

Transport, Degradation and Mechanical Evolution in Vat-Printed Tissue-Engineering Scaffolds: Coupled Design and Qualification

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Statement of Significance

A tissue-engineering scaffold is a time-dependent transport and mechanical system, not a static porous object. In vat-photopolymerised hydrogels and degradable networks, crosslink density, hydration, pore architecture and degradation chemistry jointly determine how molecules move through the construct and how the structure carries load. The same change can improve one function while weakening another: swelling can increase molecular mobility while reducing modulus; degradation can open transport pathways while eroding structural support; higher crosslink density can improve printing fidelity while slowing swelling or hydrolysis. This review therefore reframes scaffold qualification around coupled state variables measured over time rather than around isolated fresh-sample values. The purpose is to distinguish this engineering problem from broad tissue-engineering, biocompatibility or biomaterial-portfolio reviews.

Keywords: vat photopolymerisation; tissue-engineering scaffold; hydrogel; mass transport; diffusion; permeability; swelling; degradation; mechanical evolution; crosslink density; DLP; stereolithography; scaffold architecture

Abstract

Vat photopolymerisation enables tissue-engineering scaffolds with designed pore networks, perfusable channels and spatially controlled architectures, but the realised scaffold is governed by coupled material and geometric evolution after printing. Hydration changes dimensions, polymer volume fraction and modulus; molecular transport depends on both intrinsic network mesh size and designed pore connectivity; degradation changes mass, chemistry, pore structure and mechanics; and post-processing establishes the initial crosslink state from which all later behaviour develops. Published stereolithography and DLP studies demonstrate that scaffold stiffness can be controlled through architecture and material chemistry, that perfusable networks can support complex transport regimes, and that enzymatic or hydrolytic cleavage can deliberately transform mechanical and diffusional behaviour after fabrication. This review organises the evidence around four coupled questions: what is transported, through which length scale; what mechanical function must be retained; what degradation mechanism changes the network; and at what hydrated/degraded state each property is measured. A qualification framework is proposed using time-resolved geometry, swelling, mass change, molecular-weight or chemical conversion where relevant, transport metrics and mechanical testing on matched specimens. Commercial 3Dresyns products are included only as implementation examples whose documentation illustrates different research variables; they are not used as independent evidence of tissue regeneration, clinical suitability or a universal degradation rate. The central conclusion is that scaffold performance should be reported as a trajectory through material state, not as a list of unrelated initial properties.

1. Introduction

The defining engineering advantage of vat photopolymerisation (VPP) for tissue scaffolds is geometric control. Stereolithography has long been used to fabricate mathematically defined biodegradable architectures in which pore geometry and base polymer jointly tune compressive behaviour [1]. Projection stereolithography later extended this control to porous GelMA-based hydrogel structures at smaller feature scales [2]. More recent DLP and tomographic light-based methods have enabled perfusable networks, living-tissue constructs and complex hydrogel geometries that would be difficult to obtain with conventional scaffold fabrication [5-8].

Geometry alone, however, is an incomplete qualification variable. A scaffold placed in an aqueous environment can swell before appreciable chain scission occurs. Hydration can soften the network, alter pore dimensions, increase molecular diffusion and change the effective solid fraction. Hydrolysis or enzymatic cleavage can then remove network segments, change mesh size, create new pathways and reduce load-bearing continuity. In a porous scaffold, these material changes interact with strut thickness, tortuosity, pore connectivity and overall architecture. Consequently, a dry or freshly post-cured modulus does not describe the mechanical environment after prolonged immersion, and an as-designed pore diameter does not necessarily describe later transport.

This review focuses on that coupling problem. It does not attempt to catalogue all scaffold chemistries, regenerative indications or biological endpoints. Its subject is the engineering state evolution that connects VPP fabrication to transport, degradation and mechanics. The scope deliberately moves beyond a general biomedical and biocompatibility baseline toward scaffold design, transport and qualification questions.

2. A scaffold must be defined by state, scale and time

For qualification purposes, the word “scaffold” should be expanded into a state description. At minimum, the report should identify the material chemistry, printing and post-cure state, hydration medium, temperature, specimen age, architecture and whether the measurement refers to bulk network material or to the architected scaffold. Without these descriptors, values from nominally similar systems are not commensurate.

