A strategic Analysis of Safe & Sustainable by design (SSbD) and Design2Recycle principles in smart textiles and composites

Thermoharv as an opportunity to set new industrial standards

Authors: Brecht Demedts (Centexbel) & Elbeshary Mohammed

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I. Executive Summary: Catalyzing the Green Transition

The global imperative to transition toward a circular, climate-neutral economy has spurred the development of innovative materials and products at the intersection of technology and sustainability. The Thermoharv project, a Franco-Belgian research initiative, represents a critical real-world case study for this transition. Its mission to develop smart textiles and composites for waste heat recuperation in buildings and smart garments directly aligns with the European Union's proactive policy frameworks, particularly the voluntary Safe & Sustainable by Design (SSbD) framework.[1] This report provides a strategic analysis of Thermoharv, evaluating its application of these principles from material selection to end-of-life valorization.

The central challenge faced by multi-material products like those in the Thermoharv project is a fundamental paradox: the very functional complexity that makes them innovative, such as the fusion of electronics and polymers into textiles, simultaneously undermines their compatibility with traditional recycling methods.[3] This report argues that overcoming this paradox requires a "coupled" approach, integrating next-generation circular design principles and advanced recycling technologies with new, systemic business models.[5]

The analysis concludes that Thermoharv's success is contingent upon its ability to navigate three key strategic pathways: first, by redesigning its products for easy disassembly and material separation; second, by leveraging advanced recycling technologies, such as solvent-based processes, to achieve high-purity material recovery; and third, by exploring circular business models, such as product-as-a-service, to ensure controlled end-of-life management.[6] By doing so, the Thermoharv project can serve as a blueprint for a genuinely circular and safe economy, transforming sustainability from a regulatory burden into a source of competitive advantage and innovation.

Section Title	Primary Theme	Key Takeaway
I. Executive Summary	Strategic Overview	Thermoharv is a critical test case for EU policy, facing a paradox of material complexity.
II. The Policy Landscape	Contextual Framework	The EU is shifting from reactive to proactive sustainability regulation to guide innovation.
III. The Thermoharv Project	Practical Application	Thermoharv's material and functional goals directly align with SSbD principles for energy recuperation.
IV. The Challenge of Circularity	Critical Analysis	Multi-material products face significant technical barriers and a "risk cycle" of hazardous legacy additives in recycling.

V. Towards a Circular Future	Strategic Recommendations	Success requires a coupled approach: advanced recycling, circular design, and new business models.
VI. Conclusion	Synthesis & Blueprint	Thermoharv's journey can provide a model for a new era of safe, sustainable, and economically viable innovation.

II. The Policy Landscape: A Framework for Green Innovation

2.1 The Safe & Sustainable by Design (SSbD) Framework: A Paradigm Shift

The European Commission's Safe & Sustainable by Design (SSbD) framework represents a fundamental shift in the continent's approach to environmental and chemical policy. Proposed in December 2022 as a voluntary framework, SSbD is designed to be a proactive, pre-market guide for innovation rather than a rigid, post-market regulatory tool.[1] Its primary objective is to accelerate the transition to safer and more sustainable chemicals, materials, and products by providing clear guidance for R&D, policy, and financial support.[1] Unlike regulations such as REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals), which often restrict or ban substances after their widespread use, SSbD seeks to integrate safety and sustainability considerations into the earliest design stages of a product's life cycle.[1]

