BIO-SUSHY

SSbD Guidelines for *Bio-based PFAS-free coatings for textile*

1. Scope & Application

The application of **Safe and Sustainable by Design (SSbD)** guidelines for the textile case study focuses on the development of **hybrid sol-gel coatings** that provide high-performance water and oil repellency without the use of hazardous perfluoroalkyl substances (PFAS).

- **Application.** Finishing treatments for various textile categories, including **outdoor and performance apparel, home textiles (e.g., tablecloths and upholstery), and technical textiles**. The coatings are applied via a **roll padder (dip-pad-dry-cure)** process, which is standard in textile finishing factories.
- **Functionality:**
    - **Omniphobicity.** Achieving durable water and oil repellency (W&OR) with a target surface tension between **10 and 20 mN/m**.
    - **Washing resistance.** Ensuring the coating maintains its performance after repeated domestic washing cycles (targeting stability for up to **10 washes**).
    - **Aesthetics and comfort.** Maintaining the **soft touch**, original color, and visual aspect of the fabric (e.g., polyester, cotton, or blends).
- **Materials:**
    - **Matrix.** Water-based hybrid sol-gel systems with **high organic content** to ensure flexibility on fabric substrates.
    - **Bio-based additives/linkers.** Functionalised **fatty acids** (e.g., functionalised oleic acid or stearic acid) that act as hydrophobic precursors and raise the bio-based content of the formulation to at least **25–50%**.

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  - **Fillers for surface roughness.** Functionalised inorganic particles, such as **$CaCO_3$ or ZnO** grafted with bio-based linkers, to create the micro-roughness necessary for liquid repellency.
- **Target stakeholders:**
  - **Textile industry & finishers.** Companies seeking to replace PFAS treatments to comply with emerging EU regulations and transition to toxic-free production.
  - **Outdoor & fashion brand owners.** Stakeholders interested in sustainable, high-performance gear and apparel.
  - **Chemical formulators.** Developers of bio-based resins, linkers, and functional additives.
  - **Standardisation & certification bodies.** Agencies involved in textile safety labels (e.g., **OEKOTEX**) and European technical committees (e.g., **CEN/TC 248).**

2. Application Context & Functional Requirements

The development of innovative finishes for the textile sector is driven by the urgent industrial and regulatory need to replace hazardous perfluoroalkyl substances (PFAS) with safe, durable, and high-performance bio-based alternatives.

Product system description

- **Material and format.** The case study focuses on treating diverse fabric substrates, specifically **polyester, cotton, and polyester/cotton blends**. A primary benchmark product for evaluation is a **polyester tablecloth** measuring 150 x 200 cm.
- **Application categories.** The technology is intended for **outdoor and performance apparel**, **home textiles** (e.g., upholstery and curtains), and **technical textiles** such as tents or filters.
- **Coating technology.** The system utilises **hybrid water-based sol-gel coatings** with high organic content to maintain fabric flexibility.
- **Manufacturing process.** Finishing is performed using the standard **Roll Padder (dip-pad-dry-cure)** technique. This involves an initial impregnation step followed by roll pressure to fix the coating and a fast thermal curing cycle (typically **3–5 minutes** at **120°C to 180°C**) to align with existing textile factory speeds.

Functional requirements

- **Omniphobicity (water and oil repellency):**

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  - The primary technical goal is to achieve a low surface tension between **10 and 20 mN/m** to ensure both water and oil repellency.
  - Target performance includes a domestic oil contact angle above **130°**.

- **Durability and maintenance:**
  - **Washing resistance.** The coating must remain stable after repeated cleaning. The project aims for "medium" hydrophobic properties to persist for up to **10 domestic washing cycles** at 40°C.
  - **Property retention.** The goal is to maintain at least **85–90%** of the original repellency performance after repeated abrasion or washing cycles.

