



BIO-SUSHY



# SSbD Guidelines for *Bio-based coatings* for *glass cosmetic*

## 1. Scope & Application

The SSbD guidelines for the functionalisation of glass packaging provide a strategic framework for developing **high-performance hybrid sol-gel coatings** designed without using hazardous perfluoroalkyl substances (PFAS). This specific case study focuses on creating a "**slip effect**" on the inner surfaces of glass containers to achieve durable water and oil repellency (omniphobicity). By reducing product residue waste from **20% down to approximately 5%**, these guidelines facilitate a shift toward a circular economy, prioritising "**reuse at home**" and **refill scenarios** over traditional single-use packaging. The framework integrates advanced **physics-based simulations** and **data-driven hazard assessments** to ensure that technical objectives, such as maintaining luxury aesthetics and mechanical durability, are met while simultaneously **mitigating Volatile Organic Compound (VOC) emissions** and ensuring the safety of both the manufacturing process and the final consumer product.

- **Application.** This case study focuses on the development of **hybrid sol-gel coatings** specifically designed for the **inner surfaces of glass cosmetic containers**, such as 30 ml bottles for skincare products. These coatings are applied using specialised **inner spray techniques** with long nozzles and rotating spray heads to ensure uniform coverage inside small-diameter containers.
- **Material Type.** The coatings consist of **hybrid sol-gel systems with high inorganic content**, utilising metal alkoxides like **Tetraethyl orthosilicate (TEOS)** combined with organic moieties to form a durable, glass-like network. Formulations incorporate hydrophobic additives such as **Polydimethylsiloxane (PDMS)** or **bio-based functionalised cellulose** (ethyl cellulose and hydroxypropylcellulose ) to replace conventional PFAS treatments. The solvent system is typically a **mix of alcohol and water**, with ongoing design efforts to increase the water ratio to significantly reduce VOC emissions.



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- **Functionality.** The primary technical objective is to create a "**slip effect**" (omniphobicity) that allows high-viscosity cosmetic creams to slide easily, **reducing product residue waste from 20% to approximately 5%**. The coatings must maintain the **transparency and aesthetics** required for luxury packaging while providing high **scratch, thermal, and chemical resistance**. Additionally, the low-adhesion surface facilitates the **cleaning and reuse** of containers, supporting circular "reuse at home" and refill scenarios.
- **Target stakeholders.** This guidance is intended for **cosmetic brand owners and the glass packaging industry** looking to adopt sustainable, PFAS-free non-stick solutions to meet consumer demand for more natural products. It also targets **chemical formulators and converters** responsible for the synthesis of hybrid resins and the industrial application of coatings in a production environment. Finally, **regulatory and certification bodies** are key stakeholders in aligning these innovative materials with safety standards and standardisation roadmaps for the cosmetic sector.

## 2. Application Context & Functional Requirements

The development of **hybrid sol-gel coatings** for glass cosmetic packaging is driven by the need to replace hazardous PFAS-based treatments with safe, high-performance alternatives that support the transition to a circular economy.

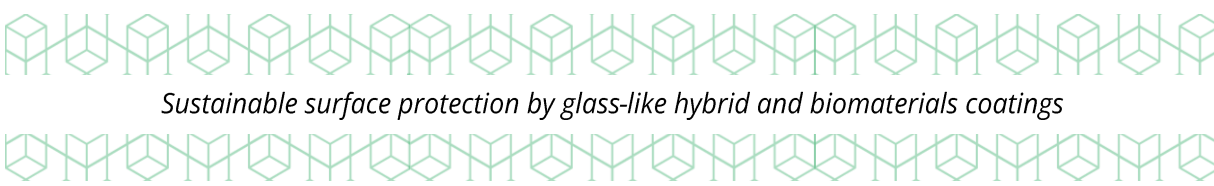
### Product System Description

- **Material and format.** The target system is the **inner surface of glass cosmetic containers**, specifically **30 ml bottles** used for viscous skincare products like face creams.
- **Coating technology.** The system utilises **glass-like hybrid sol-gel coatings** composed of a mixed metal oxide network (e.g., silica, titania) combined with organic moieties and bio-based functional additives.
- **Application method.** Coatings are applied using specialised **inner spray techniques** featuring long nozzles and rotating spray heads to ensure complete and uniform coverage of the bottle's interior.

