WHITE PAPER

The Road to Sustainable Packaging Cushioning - Foamed Cellulose Fibre

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Plastics consume 70% of primary petrochemicals and 90% of chemicals of high concern[1] ; meanwhile, only ca. 9% of the produced end products are being recycled. The bulk of the plastic waste is currently landfilled or leaked into the environment[2] with packaging products representing approximately 35% of the plastic waste. As society demands an increased circularity and higher reuse/recycling rates, exciting alternatives emerge by switching to paper packaging (paperization mantra) to enable resource efficient recycling. This whitepaper reviews and analyses the state-of-the-art in cushioning packaging technologies based on key criteria to propose solutions that recognize regional differences in materials, infrastructure, and norms. We focus on an emerging category of cushioning materials, namely, cellulose-based foams, such as those being developed by Apple, and how renewable/recycled materials categories have the potential of reducing the amount of non-recyclable or non-recycled single-use packaging materials, ultimately advancing circularity. We conclude that impact in the area requires accelerated collaboration along supply chains and across sectors to speed up development and adoption of a foamed cellulose cushioning that meet environmental, economic and sustainability goals.

Introduction

Globally, the world produces 400 million tonnes of plastic waste, annually[3]. The 2022 Greenpeace report "Circular Claims Fall Flat Again"[4] notes that the US alone generated 51 million tons of discarded plastic in 2021, of which almost 95% ended up in landfills, oceans, or scattered in the open environment. Packaging represents approximately 35% of this plastic waste[5] and the continued implementation of direct-to-consumer shipments is further increasing plastic packaging usage, especially protective/cushioning packaging[6]. This has resulted in increased generation of post-consumer packaging waste[7] and associated transportation emissions. Rising concerns of plastic leakage into the environment and the complex and divergent government regulations are making packaging decisions even more challenging[8].

The impact of feedstock, water, and energy usage during manufacturing, as well as local and regional reuse and recycling considerations are all key to understanding the full life cycle impact of a packaging solution. Moreover, packaging that combines multiple material types reduces the sustainability because typical municipal recycling systems cannot separate the materials into viable recycling streams. In cases where using a single material is not possible, combining as few and as similar material types as possible is recommended, for instance by incorporating different plant fiber sources (softwood, hardwood and non-wood pulps) into a paperboard.

A clear first solution path towards sustainability is reducing packaging and considering reuse where feasible. In applications where such considerations are already in place (or where they cannot be pursued), single-use packaging needs to utilize sustainable resources efficiently. Simultaneously, there is a demand for materials that are compostable or can be recycled as many times as possible. It is in this context and many others that the adoption of paper recycling is increasing. As reported by the World Economic Forum[3], the paper material stream is one of the most-often recycled. It accounted for half of the materials collected for recycling by weight in 2021, achieving a 68% recycling rate, with corrugated board recycling rates as high as 91.4%. Paper recycling is readily available in many parts of the world and leakage impacts are generally considered minimal because of the natural biocomposting properties of paper (if no contaminants / harmful additives are used).

Within the overall umbrella of packaging, cushioning components are key to preventing damage to fragile products by reducing the transfer of energy to the product during the journey from factory to consumer. This contrasts with containment components, whose purpose is to prevent movement of a product within packaging, either within a single package design, or in the case of the ever more common e-commerce world, between multiple primary packages within a secondary external package.

Cushioning components today are broadly produced from fossil-based polymers due to their exceptional performance, ease of incorporation, wide availability, and cost effectiveness. Market Research Future forecasted a 17.3 billion USD global foam packaging market for 2023[9]. Given that these are predominately polyolefin or polyurethane foams, a transition to sustainably managed pulp-based foams sourced from responsibly managed sources presents an opportunity to achieve better closed loop outcomes at end-of-life [10].

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Table 1. Criteria for ideal package cushioning material

Technical		Manufacturing		Environmental		Marketing	
A	Large Elastic Range	E	Easy to Incorporate into Design	I	Compatible with Recycling	M	Vehicle for Brand Image
B	Low Density	F	Low Cost	J	Renewable Feedstock	N	Conveys Product Information
C	Multiple Drop Resiliency	G	Responsible + Easily Integrated Supply Chain	K	High Quality + High Yield Recycling Output	O	Intuitively Expresses Environmental Benefits
D	Stable in High Humidity	H	Multiple Form Factors	L	Recycled Content	P	Fulfills Multiple Design Needs