- **Aesthetics and comfort:**
  - **"Soft Touch".** The finish must provide a soft hand-feel, which is achieved by optimising (lowering) curing temperatures to avoid fabric stiffness.
  - **Visual stability.** The treatment must leave the fabric's **original color and visual aspect** unchanged.
- **Adhesion and stability:**
  - Formulations incorporate **adhesion promoters** (e.g., GPTES) and **functionalised bio-based fatty acids** (like oleic acid) that covalently bond to textile fibers, improving mechanical cohesion and reducing the potential for leachate release.

Regulatory context & sustainability constraints

- **PFAS-Free and toxic-free design.** The project targets **100% replacement of PFAS**. Materials are designed to meet **REACH** compliance and align with the **EU's Chemicals Strategy for Sustainability** to ensure a toxic-free environment.
- **Upcoming bans.** The design anticipates a proposed **REACH ban on PFAS in textiles by 2030** and existing national regulations, such as France's ban on PFAS in apparel starting in 2026.
- **Safety standards.** Formulations are developed to be compatible with safety labels like **OEKOTEX®**, which are increasingly prohibiting fluorinated substances.
- **VOC mitigation.** To ensure worker safety and environmental protection, the finishes are **100% water-based**. Precursors are carefully selected to ensure that solvents formed during hydrolysis are safer alcohols (e.g., **ethanol**) rather than methanol.
- **End-of-Life circularity.** The design promotes **circularity** by extending the product's service life and ensuring that the hybrid silica-organic treatment does not degrade the **recyclability** of the base fabric.

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3. SSbD Risk Identification

The following table identifies potential risks associated with the development and industrial application of hybrid sol-gel coatings for textiles. These risks are specific to the textile case study but provide relevant insights for other sectors utilising wet chemical finishing processes on flexible substrates.

Risk Category	Specific Risk	Relevance
Human Health	**Substrate contaminant release.** Initial testing with biomembrane sensors revealed that untreated cotton and cotton/polyester blends release micro-components (possibly from the weave process) that interact with biological membranes.	Indicates a need for pre-treatment washing to ensure consumer safety and prevent the release of legacy textile pollutants during use.
	Dermal cytotoxicity. Experimental MTT assays observed cytotoxic effects on dermal cell lines (**HaCaT**) for specific thermoplastic components (e.g., **PBS and PHBV**) intended for bio-based finishes.	Critical for apparel applications where the fabric is in direct and prolonged contact with human skin.
Environment	**Laundering leachates.** Observed release of coating components into wastewater during domestic washing cycles, with release rates varying based on water pH and temperature.	Failing to secure the coating via proper adhesion promoters could lead to freshwater ecotoxicity and environmental pollution.
	Harmful solvent formation. Hydrolysis and condensation of standard silane precursors (e.g., **GPTMS**) can release hazardous **methanol** as a byproduct.	Transitioning to ethoxy-based precursors (e.g., **GPTES**) is necessary to ensure the process releases safer **ethanol** instead.
	LCA/Data quality. Lack of reliable life cycle inventory data for PFAS used in textile applications.	Limits accurate modelling of environmental impacts and reduces confidence in comparative LCA results between PFAS-based and PFAS-free textile finishing systems.
Process Safety	**High occupational hazard.** Liquid sol-gel finishing mixtures are classified as **Hazard Class D** due to associated H-	Results in a **Risk Score of II**, necessitating the mandatory use of protective masks and local exhaust

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	phrases in their chemical building blocks.	ventilation to protect workers during the finishing process.
	Flammability in curing. Use of alcohol-based precursors in high-temperature curing ovens (**120°C–180°C**).	Requires explosion-proof equipment and strict monitoring of vapor concentrations to prevent industrial fires or explosions during the drying phase.
Circularity	**Durability failure.** Rapid loss of hydrophobic and oleophobic properties after only 2 to 3 domestic washing cycles.	If durability targets (10+ washes) are not met, the environmental benefit of the treatment is lost, as the product may be discarded prematurely or require frequent re-treatment.
	Recycling contamination. Potential for hybrid organic/inorganic coatings to interfere with the chemical or mechanical recycling of polyester fibers.	Finishes must be engineered to ensure they do not degrade the quality of the recycled textile stream, maintaining the material's value in a circular economy.