### Functional Requirements

- **Barrier and surface performance:**





- **Omniphobicity.** The coating must achieve durable water and oil repellency, with a target **surface tension between 18 and 22 mN/m**.
- **The "Slip Effect".** The primary goal is to create a low-adhesion surface that allows high-viscosity creams to slide easily, **reducing product residue waste from 20% down to approximately 5%**.
- **Aesthetics and Mechanical Properties:**
  - **Transparency.** The coating must maintain the **transparency and aesthetics** required for luxury cosmetic products.
  - **Durability and adhesion.** Formulations are engineered for **high scratch resistance** and strong chemical bonding (adhesion) to the glass substrate.
  - **Washability.** For reuse scenarios, the coating must withstand multiple **washing and abrasion cycles** without losing its repellent properties.
- **Thermal Resistance:**
  - The coatings are designed for flexible industrial processing, supporting both **low-temperature curing (90°C for 30 minutes)** and **fast curing (250°C for few minutes)**, thereby facilitating reuse scenarios.

## Regulatory context & sustainability constraints

- **PFAS-Free and toxic-free design.** A core objective is the use of a formulation without the incorporation of **PFAS compounds**. All substances must comply with **REACH** regulations, avoiding substances of very high concern (SVHC); for instance, care has to be taken with **1-methoxy-2-propanol solvent** as some grades could contain 2-methoxy-1-propanol which is a hazardous isomer.
- **VOC mitigation.** To protect worker health and reduce environmental impact, formulations aim for a **reduction in VOC emissions of >50%** by increasing the water-to-alcohol ratio up to 60/40.
- **End-of-Life Circularity:**
  - **Reuse and refill.** The design prioritises "**reuse at home**" and **refill scenarios**, which LCA results indicate can reduce environmental impacts by 25% for most categories.
  - **Recyclability.** The hybrid coatings are engineered to be **fully compatible with existing glass recycling streams**, ensuring the material's recyclability is not affected by the functional treatment.

### 3. SSbD Risk Identification

The following table identifies potential risks associated with the development and implementation of hybrid sol-gel coatings for glass cosmetic packaging. While specific to this case study, these risks are generalisable to other sectors using solvent-based functional coatings on inert substrates.

Risk Category	Specific Risk	Relevance
Human Health	<b>Substance Hazard</b> Presence of hazardous isomers such as <b>2-methoxy-1-propanol</b> in solvents.	Triggers mandatory substitution requirements under EC criteria; essential for ensuring consumer safety in cosmetic products.
	<b>Leachate cytotoxicity.</b> Observed cytotoxic effects of coating leachates on <b>lung cell lines (A549)</b> during experimental testing.	Indicates potential health risks if the coating is not fully cured or if particles/vapors are inhaled during production or use.
Environment	<b>VOC emissions.</b> VOC emissions from solvent-based systems (e.g., methoxypropanol).	Sol-gel processes often rely on alcohols; failing to optimise the <b>water-to-alcohol ratio</b> impacts air quality and climate targets.
	<b>Reuse phase release.</b> Potential release of small molecules or coating components into wastewater during "reuse at home" cleaning cycles.	Critical for validating the environmental benefit of reuse scenarios and preventing aquatic ecotoxicity.
Process Safety	<b>High occupational hazard.</b> Sol-gel liquid formulations classified as <b>Hazard Class D</b> due to associated H-phrases.	Highlights the need for advanced engineering controls and personal protective equipment (PPE) to protect workers from toxic vapor exposure.
	<b>Flammability &amp; flash point.</b> Use of low-flash-point alcohol solvents in industrial spray settings.	Requires explosion-proof manufacturing environments and strict handling protocols to prevent industrial accidents.



<b>Circularity</b>	<b>Recycling stream contamination.</b> Hybrid organic/inorganic coatings interfering with the quality of recycled glass cullet.	Advanced functional treatments must remain <b>compatible with existing glass recycling infrastructure</b> to support a circular economy.
	<b>Durability loss.</b> Failure of the "slip effect" or omniphobicity after repeated washing or immersion in solvents like glycerol.	If durability targets are not met, the environmental benefits of waste reduction (reducing residue from 20% to 5%) are negated.
<b>Social</b>	<b>Supply chain transparency.</b> Lack of specific social risk data for global glass production sites in standard databases.	Creates uncertainties in social sustainability assessments; relocation of production to Europe is often needed to mitigate hidden labor risks.

