

Safe-and-Sustainable-by-Design for Photocurable Materials: Hazard, Exposure, Performance and Lifecycle Trade-Offs

Lifecycle assurance and responsible innovation

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Abstract

Safe-and-sustainable-by-design (SSbD) is a decision framework rather than a label attached after formulation. Applied to photocurable materials, it requires simultaneous visibility of hazard, exposure, technical performance and lifecycle considerations, while avoiding the false conclusion that improvement on one axis proves overall superiority. This review applies one controlling framework instrument, Commission Recommendation (EU) 2026/510, to photocurable-material development. It is therefore a framework-application article, not a literature review. Life-cycle assessment, allocation and environmental-superiority claims remain owned by ER-17. A hypothetical alternatives assessment distinguishes exclusions, weighted preferences and missing evidence and examines sensitivity to the chosen decision rule.

Keywords: safe-and-sustainable-by-design · photocurable materials · hazard · exposure · performance · lifecycle trade-offs

1. Scope and evidence statement

This article uses one authoritative framework instrument as its spine [1]. It does not represent two independent sources. The purpose is to translate SSbD logic into photopolymer engineering questions without claiming that a single framework provides material-specific limits.

2. Hazard is not the whole decision

A safer component substitution can alter viscosity, cure kinetics, conversion, extractables, mechanical performance or process robustness. Hazard reduction should therefore be evaluated with the function that the material must still perform. A substitution that prevents adequate cure can create downstream exposure or waste rather than remove risk.

3. Exposure depends on lifecycle stage

The relevant exposure state differs between raw-material handling, formulation, printing, washing, post-cure, finishing, use and disposal. A cured part cannot be assessed by the same exposure logic as uncured resin. SSbD evaluation should therefore distinguish material states and identify who is exposed, by what route and under which operational controls.

4. Performance is a safety-relevant constraint

Technical performance is not an optional commercial add-on. In a structural, dental, medical or electrical application, inadequate performance can itself create harm. The framework should therefore treat performance as a constraint that must remain explicit during safer-substitution decisions.

5. Trade-offs and decision transparency

SSbD does not eliminate trade-offs; it makes them visible within a structured assessment framework [1]. A formulation can improve hazard while increasing energy demand, reduce solvent use while worsening cleanability, or increase durability while reducing recoverability. These interactions should be recorded as decision variables, not collapsed into one sustainability score unless a justified method exists.

6. Boundary with ER-17

Life-cycle comparison, inventory modelling, allocation choices and any claim of environmental superiority remain within ER-17. ER-486 may identify that a lifecycle trade-off exists and that it must be assessed; it does not calculate or adjudicate comparative life-cycle impact.

7. A photocurable-material decision matrix

For each candidate formulation change, record: intended function; relevant hazardous properties; exposure scenario by lifecycle stage; performance requirements; manufacturing feasibility; waste and circularity considerations; data gaps; and the decision rationale. A missing datum should remain visible rather than being replaced by a default assumption.

8. Substitution and regrettable transfer

Substitution should be evaluated beyond molecular identity. A replacement can shift burden from hazard to exposure, from manufacturing to use, or from one lifecycle stage to another. The appropriate engineering question is whether the total controlled decision space improves under the declared boundary, not whether one property is lower.

9. Minimum reporting

State the SSbD framework version; the material state; intended function; hazard evidence; exposure scenario; performance constraints; lifecycle questions deferred to ER-17; assumptions; unresolved data; and the decision rule used to compare options.

10. An alternatives assessment with explicit evidence states

The proposed application compares alternatives for a defined function and manufacturing boundary. Each alternative would have separate records for technical feasibility, hazard-related evidence, exposure conditions, resource use and lifecycle considerations relevant to the selected assessment. A missing value should remain missing rather than be converted to a favourable score. The comparison would state which dimensions are directly measured, modelled, supplied by a third party or unresolved.

Consider a hypothetical pair of formulations. Alternative A has a lower measured resource input for a declared operation, while B has a better documented use-phase exposure profile. Without comparable evidence in both dimensions, an overall claim that one is safer and more sustainable would exceed the comparison. The useful result may instead be a specific data request or a conditional preference under a stated decision rule.

A screening condition that excludes an alternative should be distinguished from a weighted preference among alternatives that remain eligible. Combining the two in an opaque score can let strength in one dimension compensate for a condition that the decision maker intended to treat as non-compensatory. The chosen rule should be stated before the final ranking.

11. Use sensitivity to expose value judgments and missing evidence

Where a proposed assessment uses weights, those weights represent a decision convention and need a rationale. Varying them can show whether a preferred alternative is robust to plausible differences in priorities. It does not resolve missing measurements. If the ranking changes only because an unknown value was assigned an arbitrary midpoint, the next step is evidence collection rather than reporting a precise winner.

The functional unit also matters. Comparing a kilogram of material may answer a different question from comparing the amount required to deliver a defined accepted component over a declared use period. Yield, service function and any additional processing should be included where the selected boundary requires them. Otherwise, an apparent improvement may arise from moving a burden outside the comparison.

The proposed output is a decision record containing the function, alternatives, evidence states, exclusions, comparison rule, sensitivity and unresolved questions. It is an application architecture for the framework, not a certification of a material. A later formulation or process change would require review of the affected evidence rather than automatic inheritance of the previous assessment.

