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Biomaterials COMMENTARY

The Innovation Materials

One toolkit, many materials: How snails tune mucus for lubrication, adhesion, and protection

Yuanzhe Li,[1,*] Chenxu Liu,[2,*] and Yu Tian[3,*]

[1]Institute of Engineering Innovation, Graduate School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan

[2]Department of Chemical and Materials Engineering, University of Alberta, Edmonton T6G 1H9, Canada

[3]State Key Laboratory of Tribology in Advanced Equipment, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China

*Correspondence: liyz@t.photon.u-tokyo.ac.jp (Y.L.); chenxu9@ualberta.ca (C.L.); tianyu@mail.tsinghua.edu.cn (Y.T.)

Received: August 14, 2026; Accepted: October 20, 2026; Published Online: October 20, 2026; https://doi.org/10.59717/j.xinn-mater.2026.100251

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Citation: Li Y., Liu C. and Tian Y. (2026). One toolkit, many materials: How snails tune mucus for lubrication, adhesion, and protection. *The Innovation Materials* **4**:100251.

Snail locomotion presents a striking mechanical challenge: a single muscular foot must generate propulsion and adhesion across surfaces ranging from soft soil and rough bark to smooth vertical walls and inverted ceilings. To generate net forward motion while maintaining continuous contact with the substrate, a snail must break frictional symmetry along its foot. Classical studies have attributed this remarkable ability to the nonlinear rheology of lubricating mucus through a mechanism termed "adhesive locomotion."[1] Rather than lifting its body like an inchworm, a snail propagates waves of muscular contraction, known as pedal waves, along its ventral foot. These waves create alternating wave and interwave regions, with the latter remaining relatively stationary. As each wave passes, the underlying mucus undergoes cycles of yielding and healing, where solid-like interwave regions transmit traction and localized yielding beneath the waves allows portions of the foot to advance. More recent high-resolution imaging of dynamic traction forces has extended this rheological framework by revealing the role of local normal-force regulation.[2] Pedal waves coordinate normal and tangential stresses, producing a distributed suction-cup effect and establishing localized segmental seals that enable locomotion across horizontal, vertical, and inverted surfaces. Thus, locomotion does not rely on mucus rheology alone, but on coupling between mucus material state, active spatiotemporal deployment, and the local interfacial and mechanical environment.

Locomotion, however, is only one of the many functions served by snail secretions. Throughout its life cycle, a snail also produces mucus for long-term attachment, protection against dehydration, and defense against predators and other external threats. These functions demand markedly different and even opposing material properties, spanning easy flow and strong cohesion, effective lubrication and durable adhesion, and compliant contact and rigid protection. This raises a fundamental question: how can snails efficiently produce such a diverse repertoire of functional materials?

Snail mucus: shared molecular components, distinct material functions

In a recent study published in *Science*, Gabler *et al.* addressed this question by comparing five functionally distinct mucus-based materials produced by the terrestrial snail *Cepaea nemoralis*.[3] These include lubricating, adhesive, defensive, foamy, and epiphragm-forming materials. By combining proteomics, biochemical analysis, microscopy, mineral characterization, and nonlinear rheology, the study showed that these secretions extend beyond the conventional mucin-centered view of mucus. Mucins remain important, yet proteomic analysis revealed a broader, extracellular-matrix-like protein system. Collagen VI was among the most prominent structural proteins recurrently detected across the materials, although its abundance varied considerably among them. Although multiple collagen proteins had previously been identified in three functionally distinct secretions of the garden snail *Cornu aspersum*, with secretion-specific differences in collagen composition, Gabler *et al.* extend this evidence by showing that collagen VI is recurrently prominent across functionally distinct mucus-derived materials in *C. nemoralis*.

