

Water-Removable Sacrificial Photopolymers for Indirect Additive Manufacturing

Mechanistic Frameworks, Process Coupling and Emerging Applications

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Abstract

Indirect additive manufacturing addresses a structural limitation of direct three-dimensional printing: enclosed channels, undercuts and intertwined cavities can be difficult or impossible to manufacture directly with some processes. The indirect route prints a temporary tool — mould, mandrel, core, template or support — and removes it after the final material has been cast, injected or otherwise formed around it. Water-removable sacrificial photopolymers are now documented across seven application areas considered in this review: microfluidics and lab-on-chip devices, biomedical phantoms and surgical training, investment casting patterns, ceramic injection moulding, metal injection moulding, thermoplastic injection moulding, and inkjet support materials. The published literature remains dominated by application-specific demonstrations rather than a unified mechanistic treatment. This review therefore proposes an operational framework distinguishing three aqueous-removal pathways — direct molecular dissolution, swelling-dominated removal and hydrolytic disintegration. It further advances a testable hypothesis that formulation architecture and cure conditions can jointly influence the realised removal pathway. General free-radical polymerisation literature supports the plausibility of cure-dependent branching, autoacceleration, diffusion-controlled termination and changes in network heterogeneity, but the magnitude of these effects has not been quantified for the commercial sacrificial systems reviewed here. The framework is illustrated with documented commercial examples and compared with academic systems including N,N-dimethylacrylamide/4-acryloylmorpholine chemistry. Peer-reviewed demonstrations are available in microfluidics, vascular phantoms, investment casting, ceramic injection moulding, polymer micro-component injection moulding and inkjet support applications; evidence is substantially more limited for metal injection moulding with vat-photopolymerised water-removable sacrificial moulds. Vat-photopolymerisation and extruded water-soluble sacrificial materials occupy complementary regions of the application space, and selection should be driven by the complete process chain. Open challenges include higher thermal resistance with retained removability, faster and better-standardised removal kinetics, four-dimensional sacrificial behaviour, bioprinting integration, biodegradable formulations and controlled characterisation of storage stability.

Keywords. water-removable sacrificial photopolymer · vat photopolymerisation · stereolithography · digital light processing · LCD masked stereolithography · indirect additive manufacturing · photopolymerisation kinetics · polymer dissolution · sacrificial mould · microfluidics · biomedical phantom · investment casting · ceramic injection moulding · metal injection moulding

1. Introduction

Additive manufacturing is often described as the technology that makes any geometry printable. In practice this is only partly true. Direct three-dimensional printing of a final part imposes severe constraints when the geometry contains enclosed internal channels, undercuts that cannot be reached by support removal, intertwined cavities, or thin-walled internal networks that must remain free of residue. These features are routine in real industrial parts: cooling channels in injection moulds, vascular networks in tissue engineering scaffolds, microchannels in lab-on-chip devices, internal manifolds in fluidic chips, and intricate lattices in technical ceramic components [16].

Indirect additive manufacturing is the paradigm that addresses this limitation. The additive process prints a temporary tool — a mould, a mandrel, a template, a support — rather than the part itself. The final part is obtained by casting, injecting, depositing or growing the desired material inside or around that tool, and the tool is removed once the part is consolidated. The geometry of the final part is therefore constrained only by what the negative tool

can describe, not by what the printer can deposit. Indirect AM is increasingly the route of choice wherever direct deposition cannot reach the geometry of interest [13–16,21,22].

The sacrificial material is the keystone of the indirect route. It must print with controlled resolution since the final geometry is the inverse of the printed tool. It must be mechanically stable during the casting or injection step. It must be chemically compatible with the surrounding material — neither dissolving prematurely nor reacting with the feedstock. And it must be removable cleanly when the time comes, without damaging the part or leaving residues that compromise downstream performance [3,16].

Several sacrificial families have been deployed. Fused deposition modelling uses poly(vinyl alcohol) and butenediol vinyl alcohol copolymer water-soluble filaments, solvent-removed thermoplastics, and extruded sugar alcohols [13–15]; inkjet and material-jetting systems offer proprietary water-removable or breakaway supports [32]. Vat photopolymerisation — stereolithography (SLA), digital light processing (DLP) and liquid-crystal-display masked stereolithography (LCD MSLA) — was a late entrant because photocured networks are crosslinked thermosets, not soluble like the linear thermoplastics extruded in FDM. The development of photopolymer chemistries that are water-removable by hydrolytic dissolution, swelling-assisted disintegration, or a combination of both, has opened indirect manufacturing routes previously inaccessible to vat-photopolymerisation users [17].

Water as the removal medium has practical, regulatory and economic advantages over solvents. Using water for the sacrificial-removal stage can reduce reliance on organic solvents. The complete workflow may still require other cleaning media, and residue control, occupational controls, waste handling and final-use suitability must be assessed for the specific process. The trade-off is that designing a photopolymer network that prints with fidelity and then dissolves in water is non-trivial: the same crosslinking that gives the printed mould its dimensional stability is what must be reversible — or at least disruptible — by water exposure after casting. The polymer physics

underlying this trade-off has been extensively studied for non-photopolymer systems [1–3] and provides the conceptual anchor for the framework developed in §3.

This review covers indirect manufacturing routes in which water-removable sacrificial materials are used as temporary tooling, cores, templates or supports. After classifying sacrificial materials and outlining the chemistry relevant to their behaviour, the review examines seven application areas: microfluidics and lab-on-chip devices, biomedical phantoms and surgical training, investment casting patterns, sacrificial moulds for ceramic injection moulding, sacrificial moulds for metal injection moulding, sacrificial moulds for thermoplastic injection moulding, and inkjet support materials. Recent reviews of sacrificial biofabrication, multi-material vat photopolymerisation and microfluidic 3D printing provide broader context for these workflows [24,25,33,40]. The engineering question is therefore not whether one sacrificial strategy is universally superior, but which removal mechanism and printing route best fit the geometry, thermal-mechanical load, surrounding material and required release conditions.

