BIO-SUSHY

SSbD Guidelines for *Bio-based PFAS-free coatings for food packaging*

1. Scope & Application

The BIO-SUSHY project advances Safe and Sustainable by Design (SSbD) practices by developing paper-based food trays that combine circularity, bio-based materials, and solvent-free production methods, achieving high performance, minimal emissions, and full compatibility with paper recycling while prioritising human health and environmental safety.

- **Application.** Paper-based food trays (rigid and semi-rigid, including 3D fiber-molded products) with bio-based barrier coatings, designed as alternatives to PFAS- and PET-based packaging for hot food applications and compatible with thermoforming (120–180°C).

- **Functionality.** High grease resistance (KIT 12), low water absorption (Cobb ≤10 g/m²), and stable coating adhesion and performance under thermal and mechanical stress, achieved without hazardous substances.

- **Materials**. Bio-based thermoplastic polymers (Polybutylene succinate (**PBS**), Polyhydroxyalkanoates (**PHA**), and Polyhydroxybutyrate-valerate (**PHBV**)), functional lignin-based fillers (1–50%) and natural waxes (e.g., carnauba), applied as solvent-free powder coatings on paper and cellulosic substrates (e.g., Inverform 330 gsm).

- **Target stakeholders.** Material formulators and chemical industry, packaging converters and manufacturers, brand owners and retailers, and regulatory and certification bodies.

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2. Application Context & Functional Requirements

- **Product system description**
    - **Material Composition:** The system consists of **cellulosic fiber mats or paper substrates** (such as Inverform 330gsm) coated with **solvent-free thermoplastic powders**. The primary polymer matrices include PBS, PHA, PHBV, which are often compounded with **functionalised lignin-based fillers** to enhance performance.
    - **Product Format:** The coated paper is designed for conversion into **rigid or semi-rigid 3D food trays** (e.g., 195x130x30 mm) intended for hot meal service in canteen environments.
    - **Process Technology:** The coatings are applied via **electrostatic powder spraying**, followed by gelling and smoothing through a hot press, and finally shaped using an innovative **"dry molded fiber" thermoforming method**.
- **Functional requirements**
    - **Barrier Performance.** The coatings must provide high-level protection against food components. Key targets include a **grease resistance (KIT rating) of 12** and a **water resistance (Cobb test) of 10 g/m²**.
    - **Mechanical Integrity.** The coating must demonstrate excellent adhesion and **thermoforming compatibility**, maintaining its structural and barrier integrity while being bent and stretched into a 3D shape.
    - **Thermal Resistance.** The product system is engineered to withstand high industrial temperatures, including **gelling temperatures between 80°C and 200°C** and **thermoforming heat ranging from 120°C to 180°C**.
- **Regulatory constraints & Sustainability objectives**
    - **Food Contact Compliance.** The final trays must pass **global and specific migration tests** to ensure they meet stringent European food safety standards for direct contact with hot food.
    - **PFAS-Free and Toxic-Free Design.** A primary regulatory driver is the **100% elimination of PFAS** (per- and polyfluoroalkyl substances) and the avoidance of **Substances of Very High Concern (SVHC)** as defined under REACH.
    - **Circularity and End-of-Life.** To support a circular economy, the coated materials must be **fully repulpable** within existing paper recycling streams or certified as **compostable** according to standards like EN 13432.
    - **Zero VOC Emissions.** By utilising a dry powder application instead of solvent-based systems, the manufacturing process aims to achieve **0% Volatile Organic Compound (VOC) emissions**, protecting worker health and the environment.

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3. SSbD Risk Identification

The following table identifies potential risks for the bio-based food packaging coatings based on the development and validation phases of the project. These risks are specific to the paper-based tray system but provide generalisable insights for similar food-contact sectors.