Challenges with current cushioning packaging

Cushioning packaging materials required for delivery of fragile products such as electronics and appliances are surprisingly complex, considering access to raw materials, regulation, manufacturability, performance, marketing, and environmental factors. For example, cushioning packaging need to be resilient, withstand multiple drops and prolonged vibration, and be resistant to creep under applied force and varying relative humidity and temperature. They also need to be lightweight and absorb energy efficiently to provide the required protection in a volume as small as possible to reduce transportation costs/footprint. Equally important are the material and production costs of the packaging, which must be low for widespread adoption. The latter is often a limiting factor in the choice of a commercially viable material, which should also be a vehicle for brand imaging. The ideal packaging criteria and descriptions in Table 1 further highlight the complexity of cushioning packaging solutions. Furthermore, ideal packaging alternatives should consider low carbon intensity, avoid toxic by-products, catalysts and raw materials in production or recycling, and degrade at the end of life into non-toxic organic compounds thereby satisfying multiple environmental targets. Quantifying these effects is complex and outside of the scope of this paper.

Fossil-based plastic cushions

The majority of today's cushioning solutions are made from fossil-based plastics. These materials range from loose fill expanded polystyrene (EPS) foam pieces/peanuts, to inflated products like bubble wrap and void fill air cushions that greatly reduce mass and are typically a mono-material. Retention packs, which combine a stretchable film (to enable one package to provide shock absorption for a variety of product sizes) with corrugate, offer weight advantages but at the cost of cushioning only in certain orientations and presenting large volume, commingled materials, and incompatibility with large or heavy items. The most ubiquitous cushioning materials are plastic-based foams, commonly made from expanded polystyrene (EPS), polyethylene (EPE), or polyurethane (EPU), as moulded structures or assemblies of cut and glued slabs (Figure 1). These foams are common due to their exceptional cushioning performance, satisfying a vast array of performance metrics, and multitude of form factors at very low material cost. The latter is so low that packaging is frequently under-optimized for performance or size, leading to over-packaging and waste.

Figure 1. Conventional cushioning solutions a) retention pack, b) EPS c) EPU and EPE.

Recycling plastic packaging is often economically and practically unfeasible, therefore becoming a major contributor to pollution. Despite EPS being technically recyclable[11], research indicates that the recovery potential globally is low due to end-of-life waste management limitations[12]. The chemical robustness of plastics means that they persist in the environment after use, breaking down into microplastics on land and in the oceans with the added potential harm of leakage of chemicals of high concern[13]. Single-use plastics bans are coming into effect to different extent in many parts of the world and these bans also include packaging materials. In the United States, Washington State was the first to ban EPS 'packaging peanuts' and other loose fill packaging, starting June 2023[14]. Figure 2 gives a graphical snapshot of the properties outlined in Table 1 for conventional fossil based cushioning materials.

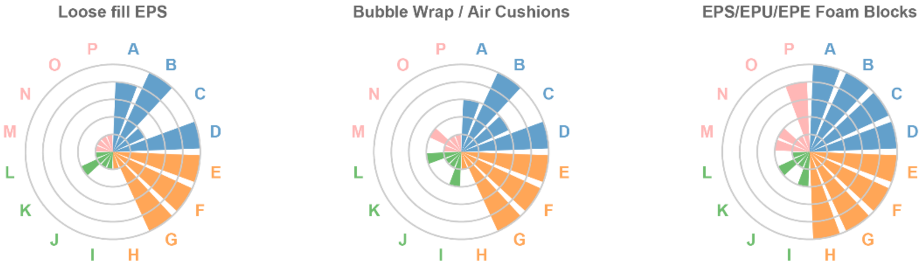
Loose fill EPS
Bubble Wrap / Air Cushions
EPS/EPU/EPE Foam Blocks

Figure 2. Summary of technical, manufacturing, environmental and marketing attributes (listed in Table 1) for conventional fossil based cushioning materials. Longer bars correlate to higher score.

Biodegradable plastics, biocomposites, bio-based materials

Material solutions utilizing bio-based and/or biodegradable plastic exist for cushioning products, including foam structures from polylactic acid (PLA), polyhydroxyalkanoates (PHA) and poly(butylene adipate-co-terephthalate) (PBAT), often in blends. While technically biodegradable through industrial composting, these foams look like other plastic foams and thus are often not composted. Even if identified and sorted correctly, facilities with the environmental conditions required to compost PLA are unavailable in many parts of the world. Biodegradable plastics are more suitable for highly controlled closed loop cycles, such as those of industrial B2B packaging or large-scale food service environments like food courts or cafeterias[15]. When leaked into the environment or not composted in the appropriate conditions, these biodegradable plastics lead to similar pollution and microplastics generation as that associated with fossil-based plastics[16].