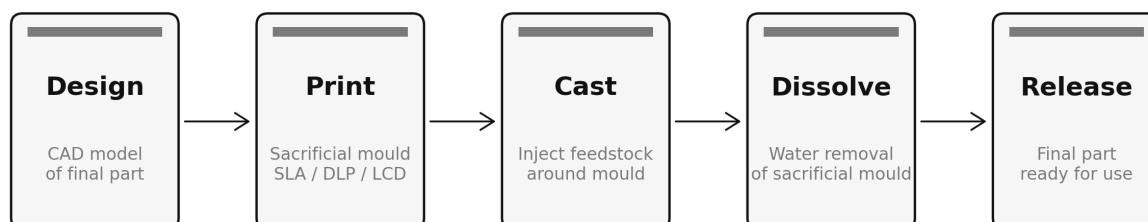


Figure 1. Indirect additive manufacturing workflow using a water-removable sacrificial mould. The sacrificial mould is printed by SLA, DLP or LCD MSLA vat photopolymerisation; the part material is cast or injected around it; the mould is removed in water by molecular dissolution, by swelling-assisted release, or by a transition between the two depending on cure conditions; and the final part is released with internal channels, undercuts or intertwined cavities that direct printing could not produce.

2. Classification of sacrificial materials

Sacrificial materials in additive manufacturing can be classified along two complementary axes: the printing technology that produces them, and the mechanism by which they are removed once their structural role has ended. Both dimensions matter for selecting a material, because each combination determines the resolution achievable, the geometries supportable, the chemistries compatible and the environmental footprint of the workflow.

Along the printing-technology axis, extrusion-based sacrificial workflows are well established. Dahlberg et al. demonstrated water-soluble PVA master scaffolds printed by FDM and dissolved after embedding in PDMS [14]. Gelber and Bhargava demonstrated 3D-printed isomalt as a water-soluble sacrificial mould [15]. Saggiomo and Velders provide a contrasting solvent-removable ABS scaffold route [13]. Material-jetting workflows can use dedicated removable supports; a peer-reviewed inkjet example is discussed in §10 [32].

Vat photopolymerisation produces cured polymer structures through light-initiated polymerisation and includes layerwise and continuous process variants [5–8,34,35]. For sacrificial use, the key difficulty is that a cured photopolymer must retain print fidelity during manufacture but later permit controlled removal. Conventional crosslinked photopolymers are generally not molecularly water-soluble, so removable systems require deliberate formulation and process design [3–6,17]. Water-removable VPP systems are documented in peer-reviewed microfluidic, biomedical, casting and injection-moulding applications [17,19,20,26,29,30].

Along the removal-mechanism axis, this review distinguishes four practical routes. Water dissolution involves solvent ingress, swelling and progressive chain or species separation into the aqueous phase [1–3]. Swelling-dominated removal involves water uptake without near-complete molecular dissolution on the process timescale [4,41]. Solvent dissolution uses a compatible organic or other non-aqueous medium, as illustrated by ABS scaffold removal [13]. Breakaway removal relies primarily on mechanical fragmentation. Real systems can combine mechanisms, so the operational label should be assigned from observed removal behaviour rather than assumed from material class.

Within VPP, the removal route must be matched to geometry and downstream process. Enclosed channels often require dissolution or disintegration because mechanical access is unavailable. Thermally and mechanically demanding injection workflows require temporary tooling that remains stable during filling; peer-reviewed demonstrations exist for ceramic injection moulding and thermoplastic micro-injection moulding [29,30], while the MIM route discussed in this review is supported mainly by manufacturer documentation (§8). Compliant or externally accessible geometries may tolerate swelling-dominated or mechanical removal. Selection therefore requires application-specific validation.

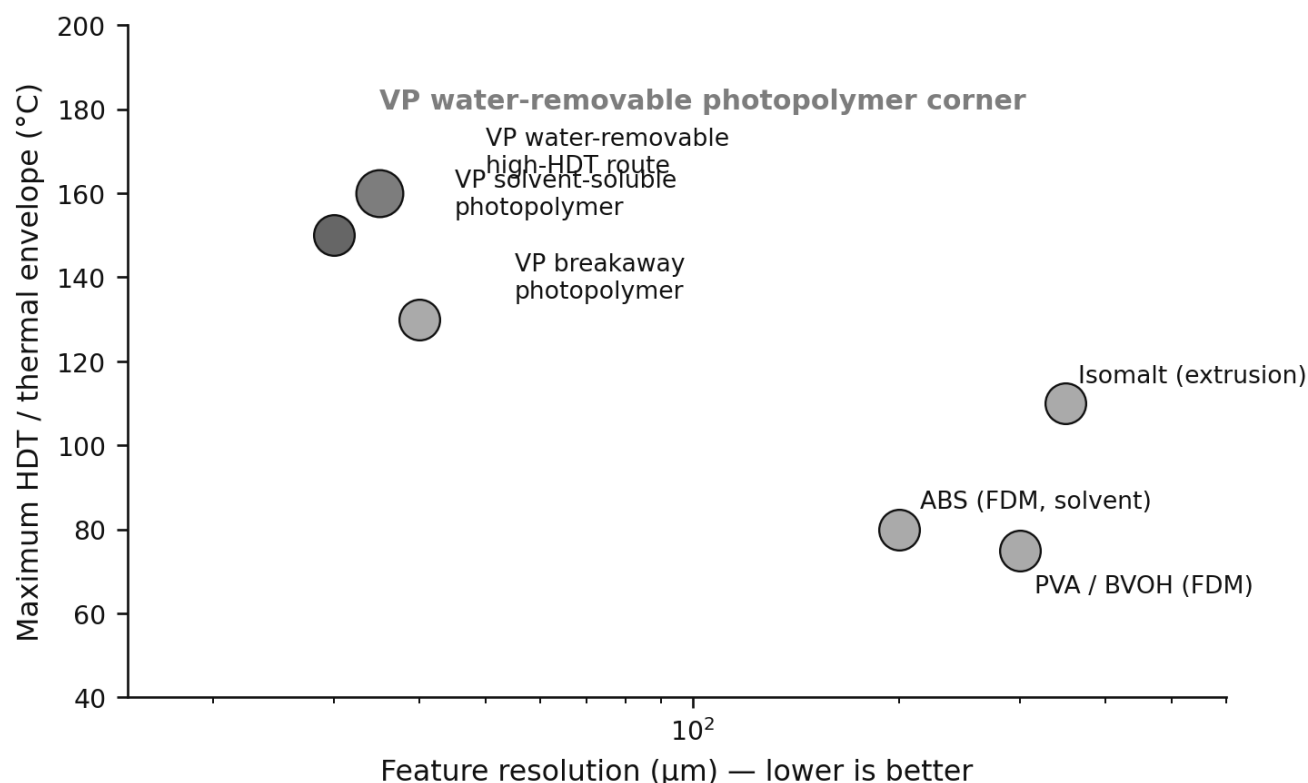


Figure 2. Conceptual sacrificial-material landscape positioned by feature resolution and thermal envelope. The plotted positions are illustrative examples based on the documented systems discussed in the text, not universal limits of the printing technologies or material classes. Printer-, geometry- and material-specific validation is required.