Risk Category	Specific Risk	Relevance
Human Health	**Chemical migration.** Potential transfer of substances from the coating to food during use.	Essential to ensure food contact safety and compliance with global migration limits.
	Dermal cytotoxicity. Observed cytotoxic effects of biopolymers like PBS and PHBV on human skin cells (HaCaT).	Highlights the need for safe handling practices and fully optimised formulations.
	Bio-membrane interaction. Concentration-dependent interaction of lignin and/or thermoplastic polymers lecheates with biological cell membranes, including potential risks associated with bio-membrane interactions.	Indicates the importance of limiting release of coating components under high-exposure conditions.
Environment	**LCA performance gap**. Failure to reach the target of a 25% reduction in environmental impact compared to benchmark.	Shows that environmental benefits are not yet fully realised across all impact categories.
	Data quality uncertainty. Lack of reliable environmental data for biopolymers like PHA and PBS, as well as limited data availability in existing databases.	Creates uncertainty in assessing the true environmental footprint of bio-based alternatives.
Process Safety	**Particulate exposure**. Risk of worker exposure to inhalable dust during powder handling.	Requires strict occupational monitoring despite VOC-free processing.
	Thermal stress. High energy consumption or material degradation at gelling and thermoforming temperatures (up to 200°C).	Impacts both environmental footprint and structural integrity of the coating.

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Circularity	**Repulping interference.** Coatings failing to separate from paper fibers during recycling.	Can contaminate recycled pulp if bio-polymers do not break down properly.
	End-of-Life mismanagement. Consumer confusion on recycling vs. Composting.	Social awareness is critical to ensure trays enter the correct circular value chain.
Social	**Supply chain ethics.** Labor rights risks in global production or raw materials (PHB/PLA).	High-risk hotspots suggest relocating production to Europe to reduce social impact.

4. SSbD Design Principles

The **Safe and Sustainable by Design (SSbD)** approach for food packaging is governed by universal principles applied across the BIO-SUSHY project to ensure that innovation does not compromise human safety or environmental integrity. These principles guide the iterative development of **paper-based food trays** from the earliest design stages.

- **Use low-hazard substances.** The primary goal is to select chemical building blocks with the lowest possible intrinsic hazard. In the food tray case study, all selected raw materials and coating formulations **passed the SSbD hazard assessment**, with most substances falling into lower-hazard Groups B or C.
- **Use bio-based materials.** To reduce reliance on petrochemicals, the project prioritises renewable resources. Formulations utilise **bio-based thermoplastic matrices** (such as PBS, PHBV, and PHA) and incorporate **modified lignin-based fillers**, achieving a total bio-based content of up to **90%**.
- **Avoid PFAS and SVHCs.** A core design driver is the **100% replacement of PFAS** and the absolute avoidance of SVHCs that would trigger mandatory substitution. Rigorous screening ensured that no chemicals in the food tray formulation were classified in **Group A** (the highest hazard category).
- **Design for circularity.** Products are engineered to fit within existing circular value chains. The selected biopolymer coatings are specifically chosen for their **compatibility with paper recycling streams** (repulpability) or their potential for **compostability** according to EN 13432.
- **Minimise emissions.** The design prioritises processes that eliminate harmful releases. By utilising **solvent-free thermoplastic powder coatings** instead of organic solvent-based systems, the project has demonstrated the ability to achieve **0 VOC emissions** during the coating production phase.

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- **Ensure resource efficiency.** The design process aims to match high functionality with minimal resource inputs. This includes optimising **powder particle size** (e.g., <80 μm) to reduce the total amount of coating material applied while maintaining necessary barrier performance.
- **Validate safety early.** Safety is not an afterthought but a prerequisite for development. The project utilises a **tiered assessment strategy**, integrating **QSAR modeling, digital data-mining**, and **experimental bio-membrane sensors** to identify potential risks long before the product reaches the industrial scale.

5. Recommended SSbD Measures

The following measures are **actionable, concrete, and replicable** steps taken within the BIO-SUSHY project to ensure that paper-based food trays meet high safety and sustainability standards. These recommendations serve as a blueprint for the industry to transition away from hazardous substances while maintaining high technical performance.