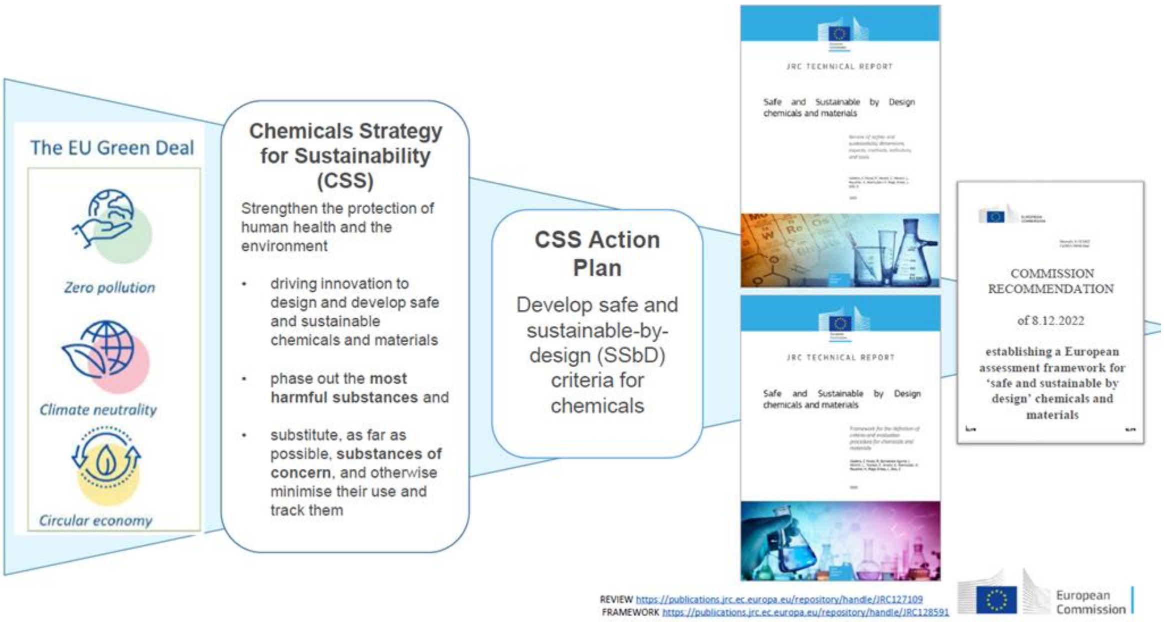

Figure 9. Core principles for SSbD framework

This pre-emptive approach aims to avoid the significant economic and technical barriers that frontrunners in sustainable innovation have historically encountered.[1] The framework (Figure 2) provides new, explicit definitions for its core tenets: "safe" is defined as the absence of unacceptable risk to humans and the environment, preferably achieved by avoiding intrinsically hazardous materials, while "sustainable" refers to a material's ability to deliver its function without exceeding environmental and ecological boundaries over its entire life cycle, while also providing socio-economic benefits.[1] The iterative nature of the framework, which is currently undergoing a testing and revision phase with feedback from over 80 case studies, indicates that the Commission intends it to be a dynamic and practical tool for industry and academia.[2] By aligning with SSbD, companies gain "regulatory preparedness" and "future-proofing," effectively transforming sustainability from a potential compliance cost into a strategic competitive advantage.[10] The Thermoharv project's foundational commitment to an "eco-responsible approach" to material selection positions it as an invaluable pilot for this evolving policy, providing the kind of practical feedback that will shape the framework's ongoing development.[12]

2.2 The Circular Economy and Design2Recycle: Beyond the Linear Model

The concept of a circular economy provides the economic and systemic foundation for the SSbD framework. It stands in stark contrast to the traditional, linear "take-make-dispose" model, which relies on the continuous extraction of finite resources.[13] The circular economy is a systemic approach based on three core principles, all of which are driven by design: first, eliminate waste and pollution; second, circulate products and materials at their highest value; and third, regenerate nature.[14] The principles are underpinned by a transition to renewable energy and materials, creating a resilient system that decouples economic activity from the consumption of finite resources.[14]

Within this framework, "Design2Recycle" is not a simple end-of-pipe solution but a foundational philosophy. It demands a complete rethinking of the manufacturing process from the very outset, where designers have the power to influence the entire product lifecycle.[13] This involves designing products for durability, reparability, and modularity, and considering the end-of-life journey of a product from its inception.[13] The SSbD principle of "Design for end of life" directly mandates this approach for innovators and researchers.[11] The adoption of this philosophy is driven by more than just environmental responsibility. It offers significant economic benefits, including reduced resource depletion, cost savings through material efficiency, and the creation of new revenue streams and green jobs.[13] The Thermoharv project, by its very nature, must embody this philosophy to succeed, as its complex, multi-layered products would otherwise become difficult-to-recycle waste streams at the end of their useful life.[4]

2.3 The EU's Textile and Composites Strategies: A Sector-Specific Mandate

The Thermoharv project operates at the confluence of two high-priority sectors for the European Union's green transition: textiles and composites. The EU Strategy for Sustainable and Circular Textiles sets an ambitious 2030 vision where all textile products placed on the market are durable, repairable, recyclable, largely made of recycled fibers, and free of hazardous substances.[17] This strategy is supported by key legislative tools like the Ecodesign for Sustainable Products Regulation (ESPR) and the proposed introduction of mandatory and harmonized Extended Producer Responsibility (EPR) rules for textiles.[17] These policies aim to reverse overproduction and overconsumption and incentivize producers to design more sustainable products.[17]

