

ER-86

Analytical Extractables and Leachables from Vat-Printed Photopolymers: Specimen State, Extraction Design, Analytical Coverage and Cross-Study Comparability

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Statement of Significance

Extractables and leachables data from vat-printed photopolymers are often presented as if the measured concentration or total released mass were an intrinsic property of a resin. The controlled evidence does not support that interpretation. Release measurements depend on the exact printed-specimen state, extraction intent and severity, geometry and accessible area, sampling schedule, analytical platform, method performance and normalization basis. Studies also differ in whether they measure direct resin-to-fluid release or indirect transfer through an intermediate material such as PDMS. These differences can prevent quantitative comparison even when every individual experiment is internally valid.

ER-86 develops a VPP-specific reporting and interpretation architecture for direct or indirect fluid-contact analytical release from vat-printed photopolymers. It does not prescribe one universal extraction protocol, set toxicological acceptance limits, rank commercial resins or replace ISO 10993 chemical-characterisation and toxicological-risk-assessment standards. Its contribution is to define the minimum analytical state that must be disclosed before cross-study comparison is attempted.

Abstract

Vat photopolymerisation creates chemically and spatially heterogeneous material states through printing, washing, post-curing, sterilisation, coating, ageing and other post-process operations. Extractables and leachables measurements made on these materials are therefore conditional on both the specimen history and the analytical design. Published studies use different extraction media, temperatures, durations, specimen geometries, surface-to-volume ratios, sampling schedules, target lists, analytical platforms and normalization bases. Consequently, a low or high reported release value cannot be interpreted independently of the method that generated it.

This review develops a reporting and comparison framework for analytical release from vat-printed photopolymers used in direct or indirect fluid-contact workflows. The evidence base spans dental and orthodontic materials, biopharmaceutical and cell-and-gene-therapy components, SLA moulds used for PDMS replication, organ-on-chip parts and indirect mould-to-PDMS-to-fluid transfer. The framework separates manufacturing purification from analytical extraction; extractables from leachables; direct from indirect transfer; targeted from broader analytical coverage; and chemical characterisation from downstream toxicological evaluation. It treats coating, irradiation, autoclaving, ageing and other treatments as part of specimen identity rather than as generic improvements.

A minimum qualification architecture is proposed covering printed-specimen state, extraction design, geometry and accessibility, analytical coverage, method performance, normalization, time-resolved interpretation and toxicological handoff. Quantitative pooling is considered defensible only when these states are matched or explicitly reconciled. Where they are not, qualitative or stratified comparison is more appropriate than numerical ranking. The resulting framework is intended to improve reproducibility and cross-study interpretability without converting heterogeneous study conditions into a universal VPP extraction standard.

Keywords: vat photopolymerisation; extractables; leachables; analytical extraction; chemical characterisation; LC-MS; GC-MS; NMR; specimen state; post-processing; cross-study comparability; ISO 10993

1. Introduction

A release measurement from a vat-printed photopolymer is not a property of formulation identity alone. It is a property of a defined material state interrogated by a defined analytical procedure.

The same nominal resin can exist as materially different analytical specimens after changes in printing conditions, wash history, post-cure, sterilisation, irradiation, coating, ageing, storage or surface preparation. Likewise, the same specimen can generate different chemical profiles when exposed to different media, temperatures, durations or extraction ratios. ER-06 identified this heterogeneity as a recurrent limitation in comparing photopolymer release studies [E1].

Published primary studies confirm the importance of this distinction. Berghaus and co-workers related conversion and monomer elution under defined extraction conditions and showed that conversion and release must be treated as separate measurements [1]. Bouchema and co-workers separated leaching-oriented and extractables-oriented test conditions within a study of printed orthodontic materials [2]. Willi and co-workers used a targeted LC-MS/MS design for two defined analytes and tied non-detect interpretation to method-specific analytical thresholds [3]. Hampe and co-workers reviewed how extraction design, calibration, detection and quantification choices condition monomer-release measurements [4].

