Ecosystems Long-cycle Materialogy: Bioresources as the Origin of Future Life

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Modern society faces an environmental crisis driven by non-degradable components, including synthetic plastics in daily products and industrial agriculture. Beyond simple plastic replacement, this editorial introduces "Ecosystems Long-cycle Materialogy"—a new paradigm that redefines human-made materials as integral elements of natural biogeochemical cycles. Within this framework, forests and oceans are envisioned as vast hubs for ultralong material circulation. For example, wood-mimetic microbeads for cosmetics are designed with the expectation that they will eventually enter natural biogeochemical cycles in a safe and controlled manner. Therefore, rather than becoming problematic waste, these deliberately designed bio-based materials participate in an extended carbon cycle. Once entering the ocean, they biodegrade and sequester carbon in the deep seabed, potentially on the order of 500 to 1,000 years. This philosophy shifts our objective from reducing environmental burden to complementing ecosystem cycles. By acknowledging that every material serves as the starting point for the next form of life, we can align manufacturing with the Earth's long-term resilience and survival.

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The Dilemma of Modern Materials and the Paradigm of Ecosystems Long-cycle Materialogy

Modern society is built upon a heavy reliance on finite fossil resources. This systemic dependency continues to drive the twin global crises of anthropogenic climate change and pervasive plastic pollution. The alarming scale of these issues is underscored by the realization that microplastics have now infiltrated every environmental compartment on Earth, from the atmosphere to the deepest oceanic trenches (Bank *et al.* 2022). While current technological interventions, such as "biodegradable" polymers with trigger-based switches or the direct replacement of petroleum plastics with bio-based alternatives, are steps in the right direction, they often remain confined to a linear and short-sighted paradigm. These efforts typically focus on minimizing "waste" or "environmental burden" within a 1-to-100-year cycle, failing to bridge the fundamental gap between industrial manufacturing and natural biogeochemical processes.

To overcome these limitations, this editorial proposes a transformative paradigm: "Ecosystems Long-cycle Materialogy", as illustrated in Fig. 1. Unlike conventional bio-based materials, which primarily aim to reduce environmental impact within short human-centered timescales, Ecosystems Long-cycle Materialogy explicitly designs materials to function as active participants in multi-century biogeochemical cycles. This

paradigm introduces a fundamental shift from "eco-friendly substitutes" to materials whose lifecycle is scientifically aligned with ecosystem processes from the outset. In this view, we move beyond the conventional taboo that "human-made objects must never be released into nature." Instead, we design materials—derived from carbon-sequestering bioresources—with the expectation that they will ultimately be integrated into natural cycles.

Within this framework, forests are envisioned as vast terrestrial and atmospheric "hubs" for material circulation. Materials used in our daily lives or agriculture are designed to follow a deliberate decomposition route: from soil microbial degradation to transport *via* rivers into the vast ocean. Upon reaching the marine environment, these wood-derived components are gradually decomposed by deep-sea microorganisms and sequestered in the seabed. This process establishes an ultralong carbon cycle, potentially fixing carbon for 500 to 1,000 years, far exceeding the temporal scope of current recycling models. Crucially, the objective of Ecosystems Long-cycle Materialogy is not just to prevent "negative impact" but to ensure that materials are designed to be utilized by natural ecosystems. While conventional materials science focuses on the pursuit of material functionality, Ecosystems Long-cycle Materialogy decisively redefines materials and products as integral elements of natural biogeochemical cycles. In this grand vision, the materials we "discard" are no longer problematic waste; they become the essential starting point for the next form of life, harmonizing human productivity with the Earth's long-term resilience.

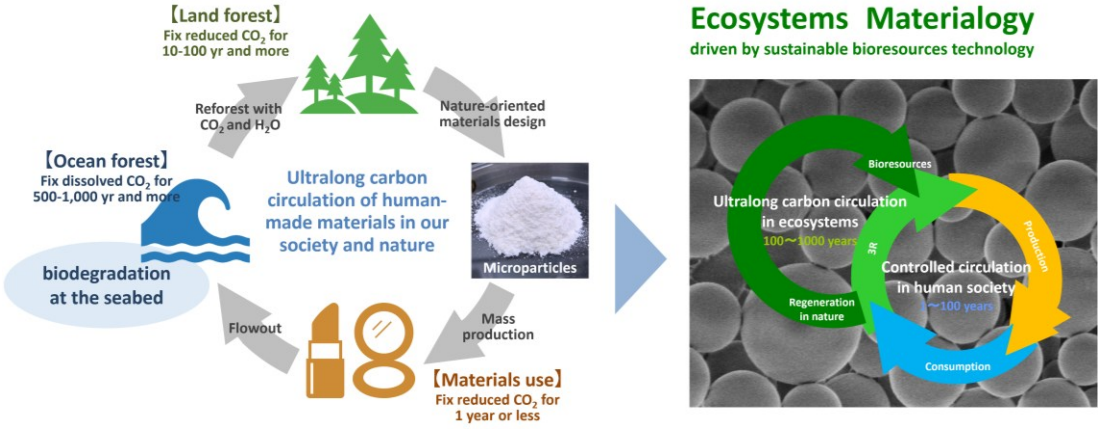


Fig. 1. Integrated schematic overview of Ecosystems Long-cycle Materialogy for wood-derived materials and ultralong carbon circulation. The left panel illustrates the ultralong material circulation mediated by wood-mimetic cosmetic microparticles, while the right panel depicts the paradigm shift toward designing materials and products that operate within natural biogeochemical cycles.