4. SSbD Design Principles

The **SSbD** approach for the textile case study is guided by universal principles that prioritise human health and environmental safety during the replacement of PFAS with high-performance bio-based alternatives. These principles are integrated into an iterative design carousel that interlinks material development with computational modeling and toxicological assessment.

- **Use low-hazard substances.** Chemical building blocks are screened to ensure they fall into safe hazard categories. In the textile case study, this includes prioritising ethoxy-based precursors (e.g., **GPTES**) over methoxy-based ones (e.g., GPTMS) to ensure that the hydrolysis process releases safer **ethanol** instead of hazardous methanol.
- **Use bio-based materials.** The project targets a bio-based content range of **25–80%** depending on the specific coating technology. Key strategies include the synthesis of tailored hydrophobic linkers from renewable **fatty acids**, such as oleic and stearic acids, which are directly incorporated into the hybrid sol-gel backbone.
- **Avoid PFAS and Substances of Very High Concern (SVHCs).** The core objective is the **100% replacement of PFAS** finishes with hybrid organic/inorganic sol-gel systems. This transition eliminates the use of persistent fluorinated side-chain polymers that accumulate in human bodies and the environment.

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- **Design for circularity.** Circular design is achieved by optimising **washing resistance** and durability, targeting at least **10 domestic washing cycles** to extend the product's service life and reduce chemical waste. Additionally, coatings are engineered to be compatible with future textile recycling streams.
- **Minimise emissions.** To protect factory workers and the environment, textile finishes are developed as **100% water-based systems**. This eliminates the need for added volatile organic solvents, significantly reducing the potential for harmful VOC exposure during the industrial padding process.
- **Ensure resource efficiency.** Resource efficiency is pursued by optimising the **Roll Padder (dip-pad-dry-cure)** process. By carefully controlling nip pressure, substrate speed, and formulation viscosity, the project aims to achieve high-performance water and oil repellency with minimal material input.
- **Validate safety early.** Safety is assessed in the pre-market phase using a tiered strategy that includes **biomembrane sensor screenings** and *in vitro* cytotoxicity assays (MTT) on skin and lung cell lines. Furthermore, safety validation extends to the fabric itself, identifying the need for **pre-treatment washing** of substrates like cotton to eliminate legacy pollutants from the weave process.

5. Recommended SSbD Measures

This is the most important section of this SSbD guidelines document.

The measures must be actionable, concrete, and replicable.

SSbD Objective	Recommended Measure	Implementation Example	Applicability
Reduce Toxicity	**100% PFAS replacement** with bio-based hydrophobic precursors.	Replace fluorinated side-chain polymers with **functionalised bio-based fatty acids** (e.g., functionalised oleic or stearic acid) that covalently bond to the sol-gel backbone.	**High**
Reduce Toxicity	Use **low-hazard chemical building blocks** to avoid toxic byproducts.	Select **ethoxy-based precursors (GPTES)** instead of methoxy-based ones (GPTMS) to ensure that the hydrolysis process releases safer **ethanol** instead of hazardous **methanol**.	**High**
Eliminate Emissions	Utilise **100% water-based** finishing systems.	Formulate sol-gel mixtures using water as the primary carrier, eliminating the need for added volatile organic solvents and	**High**