3. Chemistry and design principles

The chemistry of a water-removable sacrificial photopolymer must reconcile two requirements that are in direct tension. The cured material must be mechanically rigid and dimensionally stable enough to define a usable mould, mandrel or template; and the same cured material must subsequently lose this integrity when exposed to water, so that the sacrificial role can end without compromising the part it was used to produce. The formulation space within which both requirements can be satisfied is narrow, and the choices that govern it determine the practical performance of every water-removable sacrificial photopolymer system, commercial or academic [17].

3.1 Terminology used in this review

The water-removable sacrificial photopolymer literature uses several terms interchangeably across publications. To avoid ambiguity, this review applies the following operational definitions consistently. The framework distinguishes between the *design target* (set by formulation intent) and the *realised behaviour* (modulated by photopolymerisation kinetics, §3.5).

Term	Operational definition used in this review
Water-soluble	The cured material undergoes near-complete molecular dissolution in water; individual chains separate and enter aqueous solution.
Water-removable	Umbrella term covering any aqueous-removal route — dissolution, swelling-assisted disintegration, hydrolytic fragmentation — without distinction.
Water-swallowable	The cured network absorbs water and forms a coherent hydrated gel; the polymer remains insoluble but loses mechanical integrity and can be flushed or dislodged.
Dissolution-capable	Designed to reach near-complete molecular dissolution under appropriate cure conditions; the realised outcome depends on photopolymerisation kinetics (§3.5).
Swelling-only	Designed to reach the swollen-gel state as the intended removal mode; molecular dissolution is not the design target.
Disintegrable	The cured material breaks into discrete pieces under water exposure, with or without molecular dissolution following.

3.2 Formulation strategies

A useful distinction is between a formulation design target and the molecular architecture actually produced after cure. Monofunctional hydrophilic monomers can form predominantly linear chains under ideal chain-growth conditions, whereas multifunctional species provide direct routes to covalent network formation [5,6,37]. However, functionality alone does not establish the structure of a cured commercial photopolymer: chain transfer, branching, conversion, impurities and formulation additives can alter the outcome. The DMAA/ACMO system of Kang et al. provides a peer-reviewed example of a water-soluble VPP formulation [17]. For proprietary commercial systems, this review therefore avoids inferring exact composition or network architecture unless supported by published analytical data.

Recent peer-reviewed work has begun to publish specific formulation strategies for water-removable photopolymers. A 2026 study in the Journal of Polymer Research reported a binary system based on N,N-dimethylacrylamide (DMAA) and 4-acryloylmorpholine (ACMO), printed by LCD vat photopolymerisation and evaluated as a water-soluble pattern material for investment casting [17]. Broader reviews describe a wide range of photocurable materials and formulation strategies, but detailed compositional information for commercial

water-removable sacrificial photopolymers remains comparatively sparse [33,43]. Consequently, commercial systems should be compared primarily through documented processing behaviour and measured properties rather than through assumed composition.

3.3 Mechanism taxonomy

Three mechanisms of water-based removal can be distinguished. Direct molecular dissolution occurs when hydrated polymer species can separate and enter the aqueous phase. Polymer dissolution generally involves solvent ingress, swelling and chain disentanglement before diffusion into solution [1–3]. In a cured photopolymer, whether near-complete molecular dissolution is achieved depends on the actual architecture and cure state and must be established experimentally.

Swelling-dominated behaviour describes a different outcome: the cured material absorbs water and forms a coherent hydrated phase, but does not undergo near-complete molecular dissolution on the relevant timescale [4,41]. The swollen material may then be flushed, dislodged or fragmented depending on geometry and mechanical constraint. In this review, swelling-only denotes formulations for which that behaviour is the intended removal mode; a dissolution-targeted material may also display partial swelling under some processing conditions, but the cause of such a transition must be established experimentally rather than inferred from cure conditions alone.

Hydrolytic disintegration is the third pathway used in this framework: hydrolysable bonds cleave during aqueous exposure and the temporary structure fragments into smaller species or pieces. This is a mechanistically distinct category from direct dissolution and swelling. Direct evidence for hydrolytic disintegration in the specific commercial acrylate/acrylamide families discussed here is limited, so the category is retained as a general framework element rather than assigned to a particular commercial formulation without supporting data.

3.4 Formulation parameters

Three formulation variables are especially relevant to intrinsic post-cure behaviour. First, hydrophilic functionality governs water affinity and can promote water uptake and dissolution, although the quantitative relationship is chemistry-specific [3,4]. Second, monomer functionality and the resulting molecular/network architecture influence whether hydrated chains can separate or remain topologically or covalently constrained [5,37]. Third, photochemical reactivity governs conversion and the sensitivity of the cure state to exposure conditions [5–8]. These variables provide a useful design framework, but their relative contributions to water removability must be measured for each resin rather than inferred from formulation descriptors alone.

3.5 Process optimisation, printer dependency and cure-state effects

The realised cure state is not determined by formulation alone. Free-radical photopolymerisation kinetics depend on light absorption, initiation efficiency, radical concentration, conversion, diffusion and termination behaviour [5–12,37]. These mechanisms make it scientifically plausible that exposure conditions could alter branching, entanglement, heterogeneity or gel fraction and thereby affect aqueous removal. For the specific water-removable sacrificial resin families reviewed here, however, direct measurements linking irradiance or exposure profile to molecular-weight distribution, branching, gel fraction and water diffusivity are not available in the public literature. The cure-kinetics coupling developed in this review should therefore be read as a mechanistic hypothesis and process-development framework, not as a quantitatively validated universal law.

Irradiance dependency. Optical irradiance, exposure time, spectral match, layer thickness and the printer's optical architecture all influence photopolymerisation kinetics [5–8]. Laser-scanning SLA, DLP and LCD-MSLA systems deliver light in materially different spatial and temporal patterns, and nominal printer class alone is not sufficient to assign a universal irradiance range. For water-removable sacrificial resins, irradiance should therefore be measured or obtained from validated printer data and treated as a printer-specific process variable. Whether a change in irradiance shifts a particular material from dissolution-dominated to swelling-dominated removal must be established experimentally for that resin–printer combination.