Biocomposites are blended materials, for example, a fossil-sourced plastic resin combined with wood fibre filler, which maintains or improves properties. Whether or not CO$_2$ footprint is reduced is highly dependent on the specific applications LCA. In addition, it is typically not possible to close the material cycle if the mixed material cannot be economically separated into its base constituents. Bio-based materials, where the fossil-sourced resin is replaced with a bio-sourced one, can potentially reduce GHG emissions and enable a sustainable material cycle if managed responsibly to enable continuous production without depleting Earth's resources. However, care must be taken to ensure that any fillers and modifiers are compatible to the base so that they do not contaminate the recycling stream or require separation. Effective recycling to enable circularity is challenging, more so if specific identification and dedicated recycling loops for the specific chemistry are required.

Home compostable solutions based on biopolymers include starch-based packaging peanuts, chitin-based foams, as well as mycelium (mushroom) based materials (Figure 3) which are degradable in residential composting environments.

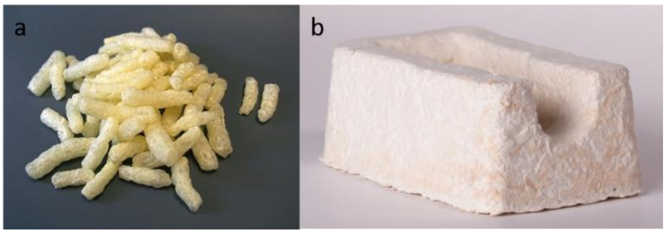

Figure 3. a) Starch-based loose fill, b) mycelium-based 3D formed cushion

Studies are needed to understand the benefits of the bio-sourced nature *vs* the single-use design principle. The engineering performance varies widely in the category, particularly with moisture resistance. Challenges exist around industrial scaling in the context of the size of the cushion market, consumer acceptance and other marketing requirements (Figure 4).

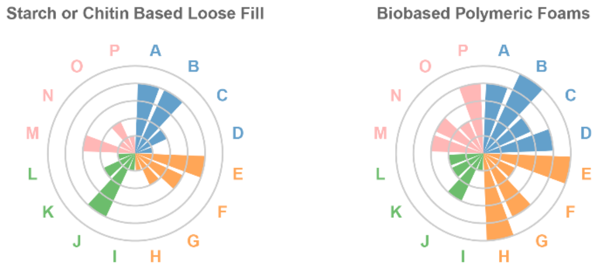

Figure 4. Summary of technical, manufacturing, environmental and marketing attributes (listed in Table 1) for bio-based cushioning materials. Longer bars correlate to higher score.

Cellulose fibre-based packaging

Paperboard, grayboard/chipboard, and corrugated board are the most common cellulose fibre-based packaging materials. The majority of these materials are already bio-based and with low environmental impact when the fibre is responsibly sourced from sustainably managed producers or recyclers. Care is taken in additive selection (e.g. adhesives, coatings, sizing agents), and addition levels to ensure performance while maintaining compatibility with paper recycling streams, further lowering environmental impact and cost.

A common limitation of cellulose fibre-based packaging is the difficulty to convert them into large components and their modest cushioning resiliency. In addition, energy absorption is limited in high-density flat forms. The design of complex 3D structures is typically necessary to achieve suitable cushioning performance, commercially available solutions include honeycomb and macro-scale corrugated cardboards. Apple has taken the path of adopting highly engineered origami corrugated springs for iMac and Studio Display packaging (Figure 5). These engineered structures are normally customized to the specific product, which is often a complicated and costly process. Noting that only a small percentage of the mass of the packaging material provides energy absorption in the cushion, industry needs to address the low material efficacy and the challenges of packaging volume (e.g., in transportation, etc.).