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		significantly **reducing worker exposure to VOCs** during padding.	
Enable Circularity	**Design for durability** to extend the product service life.	Optimise the concentration of **adhesion promoters** and crosslinking agents to maintain repellent properties for at least **10 domestic washing cycles**, preventing premature disposal.	**High**
Improve Safety	Implement **tiered hazard screening** for substrates and leachates.	Conduct **pre-treatment washing** of natural substrates (e.g., cotton) to remove legacy pollutants and perform **MTT cytotoxicity assays** on dermal (HaCaT) cell lines for all new finishes.	**High**
Ensure Resource Efficiency	**Optimise industrial process parameters** to minimise material input.	Fine-tune the **roll padder settings** (nip pressure, substrate speed, and viscosity) to achieve target water and oil repellency with the **minimal required chemical loading**.	**Medium**
Strengthen Social Acceptance and Public Trust	**Engage value chain actors and consumers early** to address concerns around the safety, performance, and credibility of PFAS-free bio-based textile finishes.	Identify acceptance barriers and support **transparent communication** regarding the maintenance of repellency through repeated washing and the preservation of fabric aesthetics such as **"soft touch" and original color.**	**Medium**

6. Process & Manufacturing Considerations

The transition of perfluoroalkyl substances (PFAS)-free textile finishes into industrial reality focuses on utilising standard equipment and safer, water-based chemistry to ensure high productivity and worker protection.

Processing conditions

- **Application method.** The project utilises the **roll padder (dip-pad-dry-cure)** technique, which is standard in textile finishing factories. This process involves an initial impregnation step (dipping), followed by roll pressure to fix the coating and squeeze out excess formulation.
- **Curing cycles.** Thermal curing is designed to be fast, typically lasting between **3 and 5 minutes**. Depending on the specific fabric and throughput needs, curing is performed at

120°C (for 5 minutes) or **180°C (for 3 minutes)**. UV curing is also an investigated alternative for rapid processing.

- **Optimisation for aesthetics.** A key process adjustment involves **decreasing curing temperatures** to ensure the fabric maintains a **"soft touch"** and avoids excessive stiffness.
- **Solvent system.** The formulations are developed as **100% water-based** systems to eliminate the need for added volatile organic solvents. While the initial mixture is water-based, the hydrolysis of precursors naturally forms small amounts of alcohol; the project specifically selects precursors like **GPTES** to ensure the byproduct is safer **ethanol** rather than hazardous methanol.

Worker Safety Measures

- **VOC exposure control.** Moving to water-based systems is a critical safety measure because finishing solutions are frequently left in open air, where workers could otherwise be exposed to high concentrations of volatile organic compounds (VOCs).
- **Hazard and risk classification.** The liquid sol-gel finishing mixtures are classified as **Hazard Class D** due to associated H-phrases. Occupational risk assessments using Stoffenmanager® indicate that while the process has a high hazard classification, the **risk score is II**, provided appropriate controls are in place.
- **Personal Protective Equipment (PPE).** To maintain a low exposure classification, the mandatory use of **protective masks** is required during the industrial finishing phase.

Industrial compatibility & scalability

- **Standard infrastructure.** The pad-coating process is highly compatible with **traditional textile application lines**, requiring no major capital expenditure for factories already equipped with padding and curing ovens.
- **Scalability.** Formulations have been successfully scaled for pilot applications, with hybrid formulation volumes of **20–50 liters** prepared for semi-industrial validation.
- **Process efficiency.** While "double-padding" has been shown to improve performance, researchers are currently optimising the single-pad process to avoid time-consuming iterations that might be unfit for high-speed industrial lines.
- **Supply-chain sensitivity.** LCA results were strongly influenced by the geographical origin of the textile substrate (e.g., India versus Portugal), demonstrating that sourcing scenarios and transport distances can substantially affect the overall environmental performance of the finishing system.

Waste management & circularity

- **Durability and waste reduction.** By engineering the coating for **washing resistance (targeting 10+ domestic washes)**, the project extends the service life of the textile, reducing both chemical waste from frequent re-treatment and the premature disposal of garments.
- **Recycling stream integrity.** The use of hybrid organic/inorganic silica-based networks is intended to ensure the finish remains **compatible with future textile recycling** processes, supporting a circular economy for polyester and cotton fibers.
- **Pre-treatment safety.** Manufacturers must implement a **pre-treatment wash** for natural substrates like cotton to eliminate legacy micro-components from the weave process that can interfere with biological safety assessments.