## 4. SSbD Design Principles

The SSbD approach for glass packaging is governed by universal principles designed to harmonise high-performance luxury aesthetics with toxic-free and circular innovation.

- **Use low-hazard substances.** Prioritise chemical building blocks with minimal intrinsic hazard. For glass coatings, this involves identifying and excluding hazardous isomers, such as those found in some grades of **2-methoxy-1-propanol**, found in certain commercial solvents.
- **Use bio-based materials.** Transition away from petrochemical additives by incorporating **bio-based functional fillers** like ethyl cellulose into the sol-gel matrix.
- **Avoid PFAS and SVHCs.** Ensure a **100% PFAS-free** formulation. Design efforts focus on utilising **hybrid sol-gel technology** and polydimethylsiloxane (PDMS) linkers to achieve oil and water repellency without fluorinated compounds.
- **Design for circularity.** Engineer coatings to facilitate **"reuse at home" and refill scenarios**. By creating a low-adhesion surface that prevents product buildup, the packaging becomes easier to clean and prepare for multiple life cycles.



- **Minimise emissions.** Focus on reducing the environmental footprint of the application process. By optimising the **water-to-alcohol ratio** in sol-gel formulations, VOC emissions can be reduced by up to **50%**.
- **Ensure resource efficiency.** Maximise product recovery through the "**slip effect.**" High-performance coatings are designed to reduce product residue waste from **20% down to 5%**, ensuring that almost 100% of the cosmetic content is available to the consumer.
- **Validate safety early.** Utilise a tiered strategy integrating **computational QSAR modeling** and **biomembrane sensors** to screen for potential hazards before the coating moves to pilot-scale production.

## 5. Recommended SSbD Measures

The following table outlines the actionable and replicable **SSbD** measures developed for the functionalisation of glass cosmetic packaging. These measures translate safety and sustainability objectives into concrete industrial practices for the implementation of hybrid sol-gel coatings.

SSbD Objective	Recommended Measure	Implementation Example	Applicability
Reduce Toxicity	Development of <b>100% PFAS-free</b> and substitution of hazardous industrial solvents.	Replace fluorinated precursors with <b>functionalised fatty acids</b> (e.g., oleic acid) or functionalized cellulose; explicitly substitute <b>1-methoxy-2-propanol</b> (flagged for hazardous isomers) with safer alcohol-water mixtures.	High
Eliminate/Mitigate Emissions	<b>Optimise solvent formulations</b> to reduce the environmental and occupational footprint.	Increase the <b>water-to-alcohol ratio up to 60/40</b> in sol-gel recipes, which has been validated to <b>reduce VOC emissions by 50%</b> .	High
Enable Circularity	Implement " <b>slip effect</b> " <b>technology</b> to minimise product waste and facilitate reuse.	Create high-performance non-stick inner surfaces to <b>reduce cosmetic residue from 20% to 5%</b> , directly enabling durable	High





		<b>"reuse at home" and refill scenarios</b> that pass SSbD environmental criteria.	
<b>Ensure Circularity</b>	Maintain <b>compatibility with end-of-life glass recycling</b> infrastructure.	Engineer hybrid organic/inorganic coatings to ensure they do not contaminate or degrade the quality of <b>glass recycling streams</b> during standard processing.	<b>High</b>
<b>Improve Safety</b>	Utilise a <b>tiered assessment strategy</b> for early-stage hazard screening.	Combine <b>computational QSAR modeling</b> with <b>biomembrane sensors</b> and <b>MTT cytotoxicity assays</b> on human lung (A549) and skin (HaCaT) cell lines to identify potential risks of leachates before upscaling.	<b>High</b>
<b>Ensure Resource Efficiency</b>	Optimise <b>precision application</b> to minimise material waste and match functionality.	Deploy <b>inner spray techniques</b> with rotating nozzles and specialised long heads to achieve target surface energy ( <b>18–22 mN/m</b> ) with uniform, minimal coating thickness.	<b>Medium</b>
<b>Strengthen Social Acceptance and Public Trust</b>	<b>Engage value chain actors and consumers early</b> to address concerns around the safety, luxury performance, and credibility of bio-based alternatives.	Identify acceptance barriers and support <b>transparent communication</b> regarding the waste reduction benefits of the "slip effect" and the reliability of <b>"reuse at home" and refill scenarios</b> for premium cosmetic containers.	<b>Medium</b>



