

Critical-Raw-Material Exposure in Functional Photopolymer Systems: Dependency, Recovery and Performance Risk

A bounded framework for material criticality, recovery context and route-specific performance evidence

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ER-474 · Engineering Review · Version 0.1 · 12 October 2026

Abstract

Functional photopolymer systems can incorporate metals, metal compounds and other performance-enabling constituents whose supply chains are exposed to policy-defined criticality. The engineering problem is not solved by labeling a constituent “critical”: material criticality is a supply-risk classification, whereas process capability and final-part performance remain route-specific evidence questions. This review separates those layers and defines how they should be reported together without converting European critical-raw-material policy into a materials-performance claim.

Regulation (EU) 2024/1252 establishes an EU framework for secure, resilient and sustainable access to critical raw materials, including monitoring of dependencies, circularity, recycling and substitution. Commission Implementing Regulation (EU) 2026/1116 identifies product, component and waste-stream classes with relevant recovery potential. A directly relevant DLP study by Cai and co-workers demonstrates one tungsten-bearing photopolymer route in which formulation and multistage thermal conversion determine the final tungsten microstructure and properties. Taken together, these sources support an evidence architecture in which criticality, recovery potential and functional performance are linked by traceability, but are not interchangeable. No universal claim is made that functional photopolymers depend on critical raw materials, that recovered feedstock is automatically equivalent to virgin feedstock, or that substitution preserves performance. An illustrative mass balance distinguishes collected material from qualified recovered input and makes the denominator of a recovery claim explicit.

Keywords: critical raw materials; photopolymer systems; tungsten; dependency; recovery; substitution; supply risk; performance risk; vat photopolymerization

1. Significance and scope

Critical-raw-material exposure is an engineering governance problem only when a defined material in a defined process chain is actually tied to a critical or strategic raw-material class. The European framework addresses supply resilience, capacity, diversification, circularity and substitution at Union level [1]. ER-474 applies that logic narrowly to functional photopolymer manufacturing: it asks how a manufacturer should document dependency and recovery context while preserving a separate evidence path for process and performance consequences.

The review does not claim that photopolymers as a class depend on critical raw materials. The direct photopolymer evidence used here is an existence case: a water-based tungsten-containing photoresin patterned by DLP and subsequently converted through debinding and sintering to tungsten microstructures [3]. That case is sufficient to show that a functional photopolymer route can contain a critical-material dependency, but it cannot be generalized to unrelated fillers, metals, resins or performance functions.

1.1 Corpus boundary

ER-473 retains supply-chain substitution, alternate suppliers, inventory policy and requalification after supply changes. ER-474 owns the narrower question of exposure to critical-raw-material dependency, recovery context and the evidence needed to prevent policy classifications from being confused with part-performance claims. Substitution appears here only as a mitigation category explicitly bounded by revalidation; it is not the ownership axis of this paper.

2. Three evidence layers that must remain separate

The first layer is regulatory identity: whether a raw material is classified as strategic or critical and whether the relevant product or waste stream falls within an officially identified recovery context [1,2]. The second layer is process identity: the chemical form, concentration, carrier, photopolymer network, printing route and downstream conversion path in which that material is used. The third layer is delivered performance: density, defects, geometry, hardness, conductivity, thermal response or another application-specific endpoint measured on the final state.

Only the first layer can be established by regulation. The second and third require route-specific technical evidence. This distinction prevents two common errors: treating a criticality designation as proof of manufacturing risk in every formulation, and treating the existence of a recovery route as proof that recovered material can be substituted without affecting the photopolymer process.

Layer	Primary question	Permitted conclusion
Regulatory identity	Is the material strategic/critical, and is a recovery stream officially recognized?	Supply-risk and recovery context only.
Process identity	How is the material chemically and physically incorporated into the photopolymer route?	Defines the variables that can be invalidated by a material change.
Delivered performance	What properties are measured after printing and any required conversion?	Supports only the tested route, state and acceptance conditions.

Table 1. Evidence layers for critical-raw-material exposure in a functional photopolymer route.

3. Dependency and concentration risk

Regulation (EU) 2024/1252 explicitly frames criticality around economic importance and exposure to supply disruption, and seeks to reduce dependencies, diversify imports, strengthen Union capacities and moderate demand through resource efficiency and technological progress [1]. For a photopolymer manufacturer, the operational translation is a bill-of-materials question: which functionally necessary inputs map to a critical-material class, in what chemical form, at what mass fraction, and with what qualified alternatives?

A useful dependency record therefore needs at least material identity, function in the formulation or converted part, supplier and origin information where available, qualified grade or purity window, consumption per accepted part, scrap and recovery streams, and the evidence state of any alternative material. None of those fields creates an automatic acceptance threshold; together they show where a supply disruption can invalidate a previously qualified route.

4. Recovery is not equivalence

Commission Implementing Regulation (EU) 2026/1116 lists product, component and waste-stream categories considered to have relevant critical-raw-material recovery potential [2]. Recovery potential is therefore a governance signal about where secondary raw materials may be obtainable. It is not a declaration that recovered material is chemically identical, photochemically neutral or automatically fit for a specific photopolymer formulation.