Similarly, for the composites industry, a strategic roadmap exists to enhance the sustainability of products throughout their lifecycle.[19] Mid-term goals (2026–2028) include the implementation of design practices that prioritize modularity, easy disassembly, and material separation.[19] This includes using lowdensity biobased materials that are easier to remove and making each composite product dismantlable by design.[19] The dual-sector relevance of Thermoharv's products—smart textiles and flexible composites—places the project at the heart of these evolving regulations. The project's success, therefore, is not just a matter of technical performance but also a function of its ability to proactively meet and help shape these specific sectoral mandates, a process that is fully aligned with the SSbD framework.

III. The Thermoharv Project: A Nexus of Policy and Practice

3.1 Project Overview and Objectives

The Thermoharv project (Fis a collaborative research initiative involving a consortium of French and Belgian partners, including the Université de Mons (coordinator), IMT Nord Europe, Centexbel, and the Université de Lille.[12] Funded by Interreg V FWVL, the project runs from October 2024 to September 2028 and is dedicated to developing innovative devices for thermal energy harvesting.[20] The core mission is to create flexible polymer-based materials capable of recovering waste heat from buildings—such as the heat from hot water pipes or solar-exposed glass surfaces—and converting it into usable electrical power.[20] This energy is intended to power low-power electronic devices and sensors, such as home automation systems, smoke detectors, or motion sensors.[20]

Figure 10.Thermoharv project overview

The project's scope extends beyond simple technology development. The consortium's aim is to "optimize the entire value chain of the devices, from the synthesis of materials to their end-of-life valorization".[20] This holistic approach signifies a direct commitment to the principles of a circular economy and the SSbD framework. By focusing on recovering energy that would otherwise be lost, Thermoharv addresses a key sustainability challenge, directly contributing to the SSbD principle of minimizing environmental impact from a life cycle perspective.[11] The project's explicit focus on an "eco-responsible approach" to material selection underscores its role as a living application of these policies.[12]

3.2 Materials and Functionality: A Technical Deep Dive

The technical foundation of Thermoharv's devices lies in the physical principles of thermoelectricity and pyroelectricity.[12] Thermoelectricity converts a temperature difference between two surfaces into an electrical current, while pyroelectricity converts thermal fluctuations into an electric charge (Figure 4).[12] The project's core materials are flexible polymers and thermoplastics, which are integrated with printed electronics and conductive prints.[12] Centexbel, a key partner, has expertise in incorporating these printed electronics into a variety of materials, including coatings, textile materials, and composites, often using a transfer process onto a TPU-coated substrate.[12] This lamination technique is used to create prototypes, such as sleeves for hot water pipes, which are then tested in real-world conditions.[20]

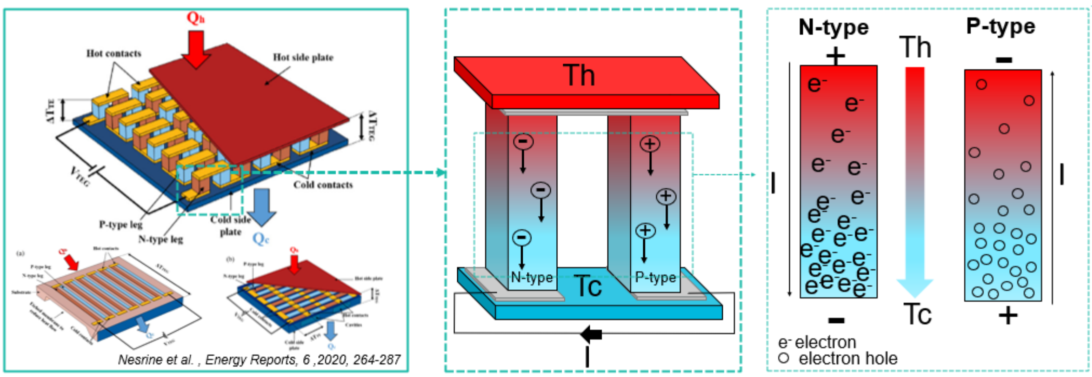

Figure 11. Principle of Themo-Electric Generator (TEG)