More strikingly, these materials draw on a substantially shared set of molecular building blocks. Their functional differences therefore do not arise from constituent identity alone, but from coordinated changes in material state along three coupled axes. First, differences in macromolecular abundance influence material mechanics. Defensive mucus contains substantially more protein and exhibits a much stronger nonlinear shear response than lubricating or foamy mucus. Second, calcium exists in different physicochemical states. The study identified amorphous calcium carbonate (ACC) in secretory tissues and mucus-derived materials, together with crystalline mineral phases in dried protective structures. In wet mucus, ACC may provide Ca^{2+} ions that mediate interactions among macromolecules. During drying, transformations in calcium carbonate state may contribute to stabilization of adhesive mucus and the epiphragm. Third, spatial processing organizes related constituents into distinct architectures. Secretions may be spread into thin lubricating films, concentrated into cohesive mucus, organized at air-liquid interfaces to stabilize foam, deposited in layers, or incorporated into mineralized structures. Secretion, foaming, deposition, dehydration, and mineralization thus transform a shared molecular toolkit into materials with distinct architectures and functions.

Together, these findings reveal snail mucus not as a collection of independent secretions, but as a versatile material platform whose functional diversity emerges from coordinated tuning of macromolecular abundance, calcium availability and state, spatial organization, and processing history (Figure 1). Importantly, material function is not determined by this programmed state alone, but emerges from its coupling with how the material is actively deployed and maintained and with the local interfacial and mechanical environment. Snail mucus therefore provides a useful model for adaptive material platforms in which a common molecular toolkit supports diverse functions through coordinated programming and deployment across changing environments.

Perspective: programming multifunctional biomaterials

The versatility of snail mucus suggests that material multifunctionality does not necessarily require a separate formulation for every task. Instead, shared components can be reorganized into multiple functional states through coordinated changes in composition, ionic environment, spatial organization, and processing. This principle complements dynamic hydrogels, ionically crosslinked materials, and other stimuli-responsive systems, in which reversible interactions or external stimuli alter network states and properties.[4] The snail system further illustrates how several control dimensions can operate together to generate distinct functions from related molecular building blocks. Translating this principle into synthetic systems could enable different material states to be generated from a common precursor. In 3D printing, [5] for example, spatially controlled processing during or after deposition could tune ionic interactions, network density, hydration, or subsequent mineralization, creating mechanically, adhesively, or protectively distinct regions from a single printable formulation.

Calcium regulation provides a particularly promising route for such state control. The relevant variables include not only total calcium content but also its local concentration, availability, and physicochemical state. In the native mucus system, these parameters vary among different materials and evolve during processes such as drying and mineralization. Building on these biological observations, future materials could exploit external stimuli to regulate them on demand. Electric fields could redistribute mobile ions, while photoresponsive chelators, localized pH changes, or electrochemical stimuli could control ion release, sequestration, and binding. [4] These approaches could allow material properties to be patterned or switched without changing the underlying formulation. The snail system also highlights the importance of processing history and timescale in materials design. On short timescales, changes in Ca^{2+} availability and ionic crosslinking could mediate reversible transitions between flow and cohesion. On longer timescales, calcium carbonate transformation or mineralization could lock a temporary soft state into a persistent rigid structure. Coupling rapid reversible switching with slower structural integration could enable materials to adapt during processing or use and subsequently stabilize when required.

Translation to synthetic materials, however, introduces important practical constraints. Ion-mediated switching is transport-dependent, so diffusion may limit switching speed and spatial resolution, while repeated operation may cause ion redistribution or loss. Increasing ionic crosslinking can improve cohesion at the expense of flowability or reversibility, while mineralization may enhance long-term stability but reduce switchability. Moreover, snails