For a photopolymer process, equivalence must be re-established through the properties that control formulation and conversion: chemical species, purity, oxidation state where relevant, particle or precursor state, water and volatile content, optical absorption and scattering contribution, rheology, cure response, green-state integrity and the properties of the final converted part. A recovery programme that does not preserve those state variables may improve circularity while still requiring full process requalification.

5. Direct existence case: tungsten in a DLP route

Cai et al. describe a water-based photoresin containing a tungsten precursor that is patterned by DLP, followed by a three-step debinding and sintering sequence to obtain dense tungsten microstructures [3]. The publisher abstract reports route-specific improvements in density, surface morphology, internal defects, feature size, roughness and mechanical response. These observations demonstrate that final performance emerges from the coupled photopolymer and thermal route rather than from the raw element name alone.

The evidence does not justify transferring the reported composition, loading, feature size, roughness or mechanical values to another tungsten precursor, resin, printer or thermal cycle. For ER-474, its value is methodological: it links critical-material identity to a real photopolymer manufacturing chain in which formulation and conversion state visibly condition the final engineering outcome.

6. Performance-risk register

A performance-risk register should be built around change pathways rather than around the criticality label itself. A supply disruption may force supplier change, grade change, precursor change, recovered-content increase, process adjustment or material substitution. Each pathway should be mapped to the photopolymer state variables it can disturb and to the minimum evidence required before release.

Where the material is only a minor additive, a limited bridging study may be sufficient if identity and function remain demonstrably equivalent. Where the material dominates optical attenuation, rheology, cure, debinding chemistry or the final functional phase, a broader requalification is required. The depth of evidence is therefore a function of process leverage and failure consequence, not of policy classification alone.

7. Reporting framework

A defensible ER-474 record should report: the applicable critical-material classification; the exact material and chemical form used; the photopolymer function; qualified supplier/grade state; dependency and concentration context; relevant recovery streams; whether recycled or substitute material has been evaluated; the process variables at risk; the final-state properties at risk; and the requalification evidence attached to each material change.

This framework intentionally avoids a universal “critical-material score” for photopolymers. Such a score would collapse heterogeneous supply, chemistry and performance dimensions into a scalar that the evidence does not support. The appropriate output is a traceable dependency map with explicit technical consequences and bounded mitigation actions.

8. Change-control decision sequence

When a critical-material exposure is identified, the first decision is whether the affected constituent is functionally necessary in the qualified route or merely incidental. If it is necessary, the next decision is whether the proposed mitigation changes supplier only, grade or precursor identity, recovered-content fraction, or the material function itself. Those pathways are not equivalent and should not share an automatic bridge.

A supplier-only change may be bridged by identity and process-response evidence when the incoming material remains within a previously qualified state. A grade, precursor or recovered-content change should be treated as a material-state change until optical, rheological, cure, green-state and final-performance consequences are bounded. A functional substitution is the strongest change and returns ownership to the ER-473 substitution/requalification logic while ER-474 retains the criticality and dependency record.

The release question is therefore not “is the new material still critical?” but “does the changed material preserve the qualified manufacturing state and the delivered function?” The criticality classification can remain unchanged while technical equivalence fails, or the classification can change while the manufacturing route remains technically equivalent. Those outcomes must be recorded separately.

9. Research and data priorities

Future photopolymer work would benefit from composition-resolved dependency reporting that connects critical-material identity to photopolymer function, process sensitivity and final-part performance. Particularly valuable datasets would compare virgin and recovered feedstocks under matched resin chemistry and process conditions, and would report both incoming-material identity and downstream functional response.

Another priority is change-propagation evidence: how much variation in precursor purity, oxidation state, particle or ionic loading, moisture, optical attenuation or impurity profile can occur before cure, debinding or final functional response shifts materially? Those studies would allow recovery and substitution programmes to be qualified on measured process leverage rather than on material-name similarity.

10. A dependency calculation with an explicit denominator

A proposed material-dependency account should distinguish purchased input, material incorporated into accepted output, process loss and recovered material. For a constituent of interest, the accounting boundary could record mass entering the route and mass represented in accepted final parts. These quantities answer different questions when printing is followed by substantial conversion or when the photoresin is not the final functional material.

For illustration, suppose a hypothetical process purchases 100 mass units of a constituent and produces accepted parts containing 60 units. The remaining 40 units need a disposition record; they are not automatically available for reuse. If 20 units are collected, collection yield is 20% of input under this definition. If only 12 subsequently meet a defined incoming specification, the qualified recovered quantity is 12 units. Reporting the collection quantity as qualified replacement would overstate the demonstrated supply contribution. The example is an accounting distinction, not a recovery result for tungsten or any other material.

A recycled-content claim would also identify whether its denominator is purchased feedstock, formulated resin or the converted final part. Moving between these denominators requires the relevant mass balance. A critical-material designation does not provide that balance.