SSbD Objective	**Recommended Measure**	**Implementation Example**	**Applicability**
Reduce Toxicity	**100% Replacement of PFAS** and avoidance of petrochemical resins.	Utilise **bio-based matrices (PBS, PHBV, or PHA)** compounded with **hydrophobised lignin fillers** to achieve a KIT grease resistance rating of 12.	**High**
Eliminate Emissions	**Avoid solvent-based systems** to protect worker health and the environment.	Implement **solvent-free electrostatic powder spraying** and hot pressing, which has demonstrated **0 VOC emissions** during the production phase.	**High**
Enable Circularity	Design for **compatibility with existing recycling streams** or composting.	Select thermoplastic biopolymers that are **fully repulpable**, ensuring they do not interfere with paper fiber separation during industrial recycling.	**High**
Improve Safety	Implement **iterative hazard screening** using a tiered assessment strategy.	Pre-screen all chemical building blocks using **QSAR modeling** and **MTT cytotoxicity assays** to ensure every component passes SSbD Step 1 hazard criteria.	**High**

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Ensure Resource Efficiency	Optimise material application to **minimise waste and energy** use.	Grind coating powders to a **particle size <80 µm** to reduce the total volume of material needed while maintaining target barrier properties.	**Medium**
Mitigate Social Risks	**Optimise supply chain geography** to ensure ethical production standards.	Relocate **production steps for PHB/PLA to Europe**, which identifies as having significantly lower risks for child labor and poor labor rights compared to global production sites.	**Medium**
Strengthen Social Acceptance and Public Trust	Engage value chain actors and consumers early to **address concerns around safety, performance, and credibility** of PFAS-free alternatives.	Identify **acceptance barriers** and support transparent communication around PFAS-free paper packaging.	**Medium**

6. Process & Manufacturing Considerations

The transition of bio-based coatings from laboratory scale to industrial reality for the food tray case study relies on utilising **dry application technologies** that align with existing manufacturing workflows while maximising safety and environmental performance.

Processing Conditions

- **Application Method:** The project utilises **electrostatic powder spraying** to apply thermoplastic biopolymers (such as PBS, PHBV, or PHA) onto cellulosic substrates like **Inverform 330gsm**.
- **Gelling and Smoothing:** The applied powder film is gelled and smoothed using a **hot press**. Industrial gelling temperatures typically range from **80°C to 200°C**, with specific trials for PBS and PHBH conducted at **100°C and 155°C**, respectively.
- **Pressure and Timing:** Successful gelling has been achieved at a pressure of **77 bar** for a duration of **60 seconds**, followed by a back-cooling phase of **400 to 600 seconds** to stabilise the coating.
- **3D Shaping:** Final trays are produced via **thermoforming** using an innovative **"dry molded fiber method"** where the coated mat is shaped in a mold (e.g., 160°C for the female mold surface) for approximately **1 second**.

Worker Safety Measures

- **Elimination of VOCs:** A significant industrial advantage of this SSbD approach is the use of **solvent-free coatings**, which results in **0% Volatile Organic Compound (VOC) emissions** during the production phase. This removes the need for complex solvent recovery systems and protects workers from toxic vapor exposure.
- **Particulate Management:** Because the process uses fine powders (particle sises optimised below **80 µm**), worker safety must focus on **mitigating dust and particulate exposure** during grinding and spraying phases.
- **Risk Validation:** Occupational risk assessments using tools like Stoffenmanager® have classified the compounding and coating processes for these materials as **low risk (Class III)**, meaning standard industrial hygiene and protective equipment are sufficient under current conditions.

Industrial Compatibility and Scalability

- **Existing Infrastructure:** The coating process is designed to be **compatible with existing industrial thermoforming lines**, such as the Novatec blank feed forming machine.
- **Material Optimisation:** Trials indicate that **PHBH-based coatings** offer superior industrial processability compared to PBS, as they are less slippery and maintain better positioning in the mold during high-speed production.
- **Future Integration:** To further increase industry uptake, best-performing formulations are being explored for adaptation to **roll-to-roll dry powder application** and **extrusion coating** technologies.