Power-time decomposition of the cure dose. Radiant exposure (mJ/cm^2) is useful for process calibration, but equal total dose does not necessarily imply an identical cure state when irradiance, exposure time, spectral distribution or optical transport differ [5–8]. For the sacrificial systems reviewed here, the effect of changing irradiance at constant dose on molecular architecture and water removability has not been quantified. Power and exposure time should therefore be recorded separately and treated as independent experimental variables rather than collapsed into dose alone.

Moisture and storage effects. Hydrophilic formulations can be sensitive to environmental moisture, but the magnitude and mechanism of that sensitivity are material-specific. The public literature reviewed here does not establish a universal relative-humidity threshold or a layer-by-layer plasticisation gradient for commercial water-removable sacrificial resins. Ambient humidity, liquid-resin exposure history, post-cure state and storage conditions should therefore be controlled and reported during validation. Systematic measurements of mass uptake, dimensional drift and mechanical changes as a function of humidity and time remain an open characterisation need.

Photoinitiator chemistry and concentration are additional cure variables. The initiator system controls spectral overlap with the printer emission, radical-generation efficiency and the kinetics of initiation and termination [7,11,12]. These factors can affect conversion and cure depth, but the extent to which they control dissolution-versus-swelling behaviour in water-removable sacrificial formulations has not been isolated experimentally in the literature reviewed here.

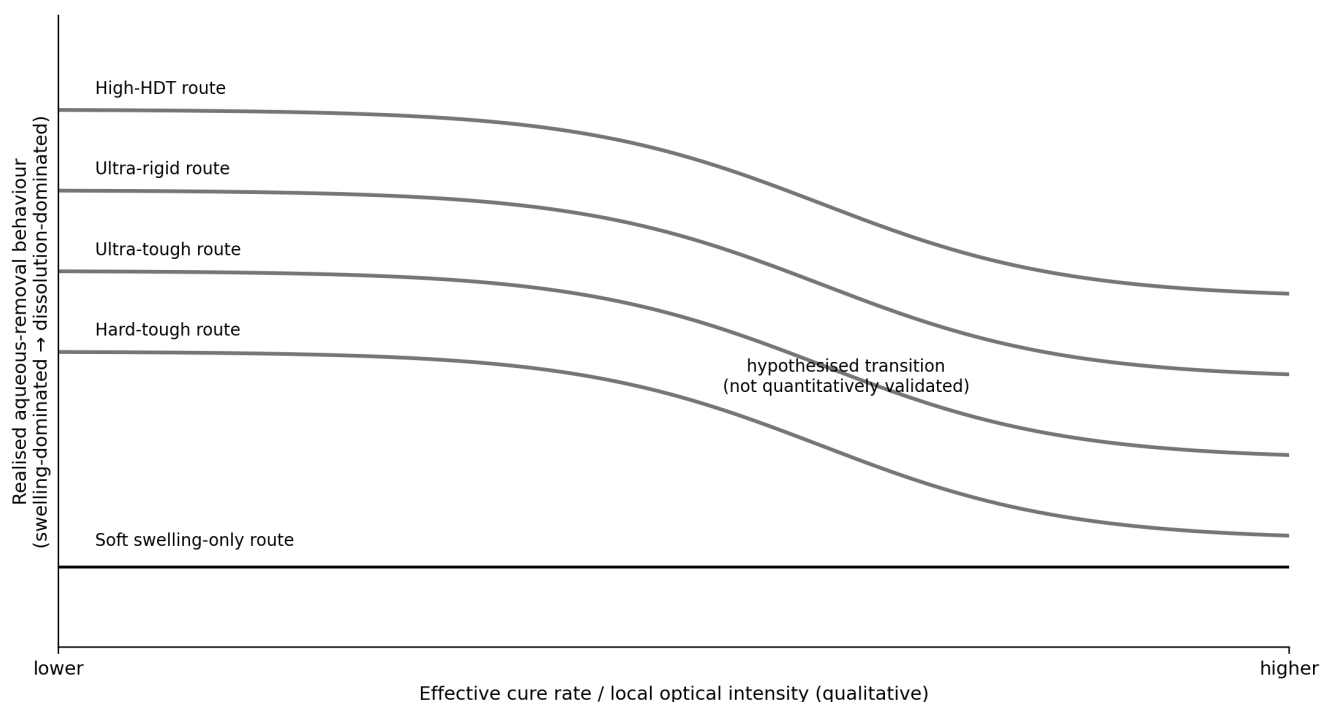


Figure 3. Proposed qualitative cure-state framework for dissolution-capable and swelling-only sacrificial photopolymers. The horizontal axis represents increasing effective cure rate / local optical intensity on a qualitative scale, not printer-class irradiance ranges. The downward trajectories are a mechanistic hypothesis: faster cure may alter network architecture and thereby reduce molecular dissolution, but resin-specific dose-response data are not currently available. The soft swelling-only route is shown separately because swelling is its design target. The diagram is conceptual and must not be used as a quantitative process window.

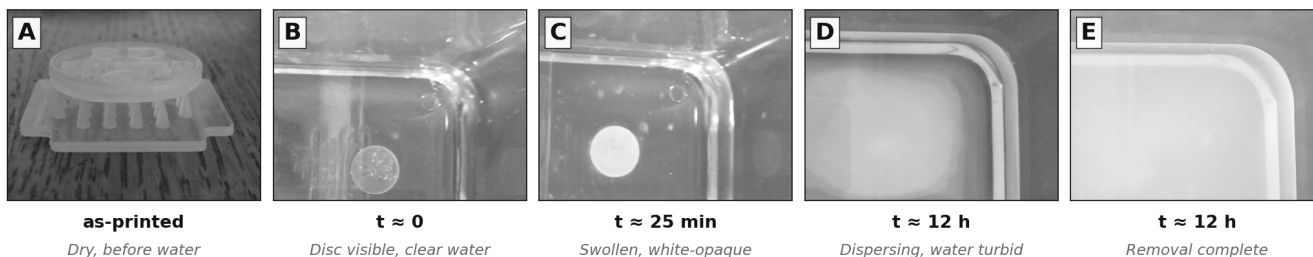


Figure 4. Photographic time series of water-based removal of a printed water-removable sacrificial photopolymer in tap water at ambient temperature. (A) As-printed sacrificial structure, dry. (B) Initial state in water: disc visible, water still clear. (C) Swelling phase: the network has absorbed water and the structure has become white-opaque due to scattering from sub-microscopic hydrated heterogeneities; the water remains clear. (D) Late dispersion: the swollen structure has progressively passed into solution and the water has become turbid. (E) Near-complete removal: water fully turbid, the structure no longer visible. The molecular-scale interpretation of the same A–E sequence is given in Figure 5.