Supplementary critical engineering analysis: Multi-objective assessment boundary: Safe-and-sustainable-by-design decisions involve potential trade-offs across uncured constituents, worker handling, emissions, cured-material performance, service life and end-of-life processing. A lower-hazard raw material is not necessarily preferable across the full product system if substantially higher energy use, shorter functional life or more demanding waste treatment is required. Conversely, good cured-part performance does not negate exposure risks during liquid-resin handling. Every comparison should state the functional unit, alternative formulation, system boundary and data quality.

Evidence maturity and substitution gates: Hazard screening, exposure modelling, lifecycle inventory and application qualification answer different questions and should not be collapsed into one aggregate sustainability claim. A proposed substitution gate would first verify the relevant hazards and exposure scenarios, then test functional equivalence and finally evaluate lifecycle trade-offs using compatible assumptions. Missing toxicology or end-of-life data should be recorded as uncertainty rather than interpreted as evidence of safety.

Additional critical synthesis: evidence, applicability and qualification: Regulatory nature of the current framework: Commission Recommendation (EU) 2026/510 of 6 March 2026 revises the European safe-and-sustainable-by-design assessment framework for chemicals and materials. The Commission presents it as a voluntary decision-making approach for innovation, not as a product approval, certification or substitute for applicable chemical, workplace or device law. That distinction matters for photocurable formulations: completion of a framework exercise does not prove that a resin is biocompatible, non-hazardous or suitable for an intended end use. Assessment should record legal obligations and voluntary design criteria separately, with the status and publication date of each source.

Functional equivalence and trade-off analysis: A substitution comparison should retain the same intended function and performance threshold. Otherwise a lower-hazard ingredient could appear preferable because the alternative has been allowed to provide less durability or require more frequent replacement. The functional unit, manufacturing yield, use phase and end-of-life route should be stated before comparing impacts. Hazard, exposure, technical performance and environmental burdens should remain separately visible until the decision rule is justified. A single unweighted sustainability score can obscure material trade-offs and poorly characterised pathways.

Data gaps and defensible conclusions: Screening information, laboratory hazard studies, process exposure measurements and lifecycle inventory data have different confidence levels. Missing evidence should be recorded as a gap, not converted into a positive finding of safety. The assessment needs the identity and range of formulation constituents, plausible liquid-handling and curing exposures, service-state performance and realistic disposal or recovery conditions. Sensitivity analyses should identify assumptions able to reverse the preferred alternative. A defensible output is a conditional design decision with an uncertainty register and a plan to collect the most decision-relevant missing measurements.

Future research on photocurable systems: Comparative evidence is especially needed at the boundary between uncured formulation hazards and the state of the manufactured article. Crosslinked materials can contain extractable constituents and may change after ageing or environmental exposure, so testing should reflect the product's final processing history and intended use. Studies should report both direct process data and downstream burden models. Results across different printer wavelengths, cleaning solvents and post-cure protocols should not be pooled as though they represented one standard material state.

Critical evidence synthesis: Safe-and-sustainable-by-design: burden shifting and comparative boundaries: Comparing photocurable formulations requires functional equivalence before comparing sustainability indicators. A lower-hazard constituent is not necessarily a lower-impact system if it creates lower conversion, a higher reject rate, more intensive washing or shorter usable lifetime. The comparison boundary should therefore include formulation, manufacturing yield, cleaning and post-curing inputs, operational exposure, service requirements and the end-of-life pathway actually available. Where disposal or recycling evidence is missing, a projected circularity benefit cannot be reported as an established environmental improvement.

The safe-and-sustainable-by-design framework provides a structured assessment direction but is not, by itself, proof of compliance or safety certification. A review must identify what has been measured, which lifecycle stages are modelled, and where proxies from other material families are being transferred. Uncertainty and sensitivity analyses should test whether the preferred option changes when assumptions about energy, solvent use, yield or use-life are varied. Conflicting objectives are a finding to report transparently rather than a problem to conceal behind a composite score.

Boundary between environmental claims and verified performance: Statements about sustainability must specify a functional unit, manufacturing boundary and allocation treatment for supports, failed prints, cleaning liquid and post-curing. A favorable material-origin claim does not demonstrate a lower environmental impact if reduced yield or increased processing burden offsets the upstream benefit. Likewise, recyclability in a controlled laboratory protocol is distinct from demonstrated collection and processing at scale. Claims should preserve these distinctions in both engineering reports and customer-facing communications.

A comparative assessment should state its reference process, assumptions about electricity, equipment utilization and the usable lifetime of the resulting part. Sensitivity analysis is necessary when those assumptions dominate the reported difference. Where a voluntary recommendation or framework is cited, its legal status must be stated accurately; it must not be presented as product certification, regulatory authorization or evidence of conformity. A decision framework should identify which additional measurements would change the conclusion and which cannot be inferred from existing data.

12. Limitations

This review applies one policy framework and therefore cannot substitute for substance-specific toxicology, occupational exposure assessment, product qualification or life-cycle analysis. It provides governance structure rather than numerical acceptance criteria.

13. Conclusions

For photocurable materials, SSbD is best implemented as an explicit multi-axis engineering decision. Hazard, exposure and performance must be evaluated in the same material-state context, while lifecycle comparison remains a separate quantified discipline under ER-17.

References

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2. European Commission. Safe and sustainable by design: revised framework and guidance, March 2026. https://research-and-innovation.ec.europa.eu/research-area/industrial-research-and-innovation/chemicals-and-advanced-materials/safe-and-sustainable-design_en (accessed 13 October 2026).

Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. The company develops and supplies photoresins and related process materials. No proprietary formulation, manufacturing sequence, process window or comparative product recommendation is disclosed.

Data availability

No new experimental dataset was generated.

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