The Thermoharv project's materials and functionality demonstrate a deliberate alignment with the "sustainable" pillar of the SSbD framework. By developing lightweight, flexible smart textiles and composites, the project delivers a valuable function—energy recuperation—while using fewer resources compared to traditional, rigid electronic systems.[21] The development of these materials contributes to the overall reduction in energy consumption in buildings, as the recovered thermal energy reduces the overall energy footprint of the structure.[12] This focus on reducing energy and resource use aligns with the SSbD principles of "Design for energy efficiency" and "Material efficiency".[11]

IV. The Challenge of Circularity: Analyzing End-of-Life Barriers

4.1 The Recycling Dilemma of Multi-Material Products

While Thermoharv's materials are designed for high performance and functionality, their multi-material nature presents a significant end-of-life challenge. The project's smart textiles and composites, like multi-layer packaging, are composed of different materials (e.g., polymers, electronics, adhesives) that are fused together.[3] This heterogeneity makes separation and recycling extremely difficult. Less than 10% of laminated films are recycled globally, with most ending up in landfills or incinerators.[4]

The primary barriers to recycling are twofold. First, there is a fundamental chemical incompatibility between different materials. For example, common plastics like polyethylene (PE) and polypropylene (PP) have different melting points (approximately 115 °C and 160 °C, respectively), making it challenging to process them together in the same recycling stream.[4] Second, the complex, tightly bonded structures of these materials are resistant to conventional mechanical separation methods, such as float-sink or air classification, which are often inadequate for thin, fused layers.[4] This creates a fundamental paradox: the very properties that make these materials innovative and durable also render them incompatible with existing recycling infrastructure. Traditional textile recycling methods, which primarily handle pre- and post-consumer materials for re-use or downcycling into wiping cloths or insulation, are not equipped to handle the complex integration of electronics and conductive polymers found in Thermoharv's products.[23] The project's success is therefore contingent on its ability to resolve this core dilemma of multi-material complexity.

4.2 The "Risk Cycle" of Legacy Additives: A Threat to Safety and Circularity

The second major end-of-life challenge is the presence of hazardous chemicals, or "legacy additives," in recycled materials. These substances, such as lead, cadmium, and specific *ortho*-phthalates like bis(2-ethylhexyl) phthalate (DEHP), were historically used in plastics but are now regulated.[24] A study on new polyvinyl chloride (PVC) flooring found that 16% of samples contained these regulated hazardous chemicals above 0.1 wt %, likely due to the use of recycled PVC.[25] This demonstrates a "risk cycle" where hazardous substances from old products are reintroduced into the market through uncontrolled recycling practices, thereby delaying their phase-out and contaminating new materials.[24]

This perpetuation of hazardous chemicals in the circular economy provides a powerful, empirical justification for the "safe" pillar of the SSbD framework. It demonstrates that a reliance on end-of-life processes to contain hazards is an insufficient strategy; the responsibility must be shifted to the design and material sourcing phases. For Thermoharv, this means that even if a perfect recycling technology is developed, the project's material sourcing strategy must actively screen for and avoid feedstocks containing these legacy additives. Without such proactive measures, the final product, despite being made from recycled content, could still be unsafe and fail to meet the SSbD criteria, compromising both the safety and long-term viability of the circular model.

V. Towards a Circular Future: Recommendations and Strategic Pathways

5.1 Redesigning for a Circular Economy: A "Coupled" Approach

A purely technical solution for recycling is insufficient for achieving true circularity. A comprehensive approach requires a "system-level innovation" [5] where the product's physical design is "coupled" with a strategic business model. For the Thermoharv project, this means designing smart garments or composite sleeves with easy-to-disassemble components that can be repaired or replaced.[19] This includes the use of modular parts and materials that can be easily separated, a core principle in the composites industry roadmap for circular design.[19] However, the effectiveness of these design methods can be restricted by existing business models and a lack of market for recycled materials.[15]

To overcome this, the Thermoharv consortium should explore and prototype circular business models that ensure end-of-life control. A compelling model is "product-as-a-service," where the consortium or an associated partner retains ownership of the thermal energy harvesting devices.[13] Instead of selling the products outright, they could lease the smart garments or building sleeves, ensuring that when the devices reach their end-of-life, they are returned to a centralized, controlled facility for valorization.[8] This model, which is gaining traction in the textile industry, would keep the products in circulation longer and prevent them from entering a fragmented, unequipped waste stream.[8] This business strategy would provide a direct feedback loop to designers, allowing for continuous product improvement and material innovation, thereby closing the loop in practice, not just in theory.