The problem is therefore not that analytical chemistry lacks standards or methods. The problem is that chemically different specimens and analytically different experiments are often compared without an explicit reconciliation step.

ER-86 asks one engineering question:

What minimum specimen-state record, extraction design, analytical coverage and normalization are required before extractables or leachables data from vat-printed photopolymers can be interpreted or compared across studies?

The paper is restricted to analytical release from direct or indirect fluid-contact workflows. It does not determine biological acceptance, toxicological safety or product superiority.

2. Terminology and evidence states

Several terms must remain distinct because they describe different experimental questions.

Table 1. Analytical terms that must not be conflated

Term	Operational meaning in ER-86	What it does not establish by itself
Residual species	Unreacted or retained chemical species present in the material	That the species will migrate under use conditions
Manufacturing purification	Washing, extraction or conditioning performed to reduce mobile material before use	The analytical release profile under a defined test condition
Analytical extraction	Controlled operation designed to characterise constituents released under a declared analytical condition	A production wash recipe or universal service condition
Extractables	Constituents released under defined laboratory extraction conditions intended to characterise potential chemical release	Actual use exposure or toxicological acceptability
Leachables	Constituents released under actual or simulated-use conditions	Exhaustive extractable inventory
Targeted analysis	Measurement of predefined analytes with analyte-specific method performance	Absence of unmonitored species
Screening / broader analysis	Analytical search beyond a predefined target list	Automatic structural identification or quantitative completeness
Non-detect	Signal below the decision capability of a declared method for a declared analyte	Chemical absence or safety
Chemical characterisation	Analytical identification and estimation/quantification of constituents and release	Toxicological risk assessment

Term	Operational meaning in ER-86	What it does not establish by itself
Toxicological risk assessment	Downstream interpretation of chemical exposure information within the applicable risk framework	Analytical method validation

ISO 10993-18 provides the chemical-characterisation framework relevant to extractables and leachables in medical-device contexts [S1]. ISO 10993-12 addresses sample preparation and reference materials and is not an extractables acceptance-limit standard [S2]. ISO 10993-17 provides the downstream toxicological-risk-assessment framework for device constituents and is not an analytical extraction method [S3].

3. The printed specimen is part of the analytical method

A VPP specimen can change chemically and physically at multiple stages before it ever reaches an extraction vessel. At minimum, an analytical report should identify the formulation or product version, printer/process state, wavelength, layer thickness where relevant, build orientation where relevant, wash history, post-cure, sterilisation or irradiation, coating, surface preparation, geometry, ageing and conditioning.

The purpose is not to require every parameter for every experiment. The purpose is to make the tested state reconstructable.

Berghaus et al. compared printed and non-printed resin-based materials while measuring both conversion and elution, illustrating that the material state and the release endpoint are separate dimensions [1]. Rengarajan et al. investigated leachable cytotoxicity and detoxification of printed polymers, providing adjacent evidence that post-processing changes the tested material state even when the analytical purpose differs from ER-86 [5]. Venzac et al. showed that post-treatment of SLA-printed moulds changes chemical species associated with PDMS curing inhibition [7]. Jönsson et al. likewise treated post-processing as an experimental variable in an organ-on-chip context [8].

ER-86 therefore treats specimen identity as:

formulation identity + print history + purification history + post-treatment history + geometry + conditioning state

rather than as the resin trade name alone.

Table 2. Minimum printed-specimen state record

Domain	Minimum record	Why it matters for release interpretation
Material identity	Resin/formulation identity, version or batch when available	Controls the starting chemical universe
Printing	Printer/process class, wavelength, build orientation/layer thickness where relevant, exposure state	Can alter conversion and spatial heterogeneity
Manufacturing purification	Wash media, sequence, duration and drying/conditioning state, without converting ER-86 into a wash-protocol paper	Changes residual mobile species before analysis
Post-cure	Light/thermal condition and timing	Can alter conversion and residual-species state
Sterilisation/irradiation/heat	Treatment identity and sequence	May alter release profile or generate transformation products
Coating/barrier	Coating identity and treatment state	Can alter transport and introduce its own constituents
Geometry	Dimensions, exposed area basis, internal channels/porosity/cut edges where relevant	Controls accessible transport paths
Ageing/conditioning	Time, temperature, medium and storage state before extraction	Defines the specimen actually tested

4. Manufacturing purification is not analytical extraction

A production wash is designed to reduce uncured resin, residual soluble material or other mobile species so that a printed part can proceed through its manufacturing workflow. Analytical extraction is designed to measure what is released under a defined characterisation condition.

