The Missing Piece in Cellulose Foam: Process Engineering, Not More Chemistry

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Expanded polystyrene (EPS) and polyethylene (PE) foams remain the dominant cushioning materials in protective packaging because of their low density, resilience, and impact-attenuation performance, but their environmental persistence and poor post-consumer recovery are driving increasingly strict packaging regulations. Cellulose-based alternatives — molded pulp, foam-formed and nanofibrillated cellulose (CNF) foams, and mycelium-bound composites — have each achieved partial success, yet none has simultaneously matched EPS/PE-level cushioning performance, cost, and manufacturing scale. This editorial argues that closing this gap depends less on specialty furnish chemistry — surfactants, cross-linkers, or biological cultivation steps — than on process-engineering advances that convert ordinary pulp furnish, using confined-mold vapor expansion and conventional natural binders, into a porous, EPS-like cellular structure, and calls for coordinated industrial investment in that direction.

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The Environmental Cost of Petroleum-Based Foam Packaging

Protective cushioning packaging relies heavily on petroleum-derived EPS and PE foam, which together account for a substantial share of applications requiring low density, resilience, and impact attenuation in a packaging foam market valued in the tens of billions of dollars (Global Market Insights 2025). Both materials share the same underlying problem: they are made from non-renewable feedstocks, resist biodegradation, and — once discarded — are difficult and costly to recycle due to technical and economic constraints (Su *et al.* 2018). Regulatory pressure is intensifying in response — most notably Regulation (EU) 2025/40 on Packaging and Packaging Waste, which restricts specified single-use plastic packaging and applies from 12 August 2026 (European Parliament and Council of the European Union 2025) — but policy has outpaced the availability of an adequate, fully renewable substitute.

Current Cellulose-Based Alternatives and Their Limits

Four classes of cellulose-based cushioning material are already in commercial or pre-commercial use, each with characteristic limits.

Molded pulp

Molded pulp is the most mature alternative, but its manufacturing process is fundamentally a hot-press forming and drying operation rather than a low-density foaming process; increasing wall thickness intensifies dewatering, drying, and dimensional-control

challenges (Debnath *et al.* 2022; Danielewicz 2025), and its cushioning performance remains below that of expanded-foam plastics in the most demanding applications.

Foam-formed and CNF foams

Foam forming entrains air into a fiber suspension that is dewatered and dried to lock in a cellular structure (Nechita and Năstac 2022). The resulting properties depend strongly on density, furnish, fibrillation, and additive loading (Pääkkönen *et al.* 2024), and most routes still rely on energy-intensive oven or freeze drying. The Aalto University spin-off Woamy is pursuing a continuous, room-temperature-dried process (Pulkkis 2024), but its commercial scale and cost position relative to EPS remain unverified.

Mycelium-bound composites

Fungal mycelium cultivated on agricultural residues can improve on EPS's environmental profile at low density, but Yuan *et al.* (2026) report that it can require 2.5 to 7.5 times the mass of EPS for an equivalent protective volume, and that long cultivation cycles and a lack of standardized are impeding further limit scale-up.

Commercial hybrid paper-based products

A fourth category comprises commercial or pre-commercial paper-based foams and 3D-formed products: Stora Enso's Papira® remains at pilot scale and is not yet available for general commercial sale (Stora Enso 2021); Nouryon's Expancel® BIO microspheres are a partially bio-based filler and blowing agent, but the resulting foamed plastics are still predominantly petroleum-based (Nouryon 2024); and Billerud's FibreForm® is manufactured at scale, but its forming process (cold-forming and thermoforming) limits achievable geometry for cushioning (Billerud 2023). Together these examples show that fiber-based cushioning is progressing beyond the laboratory, even as a gap remains between material demonstration, customer validation, and high-volume production.

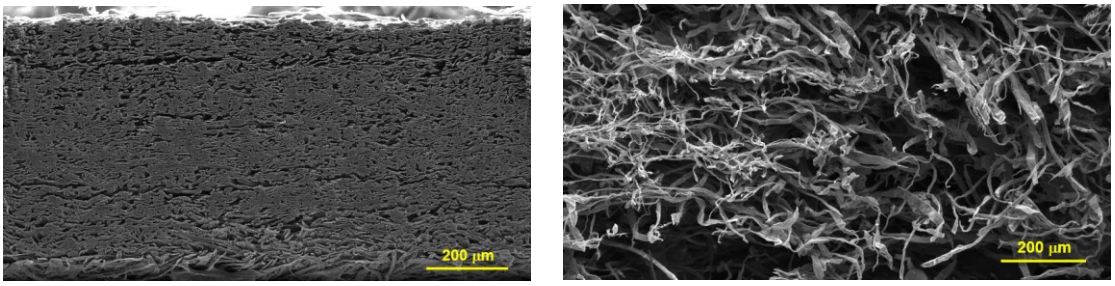
None of these approaches have yet combined EPS-level cushioning performance, cost, and manufacturing throughput in a single, fully cellulose-based product — which is why petroleum-derived foams still dominate the most demanding cushioning applications.