Three length scales are particularly important. At the molecular scale, crosslink spacing and polymer-water interactions influence diffusion and swelling. At the pore or channel scale, geometry, tortuosity and connectivity govern advective and diffusive transport. At the device scale, gradients in composition, light dose, build orientation and boundary conditions can produce spatially non-uniform behaviour. A single porosity percentage collapses these scales and therefore cannot serve as a complete transport descriptor.

Domain	State variable	Why it changes interpretation
Fabrication state	Resin/bioink composition; wavelength/exposure; layer or volumetric process; post-cure and washing	Establishes conversion, crosslink density, extractables and initial geometry.
Hydration state	Medium, temperature, ionic/protein content, equilibration time	Controls swelling, polymer volume fraction, modulus and molecular mobility.
Architecture	Porosity, pore/channel dimensions, interconnectivity, tortuosity, strut thickness	Controls fluid pathways, surface area and structural load distribution.
Transport probe	Molecule size/charge; tracer concentration; pressure or flow boundary conditions	Diffusion and permeability are probe- and condition-specific rather than intrinsic scalar labels.
Degradation state	Mechanism, medium/enzyme, mass loss, chain cleavage, erosion morphology, time	Determines whether transport changes arise from swelling, scission, erosion or geometry loss.
Mechanical state	Dry/wet; temperature; strain rate; compression/tension; cyclic history	Hydrogels and degradable networks can change modulus and failure mode substantially with conditioning.
Biological context	Cell-free material test versus cell-laden construct; culture duration	Cells and matrix deposition can change transport and mechanics; biological response is a separate evidence layer.

Table 1. State variables required to interpret a vat-printed tissue scaffold.

3. Transport: designed pores and polymer-network transport are different problems

A scaffold can transport species through open pores, through a hydrated polymer network, or through both simultaneously. Open channels permit convection and can be assessed by pressure-flow measurements, residence time, tracer breakthrough or computational fluid dynamics. A hydrogel wall without an open channel is governed primarily by diffusion and partitioning. In a porous hydrogel, solute transport becomes a multiscale combination of pore-scale flow and network-scale diffusion.

Projection stereolithography demonstrates why this distinction matters. Grigoryan et al. created entangled vascular networks in photopolymerisable hydrogels and directly examined fluid mixing, red-blood-cell flow and oxygenation in designed channels [6]. The significance for scaffold qualification is not a universal permeability value; it is that transport must be tested on the realised geometry under the relevant boundary condition. A perfusable channel establishes advection but does not by itself establish diffusion through the surrounding matrix. In vivo, the diameter, length and complexity of architected channels have likewise been shown to govern vascular infiltration [14].

Network transport evolves with chemistry. Wang et al. used an enzymatically cleavable HAMA component in DLP-printed GelMA/HAMA constructs and showed that digestion simultaneously reduced stiffness and increased tracer diffusion through the altered hydrogel [8]. This is a direct demonstration that permeability or diffusivity measured before degradation may not describe the later scaffold. Similarly, hydration-controlled hydrogel systems can show changes in swelling and release without any nominal CAD change. Transport therefore belongs inside a time-resolved material-state experiment.

4. Mechanical function depends on architecture and conditioning

The mechanical response of a scaffold is the product of material properties and architecture. Melchels et al. demonstrated that stereolithographically fabricated biodegradable scaffolds with different mathematically defined pore structures showed mechanical responses predictable from the combination of geometry and base material [1]. Gauvin et al. showed that projection-stereolithography could fabricate GelMA structures with controlled porosity while supporting cell adhesion and migration [2]. These studies establish a key distinction: bulk material modulus and scaffold apparent modulus are different quantities.

Hydrogels add another distinction between the as-cured and hydrated states. A water-rich network can have substantially lower effective stiffness than its dry or incompletely equilibrated counterpart. Xu et al. recently used DLP plus post-processing to tune hydrogel scaffold modulus from a common printed platform, illustrating that the mechanical state can deliberately be changed after printing [10]. Composite GelMA/PEGDA/F127DA networks have similarly been used to balance printability and mechanical performance in bone-regeneration scaffolds [11]. In neural-scaffold work, micro-DLP gyroid architectures similarly combined a hydrogel formulation with mesostructural design to set the final mechanical environment [15].

For engineering qualification, the recommended output is therefore not “Young’s modulus of the resin” alone. It is a matrix: bulk versus scaffold, dry versus hydrated, initial versus aged/degraded, and monotonic versus cyclic where the application imposes repeated loading. Mechanical retention should be calculated against a clearly defined baseline state rather than against whichever specimen state yields the most favourable ratio.