These operations can use similar physical actions while answering different questions.

The 3Dresyns Low-Leachables & Extractables-Control IFU makes this distinction explicitly as manufacturer implementation context [M1]. Independent studies support the broader experimental principle that post-processing state must be separated from subsequent analytical characterisation [2,5,7-9].

ER-86 does not prescribe:

- a universal number of wash baths;
- one production solvent;
- one Soxhlet condition;
- one drying endpoint;
- one post-cure recipe.

Those are manufacturing-process variables. The analytical requirement is that they be reported when they define the specimen entering the extraction experiment.

A comparison such as "resin A releases less than resin B" is therefore under-specified if resin A and resin B entered the experiment after materially different purification histories.

5. Extractables and leachables answer different questions

Extractables and leachables should be treated as related but distinct evidence states.

A deliberately aggressive extraction can help identify the chemical universe that may be available for release. A simulated-use study asks what is released under a condition intended to approximate a defined use scenario. The numerical values generated by those experiments are not interchangeable.

Bouchema et al. provide a direct example of separating extraction-oriented and leaching-oriented conditions within one printed-resin study [2]. ISO 10993-18 formalises the broader chemical-characterisation distinction between extraction conditions and use-related release [S1].

The required interpretation sequence is:

test intent

- **extraction or leaching condition**
- **measured chemical profile**
- **normalised result**
- **bounded interpretation**

A high value under aggressive extraction is not automatically a predicted in-use exposure. Conversely, a low value under one simulated-use condition does not establish an exhaustive absence of releasable constituents.

6. Extraction design defines the chemical question

Extraction conditions determine which constituents can enter the measured phase and at what rate. At minimum, the report should declare medium identity and composition, temperature, duration, agitation or flow, specimen-to-medium ratio, vessel/contact materials, sampling schedule and medium-renewal logic.

Hampe et al. identify these variables as central to study comparability and analytical interpretation [4]. Berghaus et al. and Bouchema et al. demonstrate how defined media and time histories form part of the actual result rather than being peripheral procedural details [1,2]. Ferraz et al. further show that contact ratios and sequential material interfaces matter when the pathway is indirect [9].

Table 3. Extraction-design record and prohibited shortcuts

Variable	Required record	Prohibited shortcut
Medium	Identity, composition and rationale	Assuming one solvent is universally worst-case or use-representative
Temperature	Actual test temperature and tolerance	Comparing room-temperature and elevated-temperature data as equivalent
Duration	Total duration and timepoints	Treating endpoint and time-resolved data as interchangeable
Agitation/flow	Static, agitated, circulated or flow condition	Ignoring transport enhancement
Extraction ratio	Specimen mass/area/volume relative to medium	Comparing concentrations without ratio reconciliation
Vessel/contact material	Vessel and intermediate materials where relevant	Ignoring adsorption or secondary transfer surfaces
Sampling	Aliquot size, replacement, complete renewal or no renewal	Calling endpoint concentration "cumulative release" without calculation
Test intent	Extractables, simulated-use leachables or another declared purpose	Mixing severity classes in one ranking

7. Geometry, area and accessibility

Release is a transport process. Geometric area is therefore not automatically equivalent to accessible area.

Printed parts may contain internal channels, porous regions, cut edges, rough surfaces, cavities or tortuous paths. These features can alter fluid access and diffusion distance. A specimen-to-medium ratio expressed only as mass can hide very different exposure areas, while a geometric area calculation can overestimate or underestimate the surface that actually contacts the medium.

ER-86 does not prescribe one universal normalization basis. It requires that the basis be declared and preserved during comparison.