5.2 Advanced Recycling Technologies: A Path to High-Purity Valorization

Given the inherent complexities of Thermoharv's multi-layered materials, conventional mechanical recycling is not a viable pathway to high-value circularity. The degradation of thermomechanical properties through repeated melting and the inability to separate fused layers make it a sub-optimal choice.[4] A more promising route is the application of advanced recycling technologies, specifically solvent-based processes.

Solvent-based recycling uses solvents to selectively dissolve target polymers (Figure 5), effectively separating them from additives, dyes, and other contaminants.[6] This method offers a cleaner, more targeted solution that can produce high-purity recyclates with "virgin material properties".[6] The process is less energy-intensive than thermochemical recycling and is uniquely suited for complex, contaminated plastics and composites.[6] Specific processes, such as the Solvent-Targeted Recovery and Precipitation (STRAP) method, have demonstrated the ability to recover all constituent polymer layers from multi-layer films with high material efficiency.[27] An alternative approach involves a micro-perforation process that allows chemical agents to access and remove adhesives, a simple and environmentally friendly procedure that can separate multi-layer materials without the need for organic solvents.[28] The existence of these technologies provides a clear, actionable direction for the Thermoharv project. By integrating a solvent-based recycling protocol, the project can move the end-of-life challenge from a question of "if" to "how," ensuring the valuable polymers and components are recovered and reused, thereby completing the circular loop.

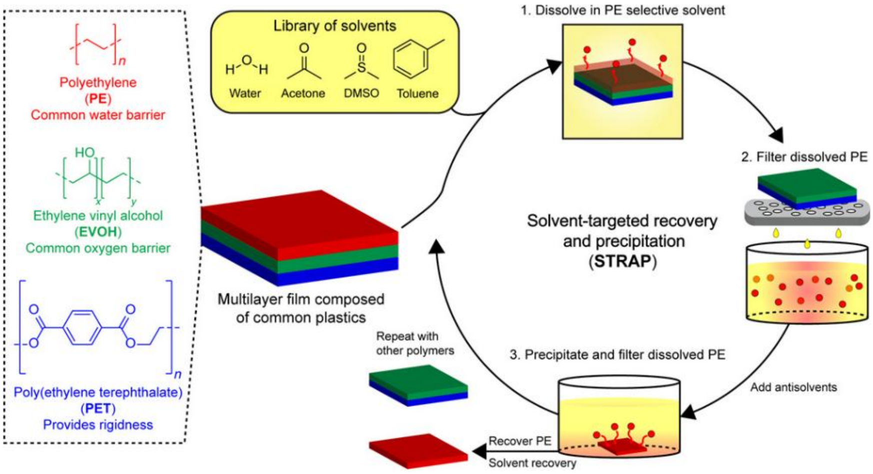

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Figure 12 Example of the dissolution of a multilayer polymer film

5.3 The Role of Next-Generation Materials: The SSbD Ideal

The most profound alignment with the SSbD framework would involve Thermoharv's material research and development exploring next-generation polymers that are inherently designed for circularity and safety. One such class of materials is Non-Isocyanate Polyurethanes (NIPUs). Conventional polyurethanes (PUs), which are likely to be used in Thermoharv's flexible composites, are typically made using isocyanates, which are highly reactive and pose safety concerns.[29] NIPUs, in contrast, are synthesized via "isocyanate-free" routes, often from bio-based precursors.[30]

The unique chemical structure of NIPUs, which includes suitable functional groups for dynamic bond exchange, makes them more easily reprocessable and recyclable.[30] The exploration of NIPUs or similar bio-based, next-generation polymers would be a powerful embodiment of the SSbD framework in action. By fundamentally solving a safety problem at the source—the removal of a hazardous chemical from the synthesis process—this material choice simultaneously satisfies both the "safe" and "sustainable" pillars of the SSbD framework.[30] It is a quintessential example of a design-for-circularity approach, where the material itself is engineered to enable a genuinely closed-loop system, representing the ideal future for projects at the nexus of technology and sustainability.