## 6. Process & Manufacturing Considerations

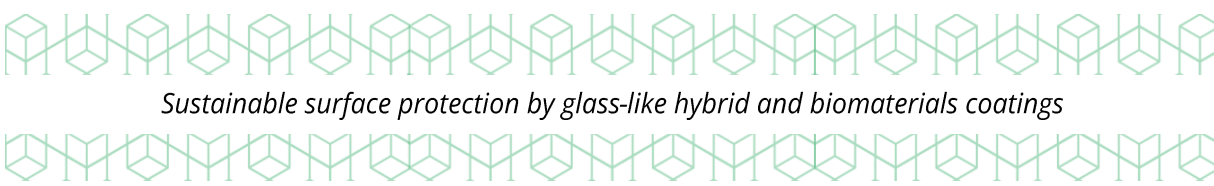
To successfully translate SSbD principles into industrial reality for glass cosmetic packaging, the manufacturing process must balance the technical requirements for luxury aesthetics with rigorous safety and circularity standards.

### Processing conditions

- **Application method.** The project utilises a specialised **inner spray technique** featuring long nozzles and rotating spray heads. This setup is specifically designed to ensure uniform and complete coverage of the interior surfaces of small-diameter containers, such as **30 ml cosmetic bottles**.
- **Solvent system.** Formulations are currently **solvent-based**, utilising a mix of **alcohol (specifically methoxypropanol)** and water.
- **Flexible curing cycles:** The hybrid coatings are engineered to support various industrial line speeds through flexible curing options:
  - **Low-temperature curing:** 90°C for 30 minutes.
  - **Fast curing:** 250°C for a few minutes.
  - **UV curing:** Potentially achievable in 1 minute (care has to be taken on the use of photoinitiators, most of them being hazardous substances).
- **Precision control.** The system is fed from a **pressurised stainless steel tank** to provide consistent fluid delivery to the rotating nozzle.

### Worker safety measures

- **VOC mitigation.** A primary occupational health objective is reducing exposure to methoxypropanol. By optimising the formulation to increase the **water-to-alcohol ratio up to 60/40**, the process can **reduce VOC emissions by up to 50%** compared to standard solvent-based hybrid coatings.
- **Risk classification.** The liquid sol-gel formulations used in the glass case study are classified as **Hazard Class D** due to associated H-phrases. Stoffenmanager® risk assessments have assigned these processes a **Risk Score II**.
- **Occupational controls.** To maintain a low exposure classification, manufacturing environments should implement **local exhaust ventilation** and require workers to use



**protective masks** during the spraying phase. Additionally, the use of alcohol solvents necessitates **explosion-proof** equipment and handling protocols.

### Industrial compatibility & scalability

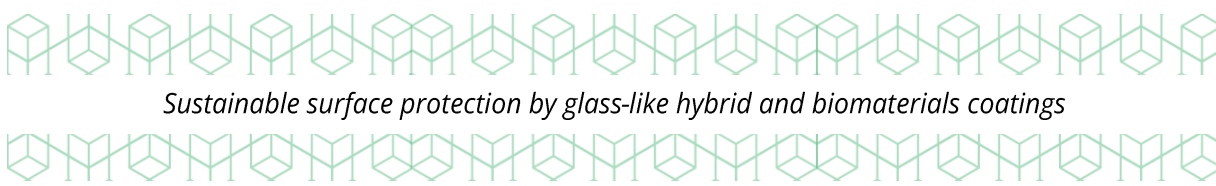
- **Existing infrastructure:** The inner spray application is designed to be **compatible with existing industrial production lines** for glass containers.
- **Scalability.** Formulations have been successfully scaled from laboratory batches to **pilot volumes of 5–10 liters**, providing the minimum amount required for semi-industrial validation.
- **Material reliability.** Validation trials using **immersion in water and glycerol for 14 days** confirmed that the coatings maintain their hydrophobic properties and sliding performance under realistic use conditions.

### Waste management & recovery

- **Reduction of product residue.** The defining industrial advantage of this technology is the "**slip effect**," which ensures that high-viscosity creams slide easily to the bottom of the container. This reduces cosmetic product residue waste from **20% down to approximately 5%**.
- **Support for circular models.** By preventing product buildup, these coatings facilitate the **cleaning and reuse** of glass containers. Life Cycle Assessments (LCA) indicate that the "**reuse at home**" and **refill scenario** fully passes SSbD environmental criteria, potentially reducing overall environmental impact by 25%.
- **Recycling stream compatibility.** The hybrid organic/inorganic coatings are engineered to be **fully compatible with existing glass recycling streams**, ensuring they do not contaminate the recycled glass cullet.