11. Test whether recovery changes the qualified route

The proposed comparison would hold the intended function explicit while examining the actual recovered material. Matching an elemental name does not show that precursor identity, particle state or impurity profile is unchanged. The selected incoming measurements should follow the variables that can influence the specific route. Downstream observations would then test whether the manufacturing and final-performance evidence remains representative.

A useful study would report rejected recovery fractions as well as accepted ones. Otherwise, an apparently successful recovery route could conceal a selection step that strongly limits usable yield. It would also state whether recovered material was tested alone, blended at a specified fraction or used only in a non-critical role. Those are different evidence claims.

The engineering decision is therefore conditional on both availability and technical suitability. A mitigation can reduce dependence on one supply stream while requiring a new process qualification. Keeping those outcomes separate permits a realistic assessment of circularity without treating the existence of recoverable material as evidence of interchangeable performance.

12. Decision-grade criticality analysis

A raw material is not technically critical merely because its chemical element appears on a statutory list. The decision unit is the specified input to a defined photopolymer manufacturing route. A dependency assessment should therefore cross-reference supplier concentration, usable inventories, minimum specifications, substitution times, and the consequences of a missed specification for the finished component. Where a listed element is present in a pigment, additive, ceramic precursor or functional filler, the element-level supply indicator and the formulated-component qualification burden remain distinct quantities.

A route-specific risk register should separate likelihood of interruption from consequence: a low-mass additive may be high consequence if it is essential to cure depth, optical attenuation or electrical response; a high-mass constituent may be more replaceable if alternative qualified grades exist. Proposed criticality classes are decision-support categories, not experimentally determined performance rankings. The formulation record must state concentration, supplier grade, relevant impurity envelope, particle-size and surface characteristics where applicable, and the tests that connect those descriptors to printed-part acceptance.

For recovery proposals, the engineering comparison is a paired manufacturing experiment rather than a claim of circular equivalence. Virgin and recovered feedstocks should be characterized at the same points in the process, including mixing, light penetration, conversion, green-state integrity, post-processing and final functional response. Lot-to-lot variation, repeated recycling cycles and residual contamination are separate factors. No recovered stream should inherit the approval status of a chemically similar virgin material merely because a nominal composition matches.

A defensible decision report identifies the statutory source and date, the product and mass denominator, the replacement hypothesis, the measurements needed to challenge that hypothesis, and the residual uncertainty. This review can define that

evidence architecture; it cannot claim that any particular recycled input passes qualification without measured, application-specific data.

Criticality is not a direct proxy for technical substitutability

The regulatory designation of a raw material as critical or strategic addresses supply exposure and policy objectives; it does not establish either its indispensability to a particular photoresin or the feasibility of changing to an alternate material. A formulation-level dependency analysis must identify the particular function of each constituent, its concentration range, where the material enters the manufacturing chain and the evidence required to replace it. A filler may have the same elemental composition as an alternate source but different surface chemistry, size distribution and dispersion behaviour, all of which can alter rheology, light transport or final-part properties.

Recovery potential must also be separated from recovery performance. A regulatory list of eligible products or waste streams does not demonstrate that an industrial photopolymer composite yields a reusable constituent at suitable purity and acceptable energy or cost. Any claim of circularity should identify collection route, separation losses, contamination profile, property retention and actual reuse conditions. The analysis here is therefore a screening framework combining exposure, technical dependency and qualification burden; it is not an experimental result or a statement that the referenced legal instruments certify a specific resin.

Criticality must reflect function rather than purchasing volume

A component can represent a small share of formulation mass or spend while controlling optical penetration, dielectric performance or the stability of a dispersion. Supplier criticality should therefore be mapped to the function that would be lost, the analytical detectability of a substitution and the time required to re-establish the accepted processing window. Price volatility alone does not measure the probability of a technically qualified replacement.

For recovery and circular-sourcing claims, the material balance must identify the recovered fraction, contaminants carried forward and the properties that depend on surface state. Recovery yield is not equivalent to qualified yield. A reclaimed additive may pass compositional screening but fail the optical or rheological controls of a specific formulation, so retained performance should be verified at both formulation and accepted-part levels.

Cross-sector critical-mineral lists provide supply-risk context but are not direct observations of photopolymer resin failure. The review should retain this distinction and describe prospective test plans instead of extrapolating sector-wide scores into numerical product-life predictions.

13. Limitations

The EU regulations are policy and governance sources; they do not establish photopolymer performance. The tungsten study is one open-access DLP existence case and does not establish class-wide critical-material dependence. ER-474 contains no supplier ranking, universal substitution rule, recovery yield, accepted recycled-content fraction or universal performance threshold.

14. Conclusions

Critical-raw-material exposure in functional photopolymer manufacturing should be handled as a linked but layered evidence problem. Regulation can establish criticality, supply-risk governance and recovery context. A manufacturing record must then establish how the identified material participates in the photopolymer and downstream process. Only route-specific testing can establish whether a supply, recovery or substitution change preserves the delivered function. Keeping those three layers separate makes the dependency visible without turning policy language into unsupported materials engineering.

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 datasets were generated for this review.

References

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