7. Validation from BIO-SUSHY Case Studies

The **SSbD** framework has been validated through technical and toxicological trials in the textile case study. These results demonstrate that hybrid sol-gel finishes can meet high-performance requirements for water and oil repellency while significantly improving the safety and environmental profile of the finishing process.

Measure	**Case Study**	**Result**
Solvent-free/Water-based process	Textile	Utilised **100% water-based formulations**, effectively minimising worker exposure to added VOCs during industrial padding.
Bio-based precursor integration	Textile	Achieved up to **50% bio-sourced components** in formulations such as Depersol-Green through the use of functionalised fatty acids.
Washing resistance optimisation	Textile	Engineered formulations (e.g., Pearlisol, Depersol) to maintain **medium hydrophobic properties for up to 10 domestic washing cycles**.
Oleophobic performance	Textile	Successfully reached a **domestic oil contact angle above 130°** using functionalised fillers like $CaCO_3$ grafted with bio-based linkers.
Toxicological safety validation	Textile	Experimental MTT assays confirmed **no cytotoxic effects** across skin (HaCaT), lung (A549), and gut (CaCo-2) cell lines for the developed textile finishes.
Strategic chemical substitution	Textile	Substituted methoxy-based precursors with ethoxy-based ones (e.g., **GPTES**) to ensure the hydrolysis process releases safer **ethanol** instead of hazardous methanol.

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Interfacial stability	Textile	Validated that **covalent bonding of functional fatty acid linkers** significantly improves adhesion and mechanical cohesion on polyester fibers.
Substrate safety screening	Textile	Identified and mitigated legacy pollutants in cotton fabrics by implementing a **pre-treatment wash**, removing micro-components that otherwise trigger biomembrane activity.

8. Trade-offs & Limitations

The implementation of the SSbD framework for textile finishing involves balancing technical performance and durability against cost and industrial throughput requirements. The following trade-offs and limitations have been identified during the development of hybrid sol-gel coatings for textiles:

Technical Performance Trade-offs

- **Washing resistance vs. hydrophilic influence.** To improve the durability of the coating through repeated washing cycles, **adhesion promoters** (e.g., GPTES) are required. However, these promoters can sometimes introduce **hydrophilic properties** due to their chemical nature, creating a design trade-off where increasing durability might slightly compromise the initial level of water repellency.
- **Water repellency vs. standard oil repellency.** While the developed formulations have successfully reached target **water repellency** (surface tension between 2 and 7 mN/m), reaching full **oil repellency** according to the **ISO 14419 standard** remains a challenge. Formulations currently show promising oil contact angles (>130°) but do not yet meet all standard rating requirements for high-performance oleophobicity.
- **Soft touch vs. curing efficiency.** Maintaining the **luxury aesthetics and "soft touch"** of textiles requires decreasing curing temperatures. However, lower temperatures may require **longer curing durations**, which can impact the overall productivity of high-speed industrial finishing lines.

Process & scalability constraints

- **Double-padding complexity.** Experimental results indicate that a **"double-padding" process** (applying two layers of the formulation) significantly improves **washing resistance** compared to single-padding. However, this additional step is more **time-consuming and complex**, potentially making it less suitable for standard industrial lines that prioritise high-speed, single-pass processing.

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- **Substrate-specific performance.** The current hybrid sol-gel coatings perform exceptionally well on **polyester** but show lower adhesion and durability on **cotton and polyester/cotton blends**. This limits the immediate applicability of the coatings across the entire range of consumer textiles without further substrate-specific optimisation.
- **Occupational hazard management.** Although the formulations are **100% water-based** to reduce VOCs, the hydrolysis of silane precursors naturally forms small amounts of alcohol. Managing these byproducts requires maintaining **strict ventilation and PPE protocols** (e.g., mandatory masks), which adds operational requirements compared to traditional non-reactive finishes.