5. Degradation is a structural transformation, not only mass loss

Degradation can occur by hydrolysis, enzymatic cleavage, oxidation or other chemistry, and its relationship to mass loss depends on the erosion mechanism. Chain scission can reduce molecular weight and mechanical strength before measurable mass is lost. Conversely, rapid dissolution of soluble fragments can change mass and pore morphology simultaneously. For this reason, gravimetric mass loss alone cannot identify the degradation mechanism or the remaining structural function.

Early stereolithography work on PPF and related degradable networks demonstrated the feasibility of photocured biodegradable scaffold architectures [3,4]. DLP studies of photocurable PGSA-containing copolymers later showed that network composition and degree of acrylation can alter both mechanical properties and degradation rate [9]. More recent poly(globalide)-based VPP materials similarly modulated gelation, mechanics and hydrolytic degradation through network composition [13], while dextran-PCL photoinks demonstrated a direct trade-off between swelling, degradation rate and mechanical reinforcement as composition was changed [16].

These examples support a general qualification rule: degradation should be tracked with at least one chemical or molecular indicator where feasible, one geometric or mass indicator and one functional indicator. If the intended scaffold must carry load, the functional indicator is mechanical retention. If its primary role is transport, permeability or diffusion may be the more relevant functional endpoint. Ideally both are tracked on the same degradation timeline.

Change	Likely transport consequence	Likely mechanical consequence	Required verification
Higher crosslink density	Usually lower network swelling/molecular mobility; pore-scale flow may be unchanged if geometry is fixed	Often higher initial stiffness and shape retention	Conversion/crosslink surrogate; equilibrium swelling; relevant diffusion/permeability; wet mechanics.
Higher hydration	Can increase molecular diffusion and alter partitioning; may enlarge or distort pores	Often lowers modulus/strength in hydrogels	Equilibrated dimensions and mass; transport and mechanics in the same medium.
Hydrolytic/enzymatic cleavage	Can increase mesh size and transport before gross erosion	Can reduce stiffness before large mass loss	Chemical/molecular degradation marker plus time-resolved mechanics and transport.
Pore enlargement / strut loss	Lower flow resistance and shorter diffusion distances	Lower apparent stiffness and buckling resistance	3D geometry (μ CT/confocal where appropriate), permeability and scaffold-level mechanical test.
Biofiller addition	May change tortuosity, water uptake and surface adsorption	May reinforce or embrittle depending on interface and loading	Dispersion, cure state, swelling/transport and mechanics; do not infer from filler identity.
Post-cure increase	Can reduce residual functionality and swelling	Can increase stiffness and dimensional stability	Report post-cure dose/temperature and test final processed state.

Table 2. Couplings that make single-property scaffold claims unreliable.

6. Crosslink state connects print fidelity to later scaffold function

VPP requires enough local network formation to preserve geometry during layer separation, washing and handling. Tissue-scaffold materials, however, often seek a hydrated, permeable and sometimes degradable final state. These requirements can oppose one another. Increasing polymer concentration, conversion or multifunctional crosslinker content can improve green strength and resolution while reducing mesh size, swelling or degradation. Wang et al. addressed this conflict by printing a temporarily stronger dual-component network and then enzymatically cleaving part of it after fabrication [8]. The strategy is notable because it separates print-state requirements from service-state requirements.

Full-alginate thiol-ene DLP work likewise illustrates that network chemistry, swelling and mechanics should be characterised together rather than treating printability as the endpoint [12]. Rebouças et al. showed that resorbable poly(globalide)-based photoresins can be formulated to adjust crosslinking and hydrolytic degradation while retaining vat-printing capability [13]. These studies do not establish a universal optimum; they demonstrate that the design variable is a trajectory from liquid resin to printed network to hydrated/degraded scaffold.

7. Architecture must be measured after fabrication and during ageing

CAD porosity is an input, not a measured scaffold property. Cure bleed, optical attenuation, washing, swelling, drying and degradation can all shift pore dimensions from the digital design. Micro-computed tomography has been used to compare stereolithographic scaffold designs with realised architecture [1], while perfusion and dye-tracer methods can test whether nominally open channels remain patent [6,8]. For hydrogels, optical or confocal methods may be more appropriate than dry μ CT because drying can collapse the network.

A time-resolved scaffold study should therefore identify a small set of geometric invariants or state variables: external dimensions, representative pore/channel size, porosity or polymer volume fraction, strut/wall thickness and connectivity. These should be measured in the state relevant to function. If swelling is part of use, dimensions should be reported hydrated. If degradation changes the pore network, architecture should be re-measured at the same timepoints used for transport and mechanical tests.