Acceptable denominators can include:

- amount per specimen;
- amount per specimen mass;
- amount per geometric area;
- amount per justified accessible area;
- concentration per contact volume;
- another explicitly justified basis.

Different denominators should not be pooled silently. Conversion between them requires the underlying geometry and an uncertainty statement.

8. Targeted analysis is not exhaustive chemical coverage

Targeted methods answer a narrow and valuable question: how much of specified analyte X or Y is present above a defined analytical threshold?

Willi et al. provide a clear targeted example using LC-MS/MS for defined constituents with blanks and analyte-specific analytical performance [3]. Such a design can support strong statements about those analytes. It cannot support the statement that no other constituents are present.

Berghaus et al. likewise demonstrate targeted quantification of residual-monomer release under defined conditions [1]. Bouchema et al. separate targeted analyte work from broader chromatographic signal interpretation [2].

ER-86 therefore requires reports to distinguish at least four evidence classes:

1. identified and quantified;

2. **identified but not quantitatively validated;**
3. **tentatively identified;**
4. **unknown signal.**

A broad chromatographic signal is not automatically an identified compound. A target-list non-detect is not evidence about compounds that were never targeted.

9. Analytical platforms are complementary

No single analytical platform covers all chemical classes with equal sensitivity and structural confidence.

Venzac et al. combined Raman spectroscopy, NMR and high-resolution mass spectrometry to investigate species associated with SLA-mould effects on PDMS curing [7]. Ferraz et al. combined GC-MS and LC-MS/MS to examine transfer from printed moulds through PDMS into a final aqueous phase [9]. Menzel et al. provide a non-dental example of analytical monitoring associated with printed polyurethane components and a barrier-coating strategy [6].

The engineering implication is not that every VPP release study requires the same multi-platform package. It is that the analytical coverage must match the chemical question.

Table 4. Analytical-coverage questions

Platform class	Typical contribution	Required caveat
GC-MS	Volatile/semi-volatile constituents and library-assisted identification	Limited for non-volatile/highly polar species without suitable preparation
LC-MS / LC-MS/MS	Non-volatile and polar/semi-polar analytes; targeted quantification or broader MS coverage	Ionisation and matrix effects are analyte- and method-dependent
NMR	Structural information and quantitative potential under validated conditions	Sensitivity and peak overlap can limit low-level or complex-mixture interpretation
Raman / vibrational spectroscopy	Material/species fingerprints and comparative structural information	Usually not a stand-alone exhaustive extractables quantification method
Complementary platforms	Broader chemical coverage and cross-confirmation	Requires reconciliation of identities, calibration and reporting conventions

A method should state not only what it detected but what it was capable of detecting.

10. Method performance controls the meaning of a number

Quantitative release values are meaningful only within the performance of the analytical method.

Hampe et al. emphasise calibration, detection and quantification, recovery, accuracy and related validation elements [4]. Willi et al. demonstrate analyte-specific calibration and threshold logic in a targeted LC-MS/MS context [3]. Berghaus et al. likewise report analytical detection/quantification characteristics for targeted monomer release [1].

At minimum, quantitative reporting should address, as applicable:

- procedural and medium blanks;
- calibration range and model;
- internal standards or equivalent controls where appropriate;
- recovery;
- selectivity and chromatographic resolution;
- matrix effects;
- analyte stability;
- limit of detection;
- limit of quantification;
- precision;
- accuracy;
- uncertainty.

The exact control set is method- and objective-dependent.

The key rule is:

non-detect means below the capability of a declared method under declared conditions; it does not mean chemical absence.

11. Normalisation determines whether studies can be compared

Two studies can measure the same analyte with the same instrument and still be quantitatively incomparable if their normalization bases differ.

For example, a reported value may be expressed per specimen, per gram, per square centimetre, per millilitre of medium or as an endpoint concentration. These are not interchangeable without the information needed to convert between them.

ER-86 therefore requires every quantitative result to carry its denominator explicitly.