Moulded fibre components for packaging are produced by widely available and scaled up industrial methods that include wet processing, which can be customized to form 3D surfaces. Designs ranging from corner caps for industrial machinery to highly finished product supporting trays (e.g. Apple Watch line) are limited by the high density of the formed structure and the manufacturing limits as far as line-of-sight geometries. Raw materials used for moulded fibre products include those typical of papermaking as well as alternative sources such as bamboo, bagasse, and wheat straw, among others. Consideration of

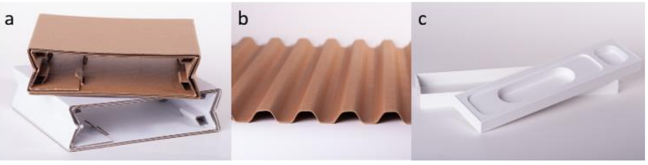

Figure 5. a) Macro-scale corrugated sheet, b) Apple's corrugated spring, and c) Apple Watch tray

Table 2. Comparison between wet-laying, typical papermaking and foam forming

Process	Fibre suspension	Water removal	Pressing process	Drying	Sheet forming
Wet laying (nonwovens)	Water (>99%), Fibre (<0.2%)	Drainage	Drums (Optional)	Heated drums	Continuous belt
Papermaking	Water (99%), Fibre (1%), Fines (10-35% of fibres)	Vacuum & Evaporation	Nip Rollers	Heated drums	Continuous belt, Calenders
Foam Forming	Air (~68%), Water (30%), Fibre (~1%), Surfactant (~1%)	Suction	N/A (Optional for some products)	Air drying, MW, RF	Moulds or continuous belt

alternative fibre sources should factor a balance between the potential benefits of upcycling, material properties and compatibility with existing material recycling streams.

Water and energy intensity need to be managed, given the wet-forming and subsequent drying steps required for moulded fibre production. Hence, an emerging technology to address this issue is dry-forming which avoids the need to add and then evacuate a large volume of water thereby significantly shortening the production time and lowering energy usage. However dry-formed materials are still limited by line-of-sight geometry challenges. Further attention is required as the technology develops to understand the environmental impacts and how it can be used in cushioning applications. When designing cellulose-fibre based packaging, one should consider the balance between mechanical strength and resilience, density, and recyclability. Moulded pulp components are usually high density, implying a higher total shipment weight. Moulded pulp products have lower shock absorption and endurance (to cyclic impacts) compared to incumbent plastic-based foams. Though, the cushioning demands of many durable and lightweight products, including Apple's, are suitably met by moulded pulp. More critical is the sensitivity to water and humidity, which in the case of moulded pulps can be addressed by additives, provided they are properly selected and sourced. Finally, design, engineering costs and assembly add to the costs of high-performance fibre-based cushioning products compared with thermoplastic counterparts (Figure 6).

Foamed cellulose fibre packaging materials

Foam forming

The challenge in the production of solid foams (foam forming), in contrast to typical paper (wet laying), is the assembly of fibres with proper spatial arrangement and binding. For this purpose, the precursor liquid foams need to be dewatered and dried while avoiding the use of vacuum and pressing. Table 2 contrasts some of the many characteristics of wet and foam laying technologies, from the point of view of processing. In foam forming, air is introduced by mechanical agitation or by air injection, creating bubbles that suspend the fibres. Foam forming is known to enable excellent dispersion and even distribution of fibres in the final product. It is differentiated from wet laying in a few critical ways: Foam forming (a) substantially reduces the volume of water used in the forming process (up to 70% of water is replaced by air), (b) therefore requires less energy for water removal, (c) leads to better fibre formation (spatial fibre distribution) in the final, solid structure, (d) accommodates different fibre types in single or multicomponent systems, (e) enables controlled porosity (or density) of the final product (from paper-like materials to solid foams, depending on the method used for drying) and, (f) favors out-of-plane orientation of fibres as opposed to the typical in-plane or layered arrangement that result from wet laying. Hence, a broad range of structural, surface and mechanical characteristics are possible. Because of their low density and high strength, cellulose fibres are the preferred alternative for foam forming. Wet foams can be dried into fiber networks of uniform density, or formed into complex shapes by using moulds and specific drying conditions (Figure 7). High compression strength can be obtained from the high local (>100 kg/m^3) and low effective (<20 kg/m^3) density of the foams and further improvement in compression strength can be achieved by changing the geometry[17]. UBC research on foam-formed cellulose dates back to 2012 for applications in specialty paper[18,19], acoustics[20], filtration[21], and thermal insulation[22,23].