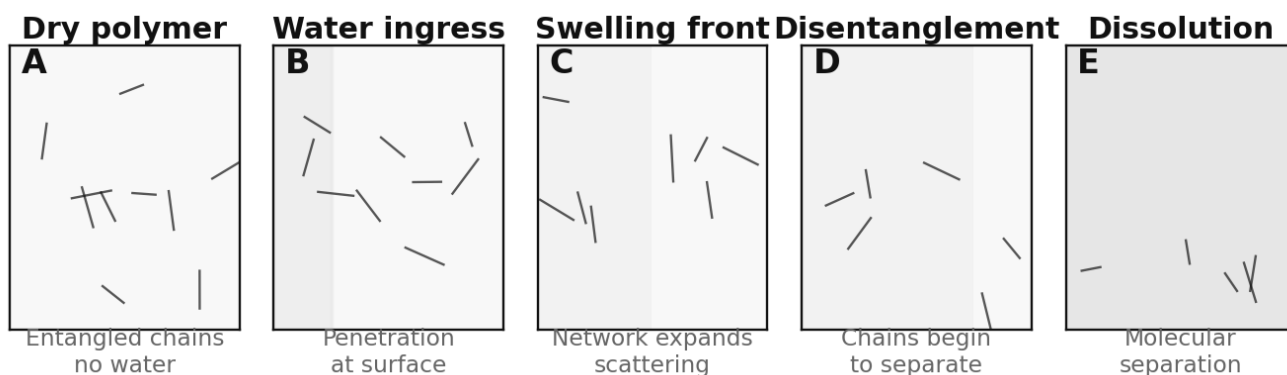


Figure 5. Schematic of the swelling-to-dissolution mechanism at the molecular scale for predominantly linear hydrophilic photopolymers. (A) Dry cured polymer with entangled hydrophilic chains in a glassy or rubbery state. (B) Water ingress at the surface. (C) Swelling front: the surface region expands as water uptake exceeds the elastic limit of the local chain assembly; refractive-index heterogeneities at sub-microscopic scale produce visible scattering. (D) Disentanglement: progressively hydrated chains begin to separate as the local glass-transition temperature drops below ambient temperature through plasticisation by water [1,2]. (E) Molecular dissolution: disentangled chains diffuse into the aqueous medium as individual macromolecules [3]. Under fast cure conditions, secondary reactions can produce sufficient branching and entanglement to suppress step (D), causing the pathway to halt at a swollen-gel state.

3.6 Worked illustration of the framework

The three-pathway framework introduced above can be illustrated against any water-removable sacrificial photopolymer system for which engineering documentation exists across the relevant axes — formulation hydrophilicity, cure-kinetics dependency, mechanical envelope, removal behaviour. The applications sections (§4–§10) draw worked examples primarily from one such system, selected for the breadth of publicly available engineering data and the relative density of independent peer-reviewed publications referencing its grades [19,20,25,29,30,32]: a commercially available family of water-removable sacrificial photopolymers and adjacent casting and inkjet-support lines [M1–M5]. The framework is not specific to this system. Other water-removable sacrificial photopolymer chemistries — academic systems based on DMAA and ACOM [17], isomalt sugar alcohol [15], hydrolysable PEGDA networks [22–24] — can be evaluated against the same formulation × cure-kinetics axes and would be expected to occupy distinct positions in the same design space. In the applications sections, the worked example is referenced by its conceptual role in the framework — most often as a *high-HDT dissolution-capable route* for demanding-temperature injection (§8–§10) or as a *hard-tough dissolution-capable route* for microfluidics and biomedical phantoms (§4–§5), with a brief reference to the *casting-pattern route* in §6. The corresponding commercial identifier is provided once per application section for traceability.