Wood-derived Materials and Wood-Mimetic Cosmetic Microparticles

The transition toward Ecosystems Long-cycle Materialogy is rooted in the inherent biological properties of wood components. While the microbial degradation of cellulose and hemicellulose in marine environments is widely recognized as a well-established natural process, crucially, the recent identification of marine lignin-degrading bacteria (Li *et al.* 2025) confirms that these bioresources as a whole can actively participate in oceanic carbon cycles. Extensive research has explored nanocellulose-based films and molded bodies for diverse applications, such as green electronics, high-performance fibers, and sustainable food packaging. Furthermore, recent reviews highlight the potential of wood-

based formulations to serve as advanced functional materials that align with a circular bioeconomy (Ali and Russell 2025). Collectively, these innovations represent a broader scientific shift toward materials that are not merely "eco-friendly" but are intentionally designed to function as active participants within natural processes.

To address the pervasive challenge of non-degradable microplastics, our research has focused on the scientific reconstruction of wood's hierarchical architecture into wood-mimetic microparticles for cosmetic applications (Tanaka *et al.* 2024). These particles are synthesized through a green, aqueous process at room temperature using an enzyme-mediated Pickering emulsion templating strategy, as shown in Fig. 2. In this system, wood-derived cellulose nanofibers (CNFs) serve as solid stabilizers (nano-surfactants) to emulsify isoeugenol—a lignin precursor analogue—as the oil phase. Subsequent dehydrogenative polymerization initiated by horseradish peroxidase yields spherical microparticles composed entirely of woody components.

By ensuring marine biodegradability through this precise structural mimicry, these microspheres are intentionally designed for safe environmental release. Unlike traditional materials designed for isolation from nature, these wood-derived microparticles follow a deliberate route from societal use to the marine environment. Upon reaching the ocean, they contribute to an ultralong carbon cycle, potentially sequestering carbon in the deep seabed for centuries. This process demonstrates how high-precision material design can align daily-use products with Earth's long-term carbon sequestration processes.

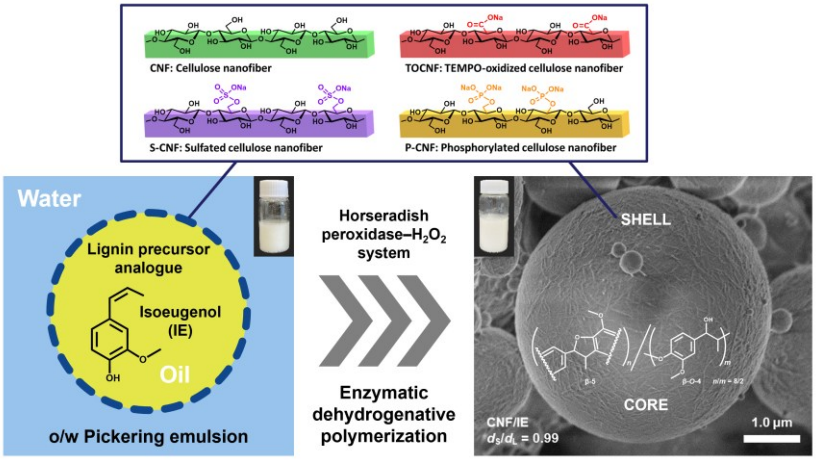


Fig. 2. Schematic illustration of an enzyme-mediated Pickering emulsion templating strategy to fabricate spherical microparticles comprising cellulose nanofibers (CNFs) and artificial lignin for green cosmetics. Reprinted under the terms of the CC-BY 4.0 license (Tanaka *et al.* 2024), Copyright 2024, the Royal Society of Chemistry.

Redefining Agriculture as a Circular Hub for Ecosystems Materialogy

The paradigm of Ecosystems Long-cycle Materialogy finds its most critical and transformative application in agriculture. Despite its "green" image, modern industrial agriculture has raised concerns about environmental degradation, in part because the expanded use of petroleum-based mulch films and chemical delivery systems is believed to contribute to microplastic pollution. This "agricultural paradox" is further exacerbated

by significant greenhouse gas emissions, which account for approximately 30% of global totals across the agriculture and food sector.

To address these systemic issues, we must move beyond the simple substitution of materials and instead redefine agriculture as a hub for sustainable material circulation. Within the framework of Ecosystems Long-cycle Materiology, we propose a new route for material flow: wood-derived materials—such as sprayable black mulch or functional coatings—are designed not only to regulate soil temperature and suppress weeds but also to serve as catalysts for the global carbon cycle. Unlike conventional plastics that fragment into persistent pollutants, these bio-based materials are engineered with the expectation that they will eventually enter natural biogeochemical cycles in a safe and controlled manner. After fulfilling their function on farmland, they decompose within the soil or are transported by rivers to the ocean, where deep-sea microorganisms gradually sequester their carbon into the seabed. This process establishes a synergy in which agricultural productivity coexists with ultralong-term carbon storage on the order of 500 to 1,000 years. By aligning food production with oceanic biogeochemical cycles, agriculture ceases to be an "environmental burden" and instead becomes a vital engine for restoring Earth's balance.

Future Opportunities: A Gift for the Next Form of Life

The transition to Ecosystems Long-cycle Materiology offers vast opportunities for interdisciplinary innovation, bridging bioresource materials science with biogeochemistry, as illustrated in Fig. 1. The goal is no longer simply to develop "environmentally friendly" materials but to scientifically embed the principles of natural circulation into the foundation of future society. This shift moves us from a linear "take-make-waste" economy toward a genuinely circular system. In this perspective, the materials we create are not merely human-centric artifacts; they become components of a continuous flow of energy and matter across ecosystems. Every product derived from forests, used in households, or applied in agriculture ultimately contributes to the next stage of ecological succession. By recognizing that each material serves as the starting point for the next ecosystem cycle, we can advance the ambitious Sustainable Development Goals (SDGs) #2, #12, #13, #14, and #15, thereby supporting the long-term resilience and stability of our planet.

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