Waste Management and Recovery

- **Circular Design:** Unlike traditional PET-coated trays, these bio-based coatings are engineered for **real compatibility with paper recycling pathways** (repulping), allowing the tray to be recovered through existing waste streams.
- **End-of-Life Alternatives:** The thermoplastic powders are selected to ensure the final product is **compostable according to EN 13432**, providing a sustainable alternative for trays contaminated by food residue that cannot be recycled.
- **Efficiency:** By optimising powder particle size and utilising electrostatic application, the process **minimises material waste** and ensures a high-efficiency transfer rate of the coating to the substrate.

7. Validation from BIO-SUSHY Case Studies

The SSbD framework has been validated through the development of the food packaging case study, demonstrating that bio-based innovations can meet industrial performance targets while ensuring safety and circularity. The following table summarises the key measures implemented and their validated results:

Measure	Case Study	Result
Solvent-free process	Food packaging	**0% VOC emissions** from solvents during the manufacturing phase.
Bio-based content optimisation	Food packaging	Achieved total **bio-based content between 80% and 90%** for PBS/lignin formulations, with some PHA-based powders reaching **up to 98-100%**.
Repulpable design	Food packaging	Biopolymer coatings are **compatible with existing paper recycling streams** (repulping process).
PFAS-Free barrier performance	Food packaging	Achieved a **KIT grease resistance rating of 12** and a **Cobb water uptake value of 10 g/m²**, matching or exceeding conventional PFAS-based benchmarks.
Early safety validation	Food packaging	**100% of chemicals** used in the food tray formulations successfully **passed the SSbD Step 1 hazard assessment**.
Toxicological safety	Food packaging	MTT assays on human cell lines (lung, gut, skin) showed **virtually no cytotoxic effects** (EC50 > 100 ppm) for modified lignin and carnauba wax additives.
Occupational safety	Food packaging	Risk assessment using Stoffenmanager® classified both compounding and coating processes as **Low Risk (Class III)**.
Waste reduction	Food packaging	The design is certified **compostable according to EN 13432**, providing an alternative circular pathway for contaminated trays.

The successful validation of these measures confirms that **thermoplastic powder coatings** are a viable industrial alternative to PET and PFAS-based solutions. By integrating **modified lignin fillers**, the project demonstrated that high functional performance (KIT 12) is compatible with a **toxic-free and circular product life cycle**.

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8. Trade-offs & Limitations

Implementing the Safe and Sustainable by Design (SSbD) framework for bio-based food packaging requires balancing safety, circularity, and performance with technical, economic, and industrial constraints. Key trade-offs and limitations identified during the development of the BIO-SUSHY paper-based tray system include:

Technical performance trade-offs

- **Film uniformity vs. bio-based content.** Higher modified lignin content (40–50%) improves water and grease resistance but can create non-uniform films in PHBV formulations, requiring higher processing temperatures for smooth, functional barriers.
- **Material processability.** PBS coatings form smooth films but can make the paper slippery during thermoforming, while PHBH coatings are easier to handle but require adjusted machine setups.
- **Bio-membrane interaction.** High concentrations of lignin and thermoplastic polymers can interact strongly with biological membranes, necessitating careful control of formulation stability to maintain safety.

Cost Constraints

- **Raw material costs.** High-performance biopolymers (PHA, PBS) and modified lignin fillers are more expensive than conventional PET or PFAS coatings. Process optimisation aims to keep total production cost increases below 20%.
- **Supply chain relocation.** Moving raw material production to Europe improves social sustainability by reducing labor risks but can increase costs due to higher operational standards.

Scalability & Industrial Constraints

- **Energy consumption.** Gelling and thermoforming at 120–200°C increase energy demand compared to cold-applied solvent-based systems.
- **Manufacturing throughput.** Scaling from lab (150 g) to industrial batches (3–5 kg) requires precise powder particle sizing (<80 µm) to maintain barrier performance at high speed.
- **Data quality gaps.** Limited environmental data for biopolymers like PHA and PBS introduces uncertainty in life cycle assessments and makes it challenging to demonstrate a consistent 25% reduction in environmental impact across all categories.