8. A coupled qualification experiment

A defensible experiment can be organised around matched specimen cohorts exposed to the same conditioning timeline. Time zero should correspond to the final printed, washed and post-cured state rather than to the uncured resin. A second baseline after hydration equilibrium is often useful because it separates rapid physical swelling from slower chemical degradation. Subsequent timepoints should be chosen from pilot kinetics rather than from arbitrary calendar intervals.

At each timepoint, the study should distinguish destructive from non-destructive measurements. Mass and external dimensions can often be repeated on the same specimen. Transport imaging or non-destructive compression may also be repeatable within limits. Chemical analysis and failure testing usually require separate specimens. The experimental design should therefore be defined before printing so that each cohort has traceable geometry, orientation and cure history.

Question	Measurement family	Minimum controls	Interpretation limit
Did hydration change the scaffold before degradation?	Equilibrium swelling/mass uptake; hydrated dimensions; wet modulus	Dry/final-post-cure baseline; fixed medium and temperature	Swelling does not prove chemical degradation.
Did chemistry degrade?	Molecular weight where applicable; spectroscopy; soluble products; enzyme-specific cleavage marker	Blank medium; non-degrading or time-zero control	Mass loss alone may lag chain scission.
Did geometry evolve?	μ CT, confocal/optical imaging, pore/channel dimensions, porosity/connectivity	Same designed geometry; state-appropriate imaging	Dry imaging can misrepresent hydrated hydrogels.
Did transport evolve?	Tracer diffusion, permeability, pressure-flow, breakthrough or perfusion test	Defined tracer size/charge; fluid viscosity; pressure/flow condition	One tracer does not represent all nutrients, proteins or drugs.
Did mechanical function persist?	Wet compression/tension; cyclic response; fracture/buckling where relevant	Matched geometry, strain rate, conditioning and orientation	Bulk-material modulus cannot substitute for scaffold apparent response.
Did biological response remain acceptable?	Application-specific cell/material endpoints after chemical and physical state are defined	Appropriate negative/positive controls and final processed specimens	A material test does not establish clinical effectiveness or device approval.

Table 3. Recommended coupled test architecture for VPP tissue scaffolds.

9. Reporting degradation and recovery metrics without overclaiming

Terms such as biodegradable, bioabsorbable and resorbable should not be used interchangeably without an operational definition and evidence for the intended environment. A material can undergo measurable hydrolysis without being fully resorbed in the relevant timeframe. A scaffold can lose mechanical integrity while much of its mass remains, or retain mass while molecular weight falls. The paper should therefore report the measured endpoint directly: percentage mass remaining, molecular-weight change, modulus retention, pore change, diffusion coefficient or other quantified state variable.

Where a percentage retention or degradation metric is used, the denominator must be named. Mechanical retention, for example, should specify whether the reference is the final dry specimen, the hydrated-equilibrated specimen or a matched non-degraded control. The same applies to dimensional change and transport enhancement. This avoids the common error of comparing aged hydrated specimens against a physically different baseline.

3Dresyns implementation examples

The examples below are commercial implementation anchors from controlled 3Dresyns documentation. They are not peer-reviewed evidence for tissue regeneration, clinical suitability or a universal degradation law, and they should not be used to transfer quantitative behaviour between formulations.

3Dresyn Research HydroGel SLA1 is documented as an SLA/DLP/LCD hydrogel R&D system for controlled swelling, permeability and release studies. Its documentation explicitly states that hydration level, exposure, geometry and post-processing affect swelling, mechanical response and release kinetics, and that the material is for research use rather than clinical or pharmaceutical use. This makes it a direct implementation example of the state-dependent framework developed in this review.

3Dresyn Bio Scaffolds2 is positioned for scaffold fabrication with controlled degradation behaviour and partial, not complete, bioabsorbability. Current controlled claims documentation explicitly states that degradation, resorption and biological response depend on geometry, curing conditions, post-processing and application environment and require user validation. The product therefore illustrates why degradation descriptors must be tied to conditions rather than treated as intrinsic universal rates.

3Dresyn Bio Scaffolds4 is positioned as a scaffold-photopolymer platform for incorporation and dispersion of post-added bio-fillers and for controlled mechanical performance. In the present framework, filler addition creates a new coupled qualification problem: dispersion and optical cure can alter realised geometry, while filler–matrix interactions can alter water uptake, transport and mechanics. No biological or degradation performance should be inferred solely from the filler identity or product positioning.