Cost constraints

- **Bio-based precursor costs.** The use of specialised **bio-based linkers** (e.g., functionalised oleic acid) and **modified lignin fillers** currently involves higher raw material costs than traditional petroleum-derived precursors.
- **Production cost target.** A core limitation is the project target to limit the total **production cost increase to less than 20%** compared to current PFAS-based treatments. Achieving this requires high material efficiency and successful scaling to large industrial volumes (e.g., >50 liters) to achieve economies of scale.

9. Implementation Roadmap

The following roadmap provides a systematic, six-step approach for implementing SSbD principles in the development of hybrid sol-gel coatings for textiles. This process ensures that hazardous substances like **PFAS** are replaced by bio-based alternatives without compromising functional durability or worker safety.

1. Screen Substances

- **Regulatory review.** Evaluate all chemical building blocks, including silane precursors, catalysts, and additives, against **CLP classifications** and **REACH dossiers**.
- **Identify byproducts.** Screen precursors for hazardous byproducts released during hydrolysis; for example, identify if a precursor releases **methanol** (high hazard) or **ethanol** (lower hazard).
- **Digital gap-filling.** Use **QSAR modeling** and the **BIO-SUSHY Registry** to predict the toxicological and physicochemical properties of substances where experimental data is missing.

2. Select safer alternatives

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- **Strategic precursor choice.** Prioritise ethoxy-based precursors (e.g., **GPTES**) over methoxy-based ones (e.g., GPTMS) to ensure the finishing process releases safer **ethanol**.
- **Bio-based feedstocks.** Replace petroleum-derived hydrophobic agents with renewable **functionalised fatty acids** (e.g., oleic or stearic acid).
- **Water-based systems.** Select **100% water-based** formulations to eliminate the need for volatile organic solvents, significantly reducing potential worker exposure to **VOCs** during the padding process.

3. Adapt formulation

- **Enhance adhesion.** Integrate **functional fatty acids** bearing triethoxysilane groups that covalently bond to textile fibers, ensuring the coating is mechanically cohesive and durable.
- **Optimise for durability.** Adjust the concentration of adhesion promoters to maintain **medium hydrophobic properties** for at least **10 domestic washing cycles**.
- **Surface structuration.** Incorporate functionalised fillers (e.g., **$CaCO_3$ or ZnO** grafted with bio-based linkers) to create the micro-roughness necessary for achieving **oil repellency**.
- **Aesthetic refinement.** Adjust curing temperatures and organic content to maintain the **"soft touch"** and original color of the fabric.

4. Validate

- **Functional testing.** Perform static contact angle measurements (water and diiodomethane) and standardised **spray tests** before and after washing cycles.
- **Safety assurance.** Conduct **MTT cytotoxicity assays** on human skin (HaCaT), lung (A549), and gut (CaCo-2) cell lines to confirm the safety of the final finish.
- **Early hazard detection.** Use **biomembrane sensors** to screen leachates from the treated textile for early molecular initiating events (MIE) that could indicate toxicity.

5. Assess End-of-Life (recycling)

- **Circularity modelling.** Develop **Life Cycle Assessment (LCA)** scenarios comparing the PFAS-free textile to conventional benchmarks, accounting for factors like energy use in fiber production and cleaning impacts.
- **Recycling stream integrity.** Ensure that the hybrid organic/inorganic network of the coating does not interfere with the mechanical or chemical **recyclability of polyester** and cotton fibers.

6. Scale-Up

- **Pilot synthesis.** Transition from laboratory batches to pilot volumes (e.g., **20–50 liters**) required for semi-industrial trials.
- **Industrial application.** Validate the formulation on standard **roll padder lines**, optimising substrate speed and nip pressure for continuous production.

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- **Process efficiency.** Test the feasibility of **"double-padding"** versus single-padding techniques to maximise washing resistance while maintaining high industrial throughput.