The preferred comparison hierarchy is:

1. **same specimen state + same extraction intent + same analytical coverage + same denominator:** direct quantitative comparison may be possible;
2. **reconcilable differences with adequate metadata:** quantitative comparison may be possible after conversion and uncertainty accounting;
3. **materially different or incompletely described states:** use stratified or qualitative comparison;
4. **unknown state or denominator:** numerical ranking is not defensible.

12. Sampling history controls time-resolved interpretation

Endpoint concentration, interval release and cumulative release are different quantities.

If medium is fully renewed after each interval, cumulative release can be reconstructed by summing interval amounts. If aliquots are removed and only partially replaced, the calculation changes. If no medium is renewed, an endpoint concentration may reflect continuing release, re-equilibration, degradation, adsorption or other transport phenomena.

Studies that use different sampling histories should not be merged without reconstructing the mass balance.

Time is therefore not just an x-axis label. The report should state:

- each sampling time;
- whether the same medium remained in contact;
- aliquot volume;
- whether medium was replaced and by how much;
- whether cumulative amount was calculated;
- whether degradation or instability of the analyte in the medium was assessed when relevant.

13. Direct and indirect transfer pathways

VPP parts do not need to contact the final fluid directly to influence its chemical composition.

Ferraz et al. demonstrate an indirect pathway in which constituents associated with SLA-printed moulds transfer into PDMS and subsequently into an aqueous phase [9]. Venzac et al. independently demonstrate chemical transfer from SLA moulds into a secondary polymer-processing environment, with consequences for platinum-catalysed PDMS curing [7].

A complete transfer map should therefore declare:

printed photopolymer

→ **intermediate material or coating**

→ **final contact medium**

for every relevant step, together with time, temperature and contact ratio.

The absence of direct resin-fluid contact is not evidence that migration cannot occur.

14. Coatings, irradiation, heat treatment and ageing define new specimen states

Barrier coatings and post-treatments can change release behaviour, but they should not be described as universal improvements.

Menzel et al. provide a non-dental example in which a parylene-C coating is investigated on vat-printed polyurethane components for biopharmaceutical and cell-and-gene-therapy applications [6]. ER-86 uses this study only to support the principle that coating and treatment history are part of specimen identity and that barrier performance must be tied to the tested condition and time window. Granular numerical claims not required for that principle are deliberately omitted from this v0.1 manuscript.

Jönsson et al. provide a separate organ-on-chip example in which autoclave post-processing is an experimental state rather than a generic synonym for "clean" material [8]. ER-86 likewise avoids relying on granular main-text or supplementary-information details that were not independently re-pinned in the source-gate review.

The reporting rule is therefore:

treatment identity + sequence + ageing state + analytical outcome

not simply:

treated = safer or permanently lower release.

15. Process residues and transformation products

The analytical universe can extend beyond residual monomers and photoinitiators.

Potentially relevant classes include:

- residual monomers and oligomers;
- photoinitiators and photoinitiator-derived species;
- additives;
- wash-solvent residues;
- coating-related species;
- thermal, oxidative, irradiation or sterilisation transformation products;
- species introduced by intermediate materials in indirect-contact workflows.

Venzac et al. are particularly important because they connect photoinitiator-related chemistry and fragments with an application-specific PDMS-cure endpoint [7]. Ferraz et al. also show that multiple analytical platforms may be needed to observe the chemical complexity of an indirect transfer pathway [9].

Unknown peaks should remain unknown unless identification confidence is sufficient. They should not be labelled degradation products merely because they appear after treatment.

16. Cross-study comparability framework

The central contribution of ER-86 is a comparison gate rather than a universal extraction recipe.