To our knowledge, no formal LCA assessments of fibre foam forming in packaging applications are publicly available. This is clearly an important void that requires attention. Important issues such as fibre source and how demand impacts land usage, water resources, and biodiversity need to be addressed. Furthermore, production of the foams where energy and water

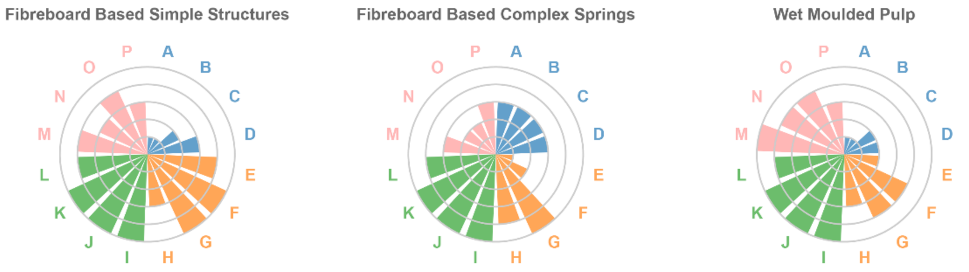
Fibreboard Based Simple Structures
Fibreboard Based Complex Springs
Wet Moulded Pulp

Figure 6. Summary of technical, manufacturing, environmental and marketing attributes (listed in Table 1) for cellulose fibre-based cushioning materials. Longer bars correlate to higher score.

usage, localized production effects, and recycling infrastructure must be accounted for, given that low density materials are environmentally and economically expensive to transport over long distances.

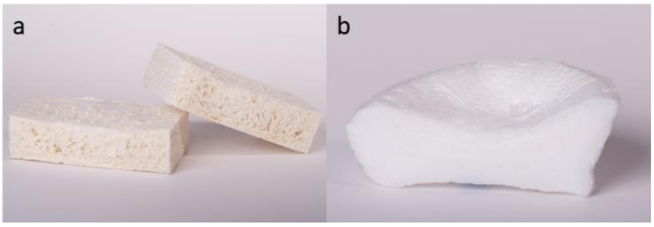

Figure 7. a) softwood pulp foam and b) 3D formed Methylcellulose foam

Apple's fibre foams

There are a few companies that have publicly adopted or consider foam forming platforms for the production of packaging materials. We here use formulations similar to Apple's under development fibre foams as a baseline to conduct an analysis of the sustainability of this emerging material category. These types of materials, (Figure 8) use responsibly sourced feedstocks (a combination of paper-grade mechanical and refined softwood pulp) to provide promising cushioning properties. The foaming approach considers commercially available production equipment and economically feasible production processes, including practical and economically viable drying strategies. The material displays desirable structural, mechanical and thermal properties while showing valuable compatibility to the existing paper recycling stream. The same applies to the additives applied for the purpose of foam generation and fiber modification, involving similar or same materials as those seen in papermaking.

The quest for sustainability often has interrelated challenges and opportunities. The benefit of a more elastic and resilient material provides benefits to all the highlighted attributes; less material needed to perform the same cushioning means less mass mobilized/transported, less energy used in production, lower logistics emissions, and lower costs. However, attention should be paid to maintain the repulpability of the material and avoid the addition of materials that contaminate or disrupt the primary hydrogen bonding chemistry that enables efficient recycling. Alternative fibre sources such as wheat straw and bamboo are recently gaining attention. Further research is required to understand the net benefit and the impact of an increasing fraction of alternative fibres in the wood pulp recycling stream.

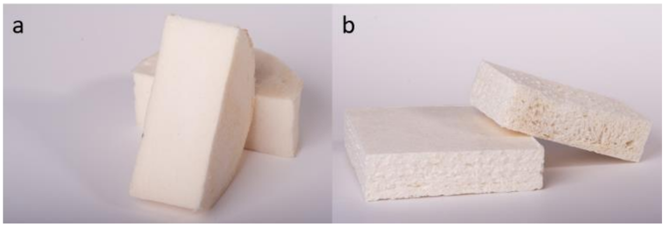

Figure 8. Apple's fibre foam a) improved foam structure formulation versus b) original formulation.

In the foam production process dewatering of the material is the most energy intensive process and therefore is the primary driver of dry foam cost. Recent improvements in foam structure through modified chemistry and foaming process result in improved performance, however at the cost of commensurate decrease in dewatering efficiency. Finding the efficiency balance between these opposing outputs requires a deep understanding of the material and application lifecycle. It can be anticipated that a range of materials, from high performance/low dewaterability to lower performance/high dewaterability, could be produced to provide the optimal material for each application. Work should also be undertaken to understand other solution spaces to the problem, including alternative drying technologies (microwave, radio frequency, impingement, etc.) as well as process or geometry improvements to aid dewatering independent of formulation. Irrespective of these improvements, dewatering energy will still be a primary emission driver; therefore, manufacturing sites should be located where clean energy is available. The impact of this on cost competitiveness *vis a vis* current polymer foams, requires further consideration once mass production parameters are known. With upcoming carbon emission pricing, the factors above could make non-fossil-sourced materials more competitive[24].