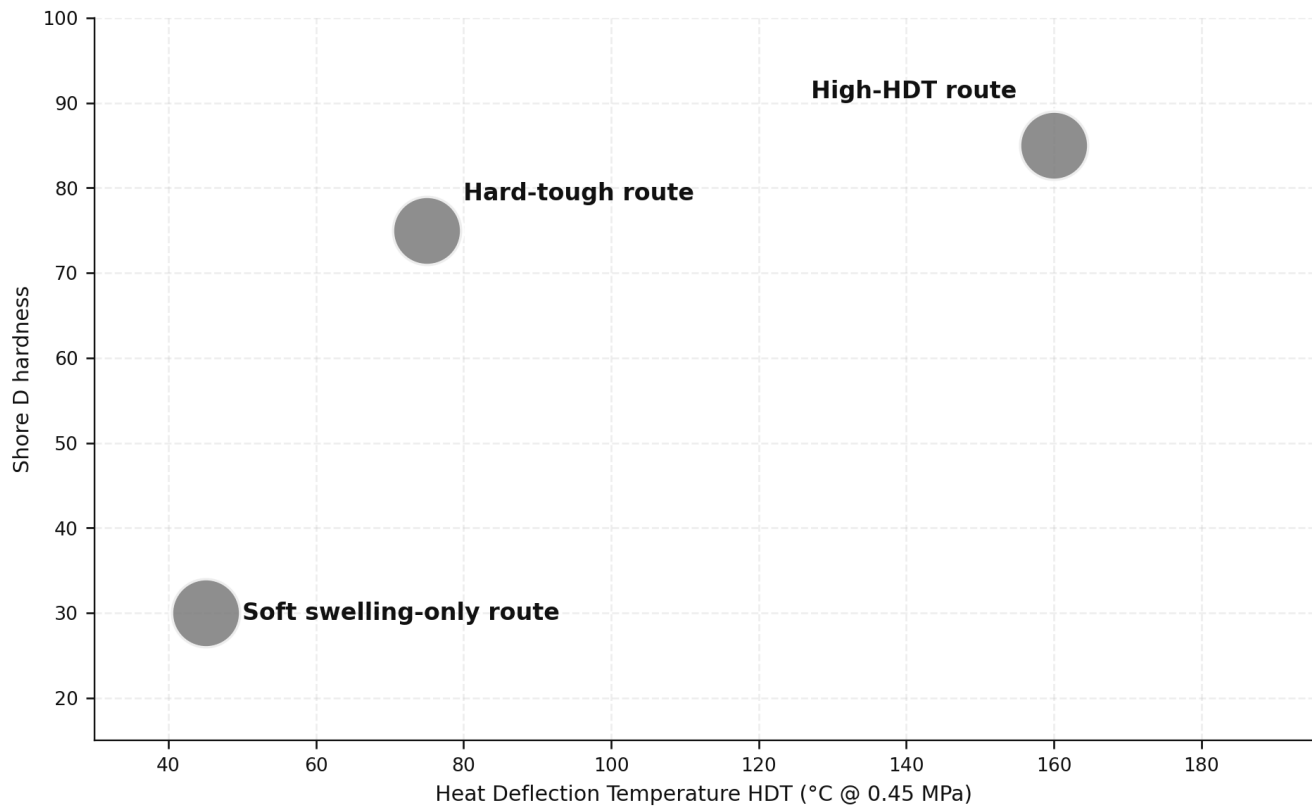


Figure 6. Mechanical–thermal envelope of water-removable sacrificial photopolymer chemistries discussed in this review, spanning from rigid high-HDT formulations to soft water-swellaable chemistries. Positions are indicative; printer- and platform-specific calibration applies.

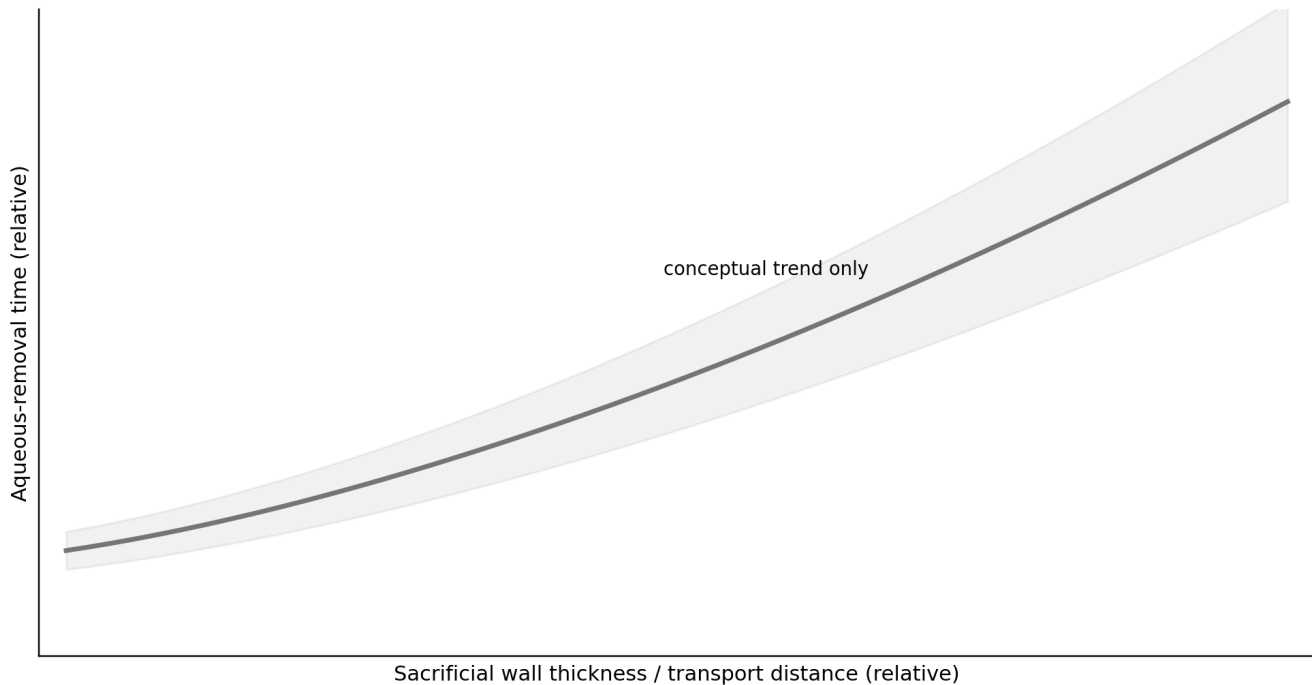


Figure 7. Conceptual relationship between sacrificial-wall thickness and aqueous-removal time. Removal time is expected to increase with transport distance, but the curve is deliberately dimensionless because quantitative kinetics depend on resin chemistry, cure state, geometry, water composition, temperature, flow/agitation and access to the sacrificial surface. No universal removal-time values are implied.

4. Microfluidics and lab-on-chip devices

Microfluidics was one of the first application areas to exploit water-removable sacrificial photopolymer resins on vat-photopolymerisation hardware. The reason is straightforward: microfluidic devices are defined by their internal channel geometry, and the channels of interest are typically smaller than 1 mm, often with intricate three-dimensional architecture that includes mixers, manifolds, droplet generators and reaction chambers. Soft lithography — the dominant fabrication method for microfluidics since the late 1990s — is based on casting polydimethylsiloxane (PDMS) against a master mould fabricated by photolithography [18]. This two-step process is robust for planar channel geometries but struggles with three-dimensional architectures, because the channel ceiling and floor have to be defined in separate steps and then bonded with sub-millimetre alignment [16].

Three-dimensional microfluidic geometries that are not accessible to soft lithography can be obtained by indirect manufacturing: a sacrificial mould is printed that describes the negative of the desired internal channels, the PDMS or epoxy resin is cast around the sacrificial mould, the cast polymer is cured, and the sacrificial mould is then dissolved to leave behind the channel network. The sacrificial material must combine high printing resolution (because the channel surface quality is the inverse of the sacrificial surface quality), water solubility (because PDMS castings are typically rinsed in water and isopropanol after cure), and sufficient mechanical stability during the cast (because the PDMS prepolymer is applied as a viscous liquid and cures under modest temperature, neither of which should distort the sacrificial geometry) [21].

A well-documented application is the patient-specific cerebral arterial phantom reported by Nilsson and colleagues in Scientific Reports [19]. The authors printed the arterial geometry using IM-HT-WS water-soluble resin (3Dresyns) on a desktop SLA platform, cast transparent PDMS around the printed sacrificial structure and then removed the structure in deionised water with ultrasonic assistance. The workflow reproduced a patient-derived cerebral arterial network as a flexible phantom; the final phantom showed a 13 % reduction in total internal volume relative to the CTA-derived model. The paper provides direct peer-reviewed evidence for a commercial water-soluble vat-photopolymer resin in an indirect biomedical moulding workflow.