Table 5. Cross-study comparison gate

Comparison dimension	Matched	Reconciled	Unmatched
Specimen state	Same material/process/post-treatment state	Differences documented and justified	Unknown or materially different state
Extraction intent	Same extractables/leachables purpose	Severity can be explicitly mapped	Aggressive extraction mixed with simulated use
Medium/temperature/time	Same or closely comparable	Conversion/mass-balance basis available	Missing or fundamentally different
Geometry/ratio	Same denominator and accessibility basis	Convertible with uncertainty	Denominator or accessibility unknown
Analytical coverage	Same target list/platform or equivalent coverage	Differences explicitly bounded	One study targeted, another broad, but treated as equivalent

Comparison dimension	Matched	Reconciled	Unmatched
Method performance	Comparable calibration/LOD/LOQ/controls	Quantitative uncertainty can be reconciled	Thresholds or validation absent
Sampling logic	Same interval/endpoint/cumulative definition	Mass balance reconstructable	Sampling history unknown
Interpretation	Quantitative comparison potentially defensible	Quantitative comparison conditional	Qualitative/stratified synthesis only

This gate prevents the common analytical error of treating values as directly rankable simply because they share the same unit.

17. Minimum reporting architecture

Table 6. Minimum reporting record for analytical release from VPP photopolymers

Domain	Required record	Minimum interpretation
Material	Identity/version/batch where available	Defines chemical starting point
Print state	Printer/process, wavelength, relevant exposure/build variables	Defines printed network state
Purification	Wash/dry/post-cure history	Defines pre-analysis mobile-species state
Treatments	Sterilisation, irradiation, heat, coating, ageing	Defines tested specimen state
Geometry	Dimensions, area/accessibility basis, channels/porosity/cut edges	Defines transport/contact basis
Test intent	Extractables, simulated-use leachables or another declared purpose	Defines meaning of severity
Extraction	Medium, temperature, duration, agitation/flow, ratio, vessel	Defines chemical challenge
Sampling	Timepoints, aliquots, renewal and cumulative logic	Defines temporal meaning
Analytics	Platforms, target list/screening scope, identification confidence	Defines chemical coverage
Method performance	Blanks, calibration, recovery, LOD/LOQ, precision/accuracy/uncertainty as applicable	Defines confidence in quantities and non-detects
Normalisation	Declared denominator	Defines comparison basis
Handoff	Identified/estimated exposure data forwarded to appropriate toxicological/biological evaluation	Prevents analytical data being mislabelled as safety conclusions

A study need not use every technique or measurement in this table. It should disclose enough information for a reader to know what was measured, what was not measured, and whether another study can be compared.

18. Standards and qualification boundary

ER-86 is not a new standard and does not replace the ISO 10993 framework.

Table 7. Standards adjacent to ER-86

Standard	Role relevant to ER-86	Explicit boundary
ISO 10993-18:2020 + Amd 1:2022 [S1]	Chemical characterisation, extractables/leachables framework, uncertainty input	Does not create a universal VPP extraction recipe or acceptance threshold

Standard	Role relevant to ER-86	Explicit boundary
ISO 10993-12:2021 + Amd 1:2025 [S2]	Sample preparation, reference materials and extract preparation	Not an extractables acceptance-limit standard; recheck current status before reliance
ISO 10993-17:2023 + Amd 1:2025 [S3]	Downstream toxicological risk assessment of device constituents	Not an analytical extraction or method-validation standard

The source gate verified these as the current editions on 26 August 2026, while also flagging ISO 10993-12 for a status recheck because a systematic-review process was open in the controlling record. This v0.1 manuscript therefore does not claim that the standards status is frozen beyond the review date.

19. Boundaries with neighbouring 3Dresyns Engineering Reviews

ER-86 is intentionally narrow.

- **ER-06** controls general biological response and evidence gaps. ER-86 uses ER-06 only to identify the cross-study analytical-comparability problem and does not repeat its biological review [E1].
- **ER-12** controls organ-on-chip and cell-contact application qualification. ER-86 uses organ-on-chip evidence only as an analytical specimen-state example.
- **ER-27** controls conversion metrology. ER-86 requires conversion to remain separate from release rather than treating it as a surrogate.
- **ER-33** controls manufacturing washing, extraction and drying. ER-86 records those operations as specimen history but does not prescribe them.
- **ER-41** and **ER-42** control application-specific qualification and sterilisation effects. ER-86 treats such operations only as analytical state variables.
- **ER-44** controls photoabsorbing fillers and cure-depth response.
- **ER-61** controls gelation, vitrification and mobility arrest.
- **ER-72** controls environmental ageing mechanisms. ER-86 records ageing only when it defines the tested specimen.