## 7. Validation from BIO-SUSHY Case Studies

The SSbD framework has been validated through the development of the glass cosmetic packaging case study, demonstrating that hybrid sol-gel coatings can achieve high technical performance while significantly improving safety and circularity profiles.



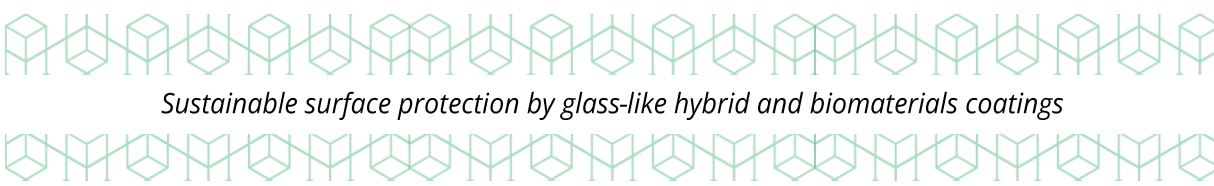
Measure	Case Study	Result
Slip effect implementation	Glass packaging	Successfully <b>reduced face cream residue waste from 20% down to 5%</b> .
VOC emission reduction	Glass packaging	Achieved a <b>50% reduction in VOC emissions</b> by optimising the water-to-alcohol ratio <b>up to 60/40</b> .
Circularity enhancement	Glass packaging	LCA validated that " <b>reuse at home</b> " and <b>refill scenarios fully pass</b> sustainability LCA and environmental criteria.
Surface performance	Glass packaging	Reached target <b>surface energy of 21–22 mN/m</b> , ensuring durable omniphobicity without PFAS.
Early safety validation	Glass packaging	SSbD hazard assessment successfully <b>identified and flagged hazardous solvent isomers</b> (e.g., 2-methoxy-1-propanol) for replacement.
Coating stability	Glass packaging	Maintained hydrophobic properties and sliding performance after <b>14 days of immersion in water and glycerol</b> .
Aesthetic preservation	Glass packaging	Validated that hybrid films maintain the <b>high transparency and luxury visual finish</b> required for cosmetic products.
Inflammatory safety	Glass packaging	ELISA assays confirmed <b>no overexpression of IL-8 protein</b> , indicating the coatings do not trigger inflammatory responses.

## 8. Trade-offs & Limitations

The development of hybrid sol-gel coatings for glass cosmetic packaging within the BIO-SUSHY project involves navigating several technical, economic, and industrial trade-offs to replace PFAS while maintaining luxury performance standards.



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## Technical Performance Trade-offs

- **Aesthetics vs. Bio-based content.** While polydimethylsiloxane (PDMS) additives provide excellent slip properties, initial trials showed they can cause a **"blurred" or "fatty" visual finish** if the formulation is not precisely balanced. Achieving 100% bio-based content while maintaining the **high transparency** required for luxury cosmetics remains a major technical challenge.
- **VOC reduction vs. oleophobicity.** To reduce Volatile Organic Compound (VOC) emissions by **50%**, the project increased the water-to-alcohol ratio to 42. While this significantly improves environmental performance, results indicate it leads to a **lower hexadecane contact angle** (oleophobicity), though the coating remains functional.
- **Formulation stability.** While the "slip effect" remains stable after 14 days of immersion in water and glycerol, experimental testing identified **cytotoxic potential in leachates** from certain glass coatings at high concentrations, particularly affecting lung cell lines (A549). This requires careful control of chemical bonding to ensure no harmful substances are released during use.

## Cost Constraints

- **Raw material costs.** Utilising innovative **bio-based linkers and functionalised cellulose** currently results in higher raw material costs compared to traditional petroleum-derived or PFAS treatments.
- **Production target.** A core project objective is to limit the total production cost increase to **less than 20%** compared to current products. Reaching this goal depends on optimising material efficiency and achieving industrial scale-up.

