribution loops, (ii) development of real-time multi-scale sensing arrays inspired by invariant cellular energy symmetries, and (iii) experimental validation of quality dispersal indices in synthetic soft actuators. Overcoming these challenges will transition bionics from passive fatigue-resisting structures to fully autonomic, life-mimetic systems capable of sustained operational homeostasis.

Declarations

Ethics approval and consent to participate: Not applicable. This study does not involve human participants, animal subjects, or clinical tissue samples.

Consent to publish: Not applicable.

Data availability: All conceptual frameworks, formulations, and data supporting the findings of this study are fully contained within the manuscript and its figures. No additional or external datasets were generated or required for this work.

Author contributions: All authors contributed to the conceptualization, theoretical formulation, visual architecture design, and writing and critical revision of the manuscript, and approved the final submission.

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Conflicts of interest

The authors declare that they have no conflict of interests.

Reference

1. Shahsavari S, Boutorabi SMA, Moradi M, et al. Formulating general energy behavior laws: a new perspective on unifying thermodynamic principles. *Int J Theor Phys*. 2025;64(10):281.
2. Mayhew KW. Improving our thermodynamic perspective. *Physics Essays*. 2011;24(2):194–202.
3. Nitzke I, Stephan S, Vrabec J. Topology of thermodynamic potentials using physical models: Helmholtz, Gibbs, Grand, and Null. *J Chem Phys*. 2024;160(21):214104.
4. Cobos-Murcia JA. Formulation of the principle of energy quality: toward a fourth law of thermodynamics. *Chem Thermodyn Therm Anal*. 2026;21:100265.
5. Shahsavari S, Boutorabi SMA. Energy structure theory: A general unified thermodynamics theory. *Int J Thermodyn*. 2023;26(3):1–16.
6. Palazzo P. Thermal and chemical aspect in equation of state and relation with generalized thermodynamic entropy. *Int J Thermodyn*. 2018;21(1):55–60.
7. Muschik W. Survey of some branches of thermodynamics. *J Non-Equilib Thermodyn*. 2008;33(2):165–198.
8. Shahsavari S. Invariant energy symmetries independent of action principle: unifying equilibrium and non-equilibrium dynamics. *Phys Open*. 2026;28:100465.
9. Magueijo J, Smolin, L. Lorentz invariance with an invariant energy scale. *Phys Revi Lett*. 2002;88(19):190403.
10. Shahsavari S. A structural reformulation of the local entropy inequality based on the thermodynamic admissibility of exchanged energy. *Next Energy*. 2027;14(2027):101160.
11. Prigogine I. *Introduction to thermodynamics of irreversible processes*. Interscience Publishers: New York, NY, USA, 1967.
12. Shahsavari S. Dynexis: a measure of dynamical accessibility in hamiltonian and non-equilibrium systems. *Results Eng*. 2026;32:113682.
13. Friston, K. The free-energy principle: a unified brain theory? *Nat Rev Neurosci*. 2010;11(2):127–138.
14. Jain RK. Normalization of tumor vasculature: an emerging concept in antiangiogenic therapy. *Science*. 2005;307(5706):58–62.
15. Vincent JFV, Bogatyreva OA, Bogatyrev NR, et al. Biomimetics: its practice and theory. *J R Soc Interface*. 2006;3(9):471–482.
16. Chen Y. 3D printing of biomimetic soft materials for bionic robotics. *Advanced Materials*. 2021;33(19):2000135.