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Summarising, achieving high barrier performance, safety, and circularity in bio-based trays involves trade-offs in **film processing, cost, energy use, and scalability**. While these challenges are manageable, they highlight areas where further optimisation is needed for industrial deployment.

9. Implementation Roadmap

The following roadmap outlines the systematic process for implementing SSbD principles in the development of bio-based barrier coatings for food packaging, moving from initial chemical screening to industrial scale-up.

1. Screen substances

- **Methodology.** Conduct a comprehensive review of the chemical inventory using harmonised **CLP classifications** and **REACH dossiers** from ECHA.
- **Gap-Filling.** Utilise digital intelligence, including **automated data-mining** from over 30 public databases and **26 trusted QSAR models**, to predict the toxicological and ecotoxicological profiles of bio-based materials where experimental data is missing.
- **Assessment.** Apply the **SSbD hazard framework** to classify substances into hazard groups (A, B, or C). In the food tray study, all chosen biopolymers and additives were confirmed to pass this stage.

2. Select safer alternatives

- **Material Selection.** Prioritise biopolymers that eliminate the need for hazardous substances. For this case study, **PBS, PHBV, and PHA** were selected to replace conventional PET and PFAS-based coatings.
- **Bio-Based enhancement.** Replace petrochemical additives with functionalised **bio-based fillers**, such as **hydrophobised lignin**, which improves technical performance without introducing the toxicity risks associated with fluorinated compounds.

3. Adapt formulation

- **Compounding.** Integrate biopolymers with modified lignin fillers at loading levels ranging from **1% to 50%** using twin-screw extrusion.
- **Process optimisation.** Refine the physical form of the material by grinding and sieving powders to a **particle size of <80 µm**. This optimisation reduces residual stress in the coating and allows for lower coating thicknesses while maintaining barrier integrity.

- **Industrial tuning.** Adjust formulations based on processability feedback, such as adding **Aerosil** to PHBH powders to reduce surface slipperiness and improve positioning during thermoforming.

4. Validate

- **Functional testing.** Ensure the coating meets stringent barrier requirements: a **KIT grease resistance rating of 12** and a **Cobb water uptake value of 10 g/m^2**.
- **Safety validation.** Perform **experimental toxicological assays** (MTT) on human cell lines (lung, gut, and skin) and utilise **bio-membrane sensors** to confirm that leachates do not pose a health risk.
- **Regulatory compliance.** Conduct **global and specific migration tests** to ensure the final product is certified safe for direct contact with hot food.

5. Assess End-of-Life (recycling)

- **Repulpability.** Select biopolymer matrices specifically for their **compatibility with industrial paper recycling** (repulping), ensuring the tray can be integrated into existing circular economy loops.
- **Alternative pathways.** Ensure formulations meet **EN 13432 standards for compostability**, providing a secondary sustainable disposal route for trays contaminated with significant food residue.

6. Scale-Up

- **Batch production.** Transition from laboratory-scale batches (150g) to pilot-scale production of **3–5 kg per formulation** using pilot extrusion plants.
- **Industrial integration.** Validate the technology on **industrial thermoforming lines** (e.g., Novatec machines) to produce full-sized trays (195x130x30 mm).
- **Advanced technologies.** Explore higher-throughput application methods, such as **roll-to-roll dry powder application** and **extrusion coating**, to facilitate broad industrial uptake.

10. KPIs

The performance and sustainability of the bio-based food tray coatings are monitored through a set of Key Performance Indicators (KPIs) designed to ensure the product meets technical, safety, and environmental benchmarks.