A separate peer-reviewed contribution by Fernandes Quero, Pereira de Jesus and Fracassi da Silva in Lab on a Chip demonstrated a custom multi-material DLP platform with a vat-inclination system and embedded peristaltic pumps [20]. The study printed flexible, rigid, water-soluble, fluorescent, phosphorescent and electrically conductive materials and reported microfluidic channels as narrow as 43 μm . The water-soluble resin used in the work was IM-HT-WS. This publication establishes multi-material process compatibility; it should not be interpreted as a general quantitative benchmark for all water-removable sacrificial formulations.

demonstrated that flexible, rigid, water-soluble, fluorescent, phosphorescent and electrically conductive resins could be combined in a single chip.

Alternative sacrificial routes provide useful context. Gelber and Bhargava demonstrated monolithic multilayer microfluidics using 3D-printed isomalt as a sacrificial mould [15]. Dahlberg and colleagues reported water-soluble 3D-printed scaffolds for rapid production of PDMS micro-fluidic flow chambers [14]. Saggiomo and Velders demonstrated an intricate scaffold-removal workflow using 3D-printed ABS removed with an organic solvent, illustrating a non-aqueous alternative [13]. Sacrificial biofabrication studies have also used fugitive or removable templates to generate vascular networks [21–24]. These routes are complementary rather than directly interchangeable, because resolution, removal chemistry, biological compatibility and thermal-mechanical demands differ by application.

5. Biomedical phantoms and surgical training

The same indirect-manufacturing principle extends from microfluidic channels to biomedical vascular phantoms: a removable internal geometry is printed, a tissue-mimicking material is formed around it, and the temporary structure is removed. Peer-reviewed studies have demonstrated such workflows for cerebral and vascular flow models using both water-soluble filament and vat-photopolymer materials [19,26,27]. The clinical or training suitability of a given phantom remains application-specific and depends on geometry, mechanical properties, imaging response and validation against the intended use.

The Scientific Reports study by Nilsson et al. [19] is a direct demonstration of a patient-specific cerebral arterial phantom using a 3Dresyns water-soluble sacrificial resin. Soloukey and colleagues subsequently reported MRI- and Doppler-ultrasound-compatible flow phantoms fabricated with customizable water-soluble resin prints [26]. Their study used IM-HDT-WS and produced geometric and patient-derived vascular phantoms; the published workflow reports complete dissolution of the sacrificial print after circulating-water removal. These studies support the use of water-removable printed forms for complex imaging phantoms, while the specific processing conditions should be taken from each original publication rather than generalized across resin grades.

Cardiac surgical-training literature also provides adjacent evidence on the mechanical design of synthetic tissue models. Ginn-Hedman and colleagues reported a conference abstract on mechanical characterisation of synthetic tissues for cardiac surgical training [28]. That work is relevant to tissue-mimicking material selection, but it does not itself constitute validation of a water-soluble sacrificial-mould workflow and is therefore treated here as contextual rather than direct evidence.

Bisighini and colleagues reported compliant and transparent hollow cerebral vascular phantoms produced by 3D-printing water-soluble inner moulds followed by spin-dip coating with silicone and hot-water removal [27]. The study compared FDM and stereolithography routes and characterised the resulting phantom geometry, silicone mechanics, wall-thickness uniformity and transparency. The paper supports the broader sacrificial-mould concept for vascular models, but its process results should not be converted into universal dissolution times or alkaline-water recommendations beyond the conditions actually reported.

6. Investment casting for jewellery and precision metal parts

Investment casting is one of the oldest industrial uses of sacrificial materials. The migration of investment casting from wax patterns to 3D-printed photopolymer patterns over the past two decades has expanded the geometric envelope of the technique, enabling intricate jewellery filigrees, dental crown and bridge architectures, and aerospace component geometries that would be difficult or impossible to produce by hand-finishing wax masters [42].

Two distinct families of water-removable photopolymer resins serve different stages of the broader sacrificial-casting workflow. The first family is water-removable casting patterns: the printed object is the positive replica of the final

part, invested in the refractory shell, and removed by water before metal pouring. The **casting-pattern route** (the system referenced as [M5] in this review) belongs to this family. The second family is water-removable sacrificial injection moulds: the printed object is the negative cavity used to shape a separate cast material, removed by water after the cast material has consolidated [29,30].

Traditional photopolymer investment-casting patterns are commonly removed thermally during burnout, which can create process constraints associated with pattern expansion, decomposition and residue. Manufacturer documentation for the Perfect Cast WS1 route [M5] describes water- or steam-assisted removal before burnout as an alternative for selected investment-casting workflows. Because those removal conditions are manufacturer-reported and depend on investment material, geometry and process settings, this review does not assign a universal steam pressure or cycle time. Independent validation remains desirable for application-specific casting performance.

A 2026 peer-reviewed study in the Journal of Polymer Research extended the academic literature on water-soluble photopolymer patterns for investment casting [17]. The authors developed a binary water-soluble resin system based on N,N-dimethylacrylamide and 4-acryloylmorpholine, printed the pattern on an LCD platform, cast a ceramic shell around the printed pattern, and dissolved the pattern in water before pouring the metal. The study reported high dimensional accuracy and mechanical strength in the printed pattern, with the binary monomer system providing both the rigidity needed for stable casting and the water removability needed for clean separation from the shell. The publication validates the academic feasibility of the water-removable pattern route and provides a peer-reviewed reference framework for the broader engineering community.

7. Sacrificial moulds for ceramic injection moulding

Ceramic Injection Moulding (CIM) is a high-volume manufacturing process for small, geometrically complex ceramic components. The process flow consists of injecting a feedstock — a viscous mixture of ceramic powder and polymer binder — into a metal mould, cooling the feedstock until it solidifies into a green part, removing the binder in a multistep debinding process, and sintering the residual ceramic skeleton at high temperature to densify it into the final part. CIM is the dominant route for the production of technical ceramic components in aerospace, medical, electronics and automotive applications [29,36].

The dominant cost driver in CIM is the fabrication of the metal injection mould. Steel moulds for CIM feedstocks must withstand high injection pressures and abrasive ceramic-loaded feedstocks, and they typically require complex multi-cavity tooling with cooling channels, ejection mechanisms and surface finishes engineered to release the green part without damage. Mould fabrication can take weeks or months and can cost tens of thousands of euros per cavity, which limits the economic feasibility of CIM for prototype runs, low-volume production and rapid iteration of part design [40]. The development of sacrificial mould approaches that bypass steel tooling has therefore been an active research direction for the past decade.