Aspect	**Description of Alignment with SSbD**
Voluntary Framework	The project's explicit "eco-responsible approach" and focus on end-of-life valorization demonstrate a proactive commitment to the voluntary SSbD principles, positioning it as a pilot for the framework's practical application.
"Safe" Definition	The consortium's material selection process must prioritize avoiding intrinsically hazardous properties and actively screen for and exclude legacy additives to ensure the safety of the final product and prevent their reintroduction into the supply chain through recycling.
"Sustainable" Definition	The Thermoharv project directly fulfills this criterion by delivering a valuable function—energy recuperation—without exceeding environmental boundaries, using waste heat to generate power and reducing the overall energy footprint of buildings.
Guiding Principle: Material Efficiency	By developing lightweight, flexible materials for energy harvesting, the project maximizes the functional output per unit of material, thereby reducing resource consumption compared to traditional, rigid electronic systems.

Guiding Principle: Design for End-of-Life	The project's success hinges on its ability to design multi-material products that can be easily disassembled, separated, and valorized at end-of-life. This requires a shift from conventional design practices to a focus on modularity and material compatibility with advanced recycling processes.
Iterative Process	As a research project, Thermoharv has the opportunity to apply the iterative, step-wise assessment approach of the SSbD framework. This allows for continuous reassessment and optimization of the product's safety and sustainability performance as the innovation matures and more data becomes available.

Recycling Protocol	Process Description	Pros	Cons & Applicability to Thermoharv
Mechanical Recycling	Grinding and melting plastics for reuse in new products, often with a different application (downcycling).[26]	Simple, relatively low-cost, and widely available.[3]	Ineffective for multi-material structures due to chemical incompatibility and difficulty of separation.[4] Thermomechanical properties degrade with each cycle.[26] Not suitable for Thermoharv's complex materials.
Chemical Recycling	Depolymerization of waste plastics into monomers or valuable small molecules using high heat or catalysts.[6]	Creates high-quality feedstock for new products.[6] Can handle some mixed waste streams.	High energy intensity, often requires harsh conditions.[26] Most common methods (e.g., glycolysis) only recover one component (polyols), not all original starting materials.[26]
Solvent-Based Recycling	Uses solvents to selectively dissolve a target polymer from a mixed material, leaving behind contaminants and other materials.	Produces high-purity recyclates with "virgin material properties".[7] Efficiently removes contaminants and	Requires specialized solvents and infrastructure. The choice of solvent is dependent on the type of plastic laminate.[27] Residues of adhesion promoters may

	High-purity polymers are recovered through precipitation.[6]	hazardous additives. Less energy-intensive than chemical recycling.[6]	remain on separated layers.[27] Most promising route for Thermoharv.

VI. Conclusion: A Blueprint for Sustainable Innovation

The Thermoharv project is more than a technical initiative; it is a crucial test case for the practical application of the European Union's Safe & Sustainable by Design (SSbD) framework and the principles of the circular economy. The project's mission to create multi-material, flexible energy-harvesting devices for buildings and smart garments directly aligns with the EU's strategic vision for a green and circular industrial transition. This analysis demonstrates that by converting waste thermal energy into usable power, the project embodies the core SSbD principles of minimizing environmental impact and delivering function within planetary boundaries.[11]

However, the analysis also reveals a significant, systemic challenge: the inherent paradox of multi-material products, where functional innovation can inadvertently create end-of-life failures.[4] Overcoming this requires a strategic, multi-pronged approach. The consortium must move beyond a simple focus on technical performance to a holistic consideration of the product's entire life cycle, guided by the SSbD framework. This includes designing products that are easily reparable and dismantlable, a design philosophy that must be "coupled" with a business model that ensures end-of-life control, such as a product-as-a-service framework.[8]

Furthermore, the project's success depends on its ability to leverage advanced recycling technologies. The evidence suggests that solvent-based recycling, with its capacity to achieve high-purity material separation and contaminant removal, represents the most viable pathway to high-value circularity for Thermoharv's complex materials.[6] A commitment to this technology, combined with a proactive material sourcing strategy that avoids legacy additives, would ensure the final products are both safe and truly sustainable.[25]

Ultimately, the Thermoharv project has the potential to become a definitive blueprint for a new era of sustainable innovation. By demonstrating that technical excellence can be seamlessly integrated with safety, circularity, and sound economic models, it can provide a tangible model for how to overcome the challenges of a linear economy and build a future that is not only functional and competitive but also inherently safer and more sustainable for people and the planet.

Acknowledgements

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