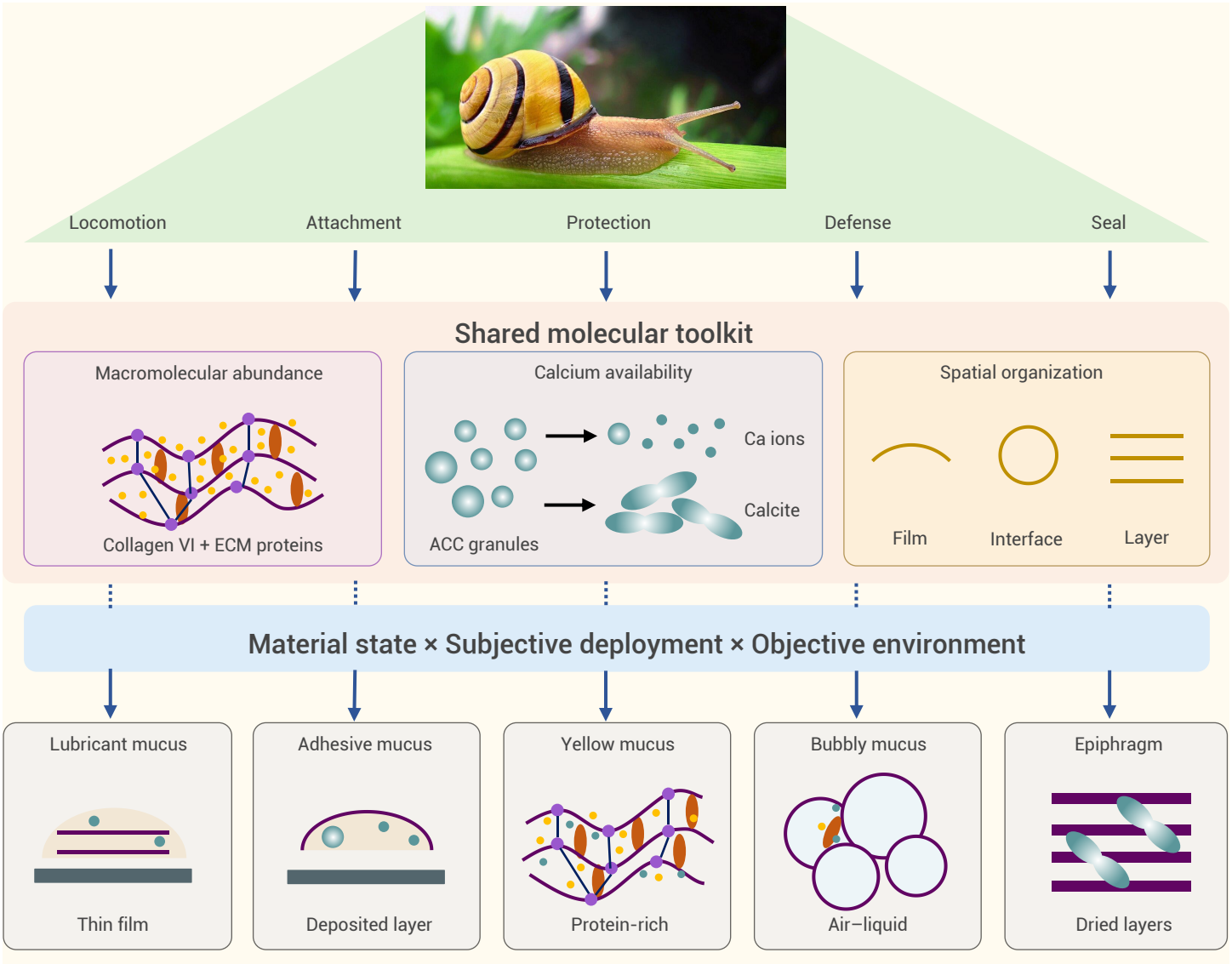


Figure 1. A shared molecular toolkit generates functionally distinct snail mucus materials through coordinated state tuning The brown-lipped snail *Cepaea nemoralis* produces five mucus-derived materials with distinct physical structures and biological functions. Their functional diversification arises from coupled differences in macromolecular abundance, calcium state, and spatial processing, together with processing history and function-specific deployment. Snail image adapted from "*Cepaea nemoralis* edit.jpg," photographed by Mad Max and edited by Papa Lima Whiskey 2, via Wikimedia Commons, under the CC BY-SA 3.0 license.

can actively regulate secretion, spreading, hydration, replenishment, and processing in response to local interfaces and mechanical conditions, whereas synthetic platforms must reproduce these functions through engineered transport and fabrication pathways and, where possible, sensing and feedback.

More broadly, natural materials show that function can emerge from coordinated changes in material state rather than from a single optimized formulation. The design challenge is therefore to program how a shared molecular toolkit transitions between functional states and responds to its environment. Snail mucus thus points toward a broader strategy for creating adaptive materials in which diverse functions arise from programmable state transitions rather than separate formulations.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used ChatGPT in order to improve grammatical accuracy. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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FUNDING AND ACKNOWLEDGMENTS

This work was supported by the JSPS Grant-in-Aid for Scientific Research (KAKENHI 26K17316). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.