## Scalability & industrial constraints

- **Energy footprint.** The project offers flexible industrial processing, including **fast curing (250°C for a few minutes)** to maintain high line speeds. However, this high-temperature requirement increases the **energy consumption** per unit compared to longer, lower-temperature drying cycles (e.g., 90°C for 30 minutes).
- **Application complexity.** Applying coatings to the inner surfaces of small-diameter containers (30 ml bottles) requires **highly specialised inner spray technology** with rotating nozzles and pressurised delivery systems. This complexity may pose barriers to adoption for manufacturers with standard external coating equipment.



- **Operational safety requirements.** Despite efforts to increase water content, the hybrid sol-gel process remains solvent-based. This necessitates **explosion-proof manufacturing environments** and the use of advanced personal protective equipment (PPE) to manage the hazards associated with alcohol-based precursors.

## 9. Implementation Roadmap

The following roadmap provides a systematic approach for implementing Safe and Sustainable by Design (SSbD) principles in the development of hybrid sol-gel coatings for glass cosmetic packaging. This sequence ensures that safety and circularity are integrated into the product lifecycle from initial chemical selection through industrial application.

### 1. Screen substances

- **Initial review.** Conduct a thorough screening of all chemical building blocks, including precursors, solvents, and catalysts, against harmonised **CLP classifications** and **REACH dossiers**.
- **Gap-filling.** Utilise digital tools, such as the **BIO-SUSHY Registry** and **QSAR modeling**, to predict toxicological profiles when experimental data is missing.
- **Hazard identification.** Apply **SSbD hazard assessment criteria** to flag substances of concern. In this case study, early screening successfully identified **1-methoxy-2-propanol** as a candidate for substitution due to hazardous isomer content.

### 2. Select safer alternatives

- **PFAS replacement.** Prioritise the selection of **PFAS-free hydrophobic and oleophobic materials**, such as hybrid sol-gel systems utilising polydimethylsiloxane (**PDMS**) or **metal alkoxides**.
- **Bio-based substitution.** Replace petroleum-based additives with renewable options, such as **functionalised cellulose** (ethyl cellulose and hydroxypropylcellulose).
- **Solvent optimization.** Move toward **water-rich formulations** to replace volatile organic solvents, aiming to significantly lower the VOC footprint.

### 3. Adapt formulation





- **Optimising the network.** Integrate bio-based linkers into the inorganic sol-gel matrix to ensure high **mechanical durability** and transparency for luxury aesthetics.
- **VOC mitigation.** Fine-tune formulation ratios, specifically targeting a **water-to-alcohol ratio of 60/40**, which has been validated to **reduce VOC emissions by 50%**.
- **Physics-based refinement.** Use atomistic simulations to predict and optimise **surface tension (target 18–22 mN/m)** and wetting behavior before physical production.

#### 4. Validate

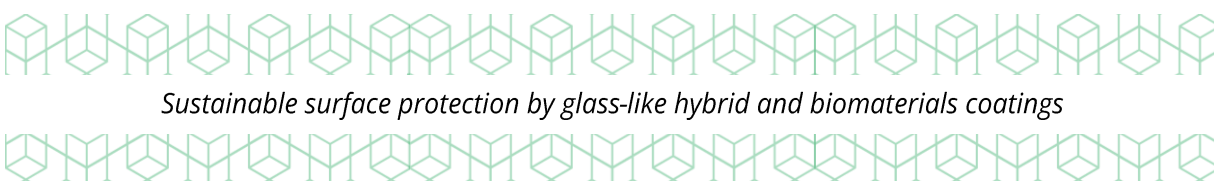
- **Functional testing.** Confirm the **"slip effect"** through contact angle and sliding angle measurements, ensuring product residue waste is reduced from **20% to approximately 5%**.
- **Safety assurance.** Perform **experimental toxicological assays** (MTT) on human lung (A549) and skin (HaCaT) cell lines to ensure leachates do not pose health risks.
- **Stability verification.** Conduct **immersion tests** in water and glycerol for 14 days to confirm the coating maintains its repellent properties under realistic use conditions.

#### 5. Assess End-of-Life (recycling)

- **Circularity modelling.** Perform a **LCA** to evaluate different scenarios, prioritising **"reuse at home" and refill** models which have shown to fully pass SSbD environmental criteria.
- **Recycling compatibility.** Ensure that hybrid organic/inorganic coatings are **fully compatible with existing glass recycling streams**, preventing contamination of the glass cullet during processing.