10. Minimum reporting framework

Category	Minimum information	Reason
Material and print state	Material identity or formulation class; printer/process; wavelength; exposure; layer/voxel condition; wash/post-cure	Defines the initial network state.
Geometry	CAD architecture plus measured hydrated or service-state dimensions; pore/channel descriptors; orientation	Separates designed from realised architecture.
Conditioning	Medium, temperature, pH/ionic content, enzyme if used, agitation/perfusion, time	Makes swelling and degradation kinetics interpretable.
Transport	Tracer or solute identity/size; diffusion or permeability method; boundary conditions; timepoint	Prevents “permeable” from becoming an undefined label.
Degradation	Mechanism, mass change plus chemical/molecular evidence where feasible; erosion morphology	Separates swelling, chain scission and material loss.
Mechanics	Bulk or scaffold level; wet/dry state; test mode; strain rate; cyclic history; retention baseline	Makes mechanical evolution comparable.
Biological evidence	Cell type and endpoint only where tested; final processed material state	Prevents material descriptors from becoming clinical claims.
Uncertainty	Replicates, specimen-to-specimen variability, measurement limitations and failure criteria	Required for a qualification claim rather than a demonstration image.

Table 4. Minimum reporting information for a coupled scaffold study.

11. Research gaps

The most important gap is simultaneous measurement. Many studies optimise printability, mechanics, degradation or biological response in separate experiments, but fewer track transport and mechanical evolution on matched degradation timelines. This makes it difficult to distinguish a genuinely coupled design rule from a collection of favourable initial properties.

A second gap is architecture-aware degradation. Material coupons cannot reveal how strut thinning, local erosion or pore coalescence changes a scaffold’s global stiffness or flow pathways. Three-dimensional imaging combined with mechanical testing and transport measurements should therefore become more common, particularly for degradable VPP networks. Computational models could then use measured geometry rather than nominal CAD to predict function over time.

A third gap is the qualification of post-print transformations. Molecular cleavage, secondary crosslinking, swelling and other post-processing strategies can deliberately decouple print-state and service-state requirements [8,10]. These approaches are powerful but create an additional validation stage: the spatial uniformity and reproducibility of the transformation must be demonstrated. Finally, commercial scaffold materials need condition-specific public datasets that separate feedstock descriptors, final printed-part chemistry, degradation trajectory, transport and biological response.

12. Conclusions

- Vat-printed tissue scaffolds should be treated as time-dependent material–architecture systems rather than static porous objects.
- Transport through designed pores and transport through the polymer network are different mechanisms and require different measurements.

- Hydration can change dimensions, diffusion and mechanics before chemical degradation begins; an equilibrated hydrated baseline is therefore often necessary.
- Degradation should be tracked using chemical or molecular evidence where feasible together with geometry or mass and at least one functional endpoint.
- Bulk material modulus and scaffold apparent modulus are not interchangeable. Architecture, hydration and degradation state must accompany mechanical values.
- Crosslink density links print fidelity to swelling, transport and degradation, so optimisation of the printing state cannot be separated from service-state qualification.
- CAD porosity is not a substitute for measured geometry. Pores and channels should be verified after processing and, where relevant, during degradation.
- 3Dresyns scaffold and hydrogel products can illustrate implementation variables, but product positioning does not establish tissue regeneration, clinical suitability or universal degradation performance.
- The strongest evidence is a coupled trajectory linking material state, realised geometry, transport and mechanics over the relevant conditioning period.

Limitations

This review is an engineering synthesis rather than a preregistered systematic review or meta-analysis. Scaffold studies differ in chemistry, architecture, hydration medium, degradation protocol and biological context; quantitative values are therefore not pooled across incompatible states or methods.

Author contributions

J.S.: conceptualisation, methodology, literature synthesis, engineering interpretation, writing, review and editing.

Competing interests

The author is affiliated with 3Dresyns by Resyner Technologies S.L. Commercial 3Dresyns products are discussed only as implementation examples and are not used as independent scientific evidence of biological or clinical performance.

Data availability

No new experimental, biological or clinical dataset is reported in this Engineering Review. The manuscript is based on peer-reviewed literature and controlled 3Dresyns product documentation. Product-specific scaffold qualification requires independent testing of the final printed and conditioned part under the intended research or application environment.

Company information

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