A Process-Engineering Path Forward

A common pattern runs through these alternatives: eco-friendly performance is generally purchased with a specialty additive, a slow process, or a compromise in geometry (Su *et al.* 2018; Nechita and Năstac 2022). We propose a different route: rather than adding surfactants, cross-linkers, or biological cultivation steps to a conventional pulp furnish, three-dimensional expansion can be driven directly from the water already present in a vacuum-formed wet fiber mat, using confined-mold heating to generate internal vapor pressure, with a conventional natural binder locking the expanded structure in place once it forms. Because this approach uses ordinary pulp furnish and requires no exotic feedstock or biological step, its raw-material economics and cycle time have the potential to track conventional molded-pulp operations far more closely than the specialty-chemical or biologically cultivated alternatives described above.

The structural effect is visible at the fiber scale: a conventional compacted pulp mold retains a dense, low-porosity network (Fig. 1a), whereas confined-mold vapor expansion of the same furnish develops an open, porous fiber network more structurally comparable to EPS and PE foam (Fig. 1b). This distinction illustrates the central argument of this editorial: a cellulose-based material can rival plastic foam in cushioning

performance only if it achieves this kind of porous, air-filled architecture — not the dense, compacted structure typical of conventional pulp molding. Translating this structural principle into a commercially viable product still requires standardized comparative testing against EPS and PE foam under matched conditions, together with further work on long-term dimensional stability, continuous-process throughput, and furnish optimization.



(a) (b)

Fig. 1. (a) Compacted, low-porosity cellulose-fiber network typical of conventional pulp molding (scale bar = 200 µm), and (b) Cellulose-fiber network after confined-mold vapor expansion, showing a porous fiber network (scale bar = 200 µm)

Conclusion: A Call for Industrial-Scale Investment

None of the cellulose-based cushioning technologies reviewed here will displace the existing volume of EPS and PE foam through laboratory refinement alone. Doing so will require sustained investment in pilot and demonstration-scale production lines, closer collaboration across the packaging value chain, and policy that rewards verified functional performance rather than partially bio-based substitutes. The pulp and paper research community already possesses the furnish science, equipment base, and industrial relationships to move a process-based cellulose foaming technology from pilot line to commercial plant faster than an entirely new materials platform could be scaled (Debnath *et al.* 2022; Danielewicz 2025). With packaging regulations tightening (European Parliament and Council of the European Union 2025) and brand owners seeking post-EPS solutions, the window for our community to shape this transition is now open.

References Cited

Billerud, A. B. (2023). "Billerud expands the FibreForm® product family for shaped paper components," Billerud AB, Stockholm, Sweden.

Danielewicz, D. (2025). "Manufacturing of form-molded pulp products (FMPPs) in the papermaking industry – A review," *BioResources* 20(2), 5114-5156. https://doi.org/10.15376/biores.20.2.5114-5156

Debnath, M., Sarder, R., Pal, L., and Hubbe, M. A. (2022). "Molded pulp products for sustainable packaging: Production rate challenges and product opportunities," *BioResources* 17(2), 3810-3870. https://doi.org/10.15376/biores.17.2.3810-3870

European Parliament and Council of the European Union (2025). "Regulation (EU) 2025/40 on Packaging and Packaging Waste," Official Journal of the European Union L of 11 February 2025; application from 12 August 2026, Brussels, Belgium.

Global Market Insights (2025). "Expanded polystyrene for packaging market — Market size, share and trends," Global Market Insights, Selbyville, DE, USA.

Nechita, P., and Năstac, S. M. (2022). "Overview on foam forming cellulose materials for cushioning packaging applications," *Polymers* 14(10), article 1963. https://doi.org/10.3390/polym14101963

Nouryon (2024). "Nouryon introduces Expancel® BIO microspheres, the first generation of partially bio-based lightweight filler and blowing agent," Nouryon, Amsterdam, Netherlands.

Pääkkönen, E., Ketoja, J. A., and Paltakari, J. (2024). "Energy absorption and resilience in quasi-static loading of foam-formed cellulose fibre materials," *Cellulose* 31(11), 7137-7152. https://doi.org/10.1007/s10570-024-06030-4

Pulkkis, N. (2024). "Cellulose-based plastic-free foams," Bioeconomy.fi, Helsinki, Finland.

Stora Enso (2021). "Stora Enso brands its recyclable cellulose packaging foam as Papira®," Stora Enso Oyj, Helsinki, Finland.

Su, Y., Yang, B., Liu, J., Sun, B., Cao, C., Zou, X., Lutes, R., and He, Z. (2018). "Prospects for replacement of some plastics in packaging with lignocellulose materials: A brief review," *BioResources* 13(2), 4550-4576. https://doi.org/10.15376/biores.13.2.4550-4576

Yuan, S., Chen, C., and Xu, W. (2026). "Mycelium-based biocomposites as sustainable polymer alternatives: Engineering strategies, structure–property relationships and circular packaging applications," *Polymers* 18(16), article 1946. https://doi.org/10.3390/polym18161946