As an optimal packaging material is generally one with low density, it can be seen that localized supply chain from foaming through recycling is critical to reduce logistics emissions and costs. Contrasted to the current versions that use virgin pulp, a high recycled content is expected to increase the material's sustainability and reduce land use impact. Virgin pulp should be responsibly sourced, sustainably harvested and locally obtained with accompanying certification from the Forest Stewardship Council (FSC), the Programme for Endorsement of Forest Certification (PEFC) or similar reputable sourcing program. A full LCA will be key to the understanding of these factors and to determine the best approach to optimize outcomes.

The novel nature of the material plus the relatively similar "look and feel" to that of plastic-based foams, coupled with existing confusion amongst consumers overwhelmed with the multitude of materials in the market, means special attention will be required to communicate the differential attributes of fibre foams, their sorting and recyclability in paper recycling stream. A snapshot of the attributes of current foamed fibre materials today and their future evolution can be seen in Figure 9.

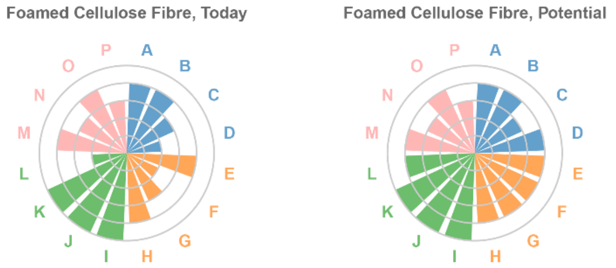

Figure 9. Summary of technical, manufacturing, environmental and marketing attributes (listed in Table 1) for current and envisioned future foamed cellulose materials. Longer bars correlate to higher score.

Vision for foam-formed cellulose based cushioning packaging

From an environmental perspective, the packaging material can be just as important and complex as the product itself. Foamed cellulose fibre packaging is a sustainable cushioning solution with an important opportunity as far as performance, versatility and cost effectiveness. They can replace fossil-based foams such as expanded polystyrene, polyethylene, and polyurethane.

The desired material performance needs to be in balance with manufacturing costs. The main points in this aspect can be divided into processing and materials. The former, principally requires attention to issues related to dewatering and drying (and drying efficiency) of bulky fibrous materials affecting throughput and cost. The latter, material, relates to chemical modification to change fibre properties to adjust mechanical performance, resiliency, and water resistance while maintaining compatibility with the recycling paper stream.

Other considerations include viable production processes and readily available components or additives, which can be quickly adopted and scaled for impact. Finding ways to reduce drying energy (e.g. less water use, more efficient technologies, better chemistry to reduce free water) as well as using commercially available drying solutions ideally powered from clean energy sources are key to both cost and environmental footprint. The overall economics of integrating the material into a packaging design need to be positive to enable widespread adoption.

Though challenges remain, the potential of foamed cellulose fibre cushioning is positive. Solutions require efficient packaging design, products designed for robustness, and regulation to incentivize a move away from non-recycled solutions. Key to success is to increase engagement and coordination of the supply chain to accelerate adoption, as well as government policies; investment and innovation will follow where demand is created. Finally, it is motivating to see driving corporate mandates, such as Apple's plastic elimination goal for packaging by 2025*, that will have an important impact in leading industry and society toward sustainability.

About the authors

The UBC BioProducts Institute (BPI), recognized as a UBC Global Research Excellence Institute, is a world leader in bio-based research, representing more than 40 researchers creating fundamental and applied knowledge from cutting-edge bio-refining technologies to novel bio-based products. Collaborating with Apple, a world innovator in personal devices and breakthrough services with driving ambition towards sustainability, BPI is championing bio-based solutions to meet our societal sustainability needs. Collectively they recognize the urgent need to address our society's packaging challenges to support the environment and to address climate change and welcome the opportunity to work with partners along the entire supply chain and across sectors to accelerate adoption of sustainable packaging solutions such as foamed cellulose fibre. Connect with us at contact.bpi@ubc.ca for further insights and to explore next steps.

Footnotes

*refers to certain consumer facing packaging; inks/coatings/adhesives and packaging of Apple refurbished products are excluded from the goal. Details can be found in Apple's 2023 Environmental Progress Report[25].

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