The distinction can be summarised as:

neighbouring ERs explain why the material state changes

versus

ER-86 defines what must be reported before release data from that state can be compared.

20. 3Dresyns implementation context

3Dresyns maintains a Low-Leachables & Extractables-Control workflow page and IFU [M1]. It is included only as first-party implementation context.

The relevant boundary is the distinction between:

manufacturing purification

and

analytical extraction / chemical characterisation.

The manufacturer documentation does not independently validate a universal low-leachables performance level, universal extraction protocol, biological safety conclusion or cross-product ranking.

Any 3Dresyns material intended for a release-sensitive workflow requires qualification of the exact printed state, process history, geometry, analytical method and intended application.

21. Failure modes in interpretation

Table 8. Common analytical interpretation failures

Observation or report style	Interpretation error	Required response
High degree of conversion	Assumed to mean low leachables	Measure release independently

Observation or report style	Interpretation error	Required response
Non-detect for one analyte	Reported as chemical absence	State target, method, LOD/LOQ and coverage
One favourable LC-MS result	Reported as complete chemical cleanliness	Define platform coverage and blind spots
Aggressive extraction value	Treated as use exposure	Separate extractables from leachables/simulated use
Low endpoint concentration	Treated as low cumulative release	Reconstruct sampling and renewal logic
Same resin name	Treated as same specimen	Report print/post-process/treatment state
Coated specimen performs better initially	Treated as permanent barrier validation	Report coating state and time-dependent retention
No direct resin-fluid contact	Assumed no migration pathway	Map indirect transfer materials and steps
Values share the same unit	Numerically ranked	Check denominator, geometry, extraction and analytical equivalence
Low total release	Reported as safe or superior	Handoff chemistry to toxicological/application assessment

22. Limitations

The direct evidence base is heterogeneous by design. It spans dental and orthodontic materials, printed polyurethane components, SLA moulds, PDMS replication and organ-on-chip workflows [1-9]. This breadth supports a reporting framework but not universal numerical release limits.

The strongest method-detail evidence is not uniformly distributed across all application classes. Two non-dental sources, Menzel et al. [6] and Jönsson et al. [8], were retained conservatively in this v0.1 manuscript: only claims that were sufficiently controlled by the source-gate record are used, and granular supplementary-information-dependent numerical details are omitted pending any further independent pinning required by the review workflow.

ISO standards status is time-dependent. The controlling source-gate record requires ISO 10993-12 to be rechecked before reliance [S2].

ER-86 does not define analytical evaluation thresholds, toxicological exposure limits, biological acceptance criteria, universal extraction conditions or manufacturer-specific performance claims.

23. Conclusions

Extractables and leachables measurements from vat-printed photopolymers are conditional analytical results, not intrinsic resin constants.

Cross-study interpretation requires a declared chain:

printed specimen state

- **manufacturing history**
- **extraction or leaching intent**
- **geometry and contact model**
- **sampling history**
- **analytical coverage**
- **method performance**
- **normalisation**
- **bounded chemical interpretation**
- **downstream toxicological or application handoff where required.**

The central engineering rule is straightforward:

Quantitative comparison is defensible only when specimen, extraction, analytical and normalization states are matched or explicitly reconciled.

Where those conditions are not met, qualitative or stratified synthesis is more rigorous than numerical ranking.

This framework does not replace standards or create a universal VPP extraction protocol. Its purpose is to make the analytical state visible enough that results can be reproduced, bounded and compared without converting methodological differences into false material conclusions.

Declarations

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Competing interests. The author is associated with 3Dresyns by Resyner Technologies S.L., which develops and commercialises photopolymer materials and maintains the manufacturer workflow page cited as [M1]. Manufacturer information is used only as implementation context and is not treated as independent evidence.

Data availability. No new experimental dataset was generated for this review. The analysis is based on the cited literature, standards and controlled corpus sources.

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