- **Bio-Based Content (%)**

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  - **Status.** The project has successfully developed formulations with high bio-based content. Thermoplastic powder coatings using **PBS and lignin** achieve a bio-based content of **80% to 90%**.
  - **Advanced target.** Formulations based on **PHA** have reached up to **98% bio-based content**, utilising only 2% weight of non-bio additives.
- **PFAS-Free**
  - **Status.** A core project objective is the **100% replacement of PFAS**.
  - **Validation.** Technical trials have confirmed that the bio-based thermoplastic coatings provide the necessary grease and water resistance (e.g., **KIT rating of 12**) without the use of any fluorinated compounds.
- **Recyclability / Repulpability (%)**
  - **Design for circularity.** The thermoplastic matrices (PBS, PHBV, and PHA) were specifically selected for their compatibility with existing **paper recycling streams (repulping process)**.
  - **Alternative End-of-Life.** The final product is designed to be **compostable according to EN 13432**, ensuring a sustainable disposal route for trays contaminated with food residue that cannot enter the paper recycling stream.
- **Hazard classification compliance**
  - **Hazard assessment. 100% of the chemicals** used in the food tray formulations successfully **passed the SSbD Step 1 hazard assessment**, with no substances requiring mandatory substitution.
  - **Toxicological safety.** Experimental MTT assays on human cell lines showed virtually **no cytotoxic effects** (EC50 > 100 ppm) for modified lignin, carnauba wax, and the biopolymer matrices.
  - **Occupational safety.** Risk assessments using Stoffenmanager® classified both the compounding and coating processes for these materials as **Low Risk (Class III)**.
- **Energy Consumption**
  - **Process optimisation.** The project targets a reduced climate change impact through the fine optimisation of processing parameters, such as **low curing temperatures and short durations**.

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  - **Operating conditions.** Gelling temperatures for the powder coatings range from **80°C to 200°C** with gelling times of only **5 to 30 seconds**. The final thermoforming step is highly efficient, requiring only **1 second** at temperatures between **120°C and 180°C**.

11. Key Takeaways

The implementation of SSbD principles for bio-based food packaging provides a definitive path toward replacing PFAS while ensuring circularity and industrial performance. The following points summarise the main actionable recommendations derived from the BIO-SUSHY food tray case study for quick reference:

- **Design for safety from the outset.** Eliminate hazardous substances before they enter the laboratory by using digital intelligence tools, such as **QSAR modeling** and automated data-mining, to screen all chemical building blocks. For food packaging, ensure every material successfully passes the **SSbD hazard assessment** to guarantee that no substances require mandatory substitution.
- **Prioritise Zero-Emission manufacturing.** Transition from solvent-based application methods to **solvent-free thermoplastic powder coatings** (such as PBS, PHBV, and PHA). This practice achieves **0% Volatile Organic Compound (VOC) emissions** during the production phase, protecting worker health and reducing the environmental footprint of the manufacturing facility.
- **Engineer for circular value chains.** Select coating materials based on their compatibility with existing end-of-life infrastructure. For paper-based trays, ensure that biopolymer coatings are **fully repulpable** within standard paper recycling streams or certified as **compostable** according to EN 13432.
- **Maximise bio-based performance.** Utilise modified bio-based fillers, such as **hydrophobised lignin**, to replace petrochemical additives. This strategy allows for formulations with **80–90% bio-based content** while meeting or exceeding industry benchmarks, such as a **KIT grease resistance rating of 12** and a **Cobb water resistance value of 10 g/m²**.
- **Validate with real-world case studies.** Move beyond theoretical safety by validating materials through industrial-scale demonstrators. In the food packaging sector, this includes ensuring that bio-based coatings maintain their mechanical and barrier integrity during high-speed **thermoforming** and hot meal service.

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- **Optimise resource efficiency.** Refine the physical form of materials, such as optimising powder **particle size to <80 µm**, to minimise the total volume of coating required without compromising barrier functionality.
- **Address social sustainability early.** Systematically screen global supply chains for social risk hotspots, such as child labor or poor labor rights. A key recommendation for food packaging biopolymers is to **relocate production steps to Europe** to significantly mitigate these ethical risks. This should also be accompanied by **transparent communication** and **stakeholder engagement** to strengthen social acceptance and public trust in PFAS-free alternatives.

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