#### 6. Scale-Up

- **Batch production.** Transition from lab-scale synthesis to **pilot volumes of 5–10 liters**, the minimum required for semi-industrial validation.
- **Industrial application.** Implement specialised **inner spray techniques** featuring long nozzles and rotating spray heads to ensure uniform coverage in small containers like 30 ml cosmetic bottles.
- **Process validation.** Test formulations on **industrial production lines** (e.g., pressurised stainless steel delivery systems) to confirm processability and coating stability at high line speeds.



## 10. KPIs

The monitoring of safety and sustainability performance for the glass cosmetic packaging case study is centered on a series of technical and environmental Key Performance Indicators (KPIs) that track the project's success in replacing hazardous substances while enabling a circular economy.

- **Bio-Based content (%)**
  - **Current status.** The hybrid sol-gel formulations have achieved a **bio-based carbon content of 5–15%** in the dry film.
  - **Optimisation target.** While the 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**
  - **Target.** A core objective is the development of **100% PFAS-free** in all coating formulations.
  - **Achievement.** 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 and reuse potential**
  - **Resource efficiency.** 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%**.
  - **Circularity.** Life Cycle Assessment (LCA) results have validated that the "**reuse at home**" and **refill scenario** for functionalised glass bottles fully passes SSbD environmental criteria, using the SSbD framework scoring system and achieving at least a **25% reduction** in impact for most categories.
  - **Recycling compatibility.** The coatings are engineered to be hybrid organic/inorganic (mainly silica-based) to ensure that the **100% recyclability of glass** is conserved without contaminating the recycling stream.
- **Hazard classification compliance**
  - **SSbD Hazard assessment.** The project requires that 100% of chemical ingredients pass the **SSbD hazard assessment** (Group B or C).



- **Early intervention.** Screening successfully flagged and removed **1-methoxy-2-propanol** due to its hazardous isomer content, ensuring the final formulation is safe for cosmetic application.
- **VOC reduction.** To protect worker health and the environment, the project successfully reduced **VOC emissions by 50%** by increasing the water-to-alcohol ratio in the formulation **up to 60/40**.
- **Energy consumption**
  - **Process optimization.** The project seeks to reduce the climate change impact by optimising processing parameters, specifically through **low curing temperatures or short durations at high temperature**.
  - **Flexible curing.** Formulations are designed to be Industrially compatible with flexible curing cycles, such as **fast curing at 250°C for a few minutes** or lower-temperature cycles at **90°C for 30 minutes** to balance throughput with energy footprints.

## 11. Key Takeaways

The following actionable recommendations summarise the implementation of **SSbD** principles for the functionalisation of glass cosmetic packaging, as demonstrated in the BIO-SUSHY project.

- **Design for safety from the start.**
  - Utilise early-stage screening to identify and replace hazardous substances. For instance, **1-methoxy-2-propanol** was flagged for substitution due to the presence of the hazardous isomer 2-methoxy-1-propanol.
  - Integrate digital intelligence, such as **physics-based simulations** and **QSAR modeling**, to predict surface performance and toxicological profiles before physical synthesis.
- **Eliminate and mitigate emissions.**
  - Optimise formulations to reduce the environmental and occupational footprint. Increasing the **water-to-alcohol ratio up to 60/40** has been validated to **reduce VOC emissions by 50%** in hybrid sol-gel coatings.
- **Maximise resource efficiency through the "Slip Effect."**



- Engineer coatings to provide durable water and oil repellency (omniphobicity) on inner surfaces. This technology **reduces cosmetic product residue waste from 20% down to approximately 5%**, ensuring nearly full product recovery for the consumer.
- **Enable and validate circular business models.**
  - Prioritise "**reuse at home**" and **refill scenarios**, which have been shown via LCA to fully pass SSbD environmental criteria and potentially reduce overall impacts by 25%.
  - Ensure that hybrid coatings are compatible with existing infrastructure. The silica-based nature of these coatings ensures that the **100% recyclability of glass** is conserved.
- **Validate with specialised industrial indicators.**
  - Move from laboratory benchmarks to real-world application. For glass containers, this includes validating the **inner spray technique** using rotating nozzles for small-diameter 30 ml bottles and confirming the "slip effect" with high-viscosity cosmetic creams.
  - Confirm safety through **experimental toxicological assays** (e.g., MTT cytotoxicity and biomembrane sensor tests) to ensure leachates from the final coated product do not pose health risks.