10. KPIs

- **Bio-based content (%).** The hybrid sol-gel formulations have achieved a bio-based carbon content of 5–15% in the dry film. While the broader project-wide target for bio-based content is 25–80%, the glass case study is working to increase its percentage by replacing activators with bio-based alternatives like citric acid and incorporating renewable additives such as functionalised cellulose.
- **PFAS-free.** A core objective is the 100% replacement of PFAS in all coating formulations. Technical validation confirmed that target surface energies of 21–22 mn/m, necessary for omniphobicity, can be reached without fluorinated compounds by utilising polydimethylsiloxane (PDMS) and hybrid inorganic/organic networks.
- **Recyclability / repulpability (%).** A major KPI for this case study is the "slip effect," which is targeted to reduce product residue waste from 20% down to approximately 5%. Life cycle assessment results have validated that the "reuse at home" and refill scenario for functionalised glass bottles fully passes SSbD environmental criteria, achieving at least a 25% reduction in impact for most categories. The coatings are engineered to be hybrid organic/inorganic and mainly silica-based to ensure that the 100% recyclability of glass is conserved without contaminating the recycling stream.
- **Hazard classification compliance.** The project requires that 100% of chemical ingredients pass the SSbD hazard assessment. For the textile finishes, this was achieved by the strategic substitution of methoxy-based precursors (e.g., GPTMS) with ethoxy-based ones (e.g., GPTES) to ensure the hydrolysis process releases safer ethanol instead of hazardous methanol. Experimental MTT cytotoxicity assays on human skin (HaCaT), lung (A549), and gut (CaCo-2) cell lines confirmed the final formulations and their leachates pose no cytotoxic effects.
- **Energy consumption.** The project seeks to reduce the climate change impact by optimising processing parameters, specifically through low curing temperatures and short durations. formulations are designed to be industrially compatible with flexible curing cycles, such as fast curing at 150°c for only 1 minute or lower-temperature cycles at 45°c for 30 minutes to balance throughput with energy footprints.

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11. Key Takeaways

The implementation of the **SSbD** framework for the functionalisation of glass cosmetic packaging highlights several actionable recommendations to achieve high performance while ensuring safety and circularity.

- **Design safe materials early.**
    - Implement early-stage hazard screening of all chemical building blocks to identify and replace hazardous substances. In this case study, **SSbD Hazard assessment successfully flagged 1-methoxy-2-propanol** for substitution due to its content of the hazardous isomer 2-methoxy-1-propanol.
    - Integrate digital intelligence, including **computational QSAR modeling and physics-based simulations**, to predict toxicological profiles and surface performance (e.g., target surface energy of 21–22 mN/m) before synthesised materials reach the pilot stage.
- **Eliminate and mitigate emissions.**
    - Optimise sol-gel formulations to reduce the environmental and occupational footprint. Increasing the **water-to-alcohol ratio to 42** has been validated to **reduce Volatile Organic Compound (VOC) emissions by 50%** without compromising the mechanical integrity or adhesion of the coating.
- **Maximise resource efficiency through the "Slip Effect."**
    - Utilise non-stick inner surface technology to facilitate nearly full product recovery. This measure **reduces cosmetic product residue waste from 20% down to approximately 5%**, which significantly lowers the overall environmental burden of the product system.
- **Ensure circularity and recyclability.**
    - Engineer coatings to be compatible with existing end-of-life infrastructure. The **silica-based hybrid organic/inorganic coatings** are designed to ensure the **100% recyclability of glass** is conserved without contaminating recycling streams.
    - Enable and validate circular business models. Life Cycle Assessment (LCA) results confirm that **"reuse at home" and refill scenarios** for functionalised glass bottles fully pass **SSbD environmental criteria**, potentially reducing overall environmental impact by 25%.
- **Validate with industrial case studies.**
    - Transition from laboratory-scale benchmarks to real-world applications by demonstrating that bio-based hybrid finishes (e.g., Pearlisol, Depersol) remain functional under realistic factory speeds when applied using standard **Roll Padder (dip-pad-dry-cure)** lines.

  - Confirm that these industrial finishes maintain target **water and oil repellency** while preserving fabric aesthetics, specifically a **soft touch**, and remain durable enough to persist through at least **10 domestic washing cycles**.