Wick-Joliat and colleagues reported a peer-reviewed study of water-soluble sacrificial 3D-printed moulds for ceramic injection moulding [29]. The authors compared FDM-printed PVA moulds with DLP-printed water-soluble resin moulds and demonstrated ceramic parts with complex geometries, including two-component ceramic injection moulding. The study used a composite feedstock containing MoSi_2 , Al_2O_3 and feldspar as well as Al_2O_3 feedstock. DLP moulds provided higher resolution for small structural features than the FDM route. Importantly, the DLP resin in that study was an academic/laboratory water-soluble system; the paper should not be cited as independent validation of a specific 3Dresyns commercial grade.

For the 3Dresyns commercial family, manufacturer documentation positions IM-HDT-WS as the highest-temperature water-soluble sacrificial route for demanding injection-moulding workflows [M1,M3]. Those product specifications and application recommendations are manufacturer-reported. They are therefore kept separate from the independent evidence in [29], and no claim is made here that the Wick-Joliat study tested IM-HDT-WS.

Peer-reviewed evidence specifically validating 3Dresyns water-removable sacrificial moulds in CIM remains limited. The independent CIM study in [29] validates the broader technical concept with PVA and a laboratory DLP water-soluble resin, whereas 3Dresyns documentation [M1,M3,M4] describes commercial routes intended for indirect ceramic and metal workflows. Resin–feedstock compatibility, injection-process windows, residue after removal and fired-part properties should be validated for each specific commercial resin–feedstock combination.

8. Sacrificial moulds for metal injection moulding

Metal Injection Moulding (MIM) applies powder-injection-moulding process logic to metal feedstocks. As in CIM, sacrificial tooling is potentially attractive for geometries or production volumes where dedicated steel tooling is difficult to justify. However, the evidence base must be distinguished carefully: the sources reviewed here provide manufacturer positioning for water-removable sacrificial MIM workflows, but no direct peer-reviewed study was identified that validates the specific 3Dresyns vat-photopolymer sacrificial moulds in a complete MIM process chain.

MIM places application-specific thermal, pressure, chemical-compatibility and surface-integrity requirements on a sacrificial mould. Their magnitude depends on the selected metal feedstock and binder system, mould geometry, filling conditions and cycle time. These requirements should therefore be measured for the intended process rather than inferred from a generic comparison with CIM.

3Dresyns technical documentation identifies water-removable sacrificial routes, including IM-HDT-WS, for indirect ceramic and metal injection-moulding workflows [M1,M3,M4]. This is manufacturer application guidance, not independent MIM validation. The relevant engineering checks are mould stability during filling, compatibility with the feedstock/binder, complete controlled removal, and preservation of green-part geometry before debinding and sintering.

Formal peer-reviewed confirmation of a complete MIM workflow using the specific commercial vat-photopolymer grades discussed in this review remains an evidence gap. Future studies should report the metal feedstock and binder chemistry, mould geometry, injection conditions, removal protocol, residue analysis, green-part dimensional fidelity and final sintered properties.

9. Sacrificial moulds for thermoplastic injection moulding

Thermoplastic injection moulding of geometrically complex parts can also use a sacrificial lost-core approach to create internal hollow features that are difficult to demould conventionally. The thermal and mechanical load on the temporary core depends on the polymer, geometry, filling conditions and cycle time, so no single injection-temperature or pressure window can be assigned to the sacrificial-material class as a whole.

Farrugia, Vella and Rochman reported a 2024 peer-reviewed study in *Progress in Additive Manufacturing* combining 3D printing with micro-injection moulding to fabricate polymer micro-components with internal hollow features [30]. The study used 3Dresyn IM-HDT-WS printed on an Asiga Max X27 DLP platform and compared it with filament-based water-soluble alternatives. The sacrificial printed core survived over-moulding and was subsequently removed to recover PMMA parts with internal channels. The paper provides direct peer-reviewed validation of IM-HDT-WS in a lost-core thermoplastic micro-injection-moulding process chain.

Zhang and colleagues reported a separate peer-reviewed study on automated vision-based inspection of mould and part quality in soft-tooling injection moulding using imaging and deep learning [31]. That work concerns additively manufactured soft tooling and process monitoring, not a water-removable sacrificial mould. It is included as adjacent evidence for quality-control methods that could be transferred to sacrificial-tooling process chains, not as validation of the water-removable route itself.

10. Water-removable inkjet support materials

Inkjet and material-jetting additive manufacturing commonly use a second material to support overhangs or otherwise enable geometries that cannot be deposited as unsupported droplets. A water-removable support can simplify post-processing when the part material and application tolerate the required aqueous removal conditions. The evidence considered here is a specific 2024 peer-reviewed demonstration rather than a claim that all industrial inkjet platforms use the same support chemistry.

Pekkarinen, Karvinen and Saarinen reported additive manufacturing of double-sided centimetre-scale optics in *Optics Express* [32]. Their support-method workflow used a transparent optical part material together with the 3Dresyns IJ WSS1-H water-removable support material. The support was sliced at 13 μm layer thickness and the optical part at 9 μm . The paper reports total transmission of 91.1 % for a 2 mm-thick printed optical plate across 420–780 nm, with internal transmission approaching 99.5 % after excluding Fresnel losses. The support was removed using an aqueous alkaline solution under the conditions described by the authors. These values apply to that documented optical workflow and should not be generalized to other inkjet resin/support combinations.

The *Optics Express* study demonstrates that a removable support can be integrated into a dual-material inkjet workflow without requiring the support to become the final functional material [32]. More broadly, support selection in material jetting must account for droplet-deposition compatibility, interfacial behaviour, removal access and the chemical tolerance of the printed part. Extension to optical, biomedical and electronic applications therefore requires material-pair and process-specific validation.

11. Cross-application comparison and design-space mapping

The application sections have addressed water-removable sacrificial photopolymer resins one application at a time. A complementary view is to compare the conceptual routes themselves across the application space, asking which fits which combination of mechanical, thermal and removal requirements. The three removal pathways defined in §3.2 — direct molecular dissolution, swelling-only network behaviour, and hydrolytic disintegration — and the high-HDT and hard-tough mechanical-thermal axes introduced in the applications sections provide the framework axes. Competing sacrificial classes (extruded water-soluble filaments, isomalt sugar alcohol templates, breakaway photopolymers, solvent-soluble photopolymers) can be positioned against the same axes.

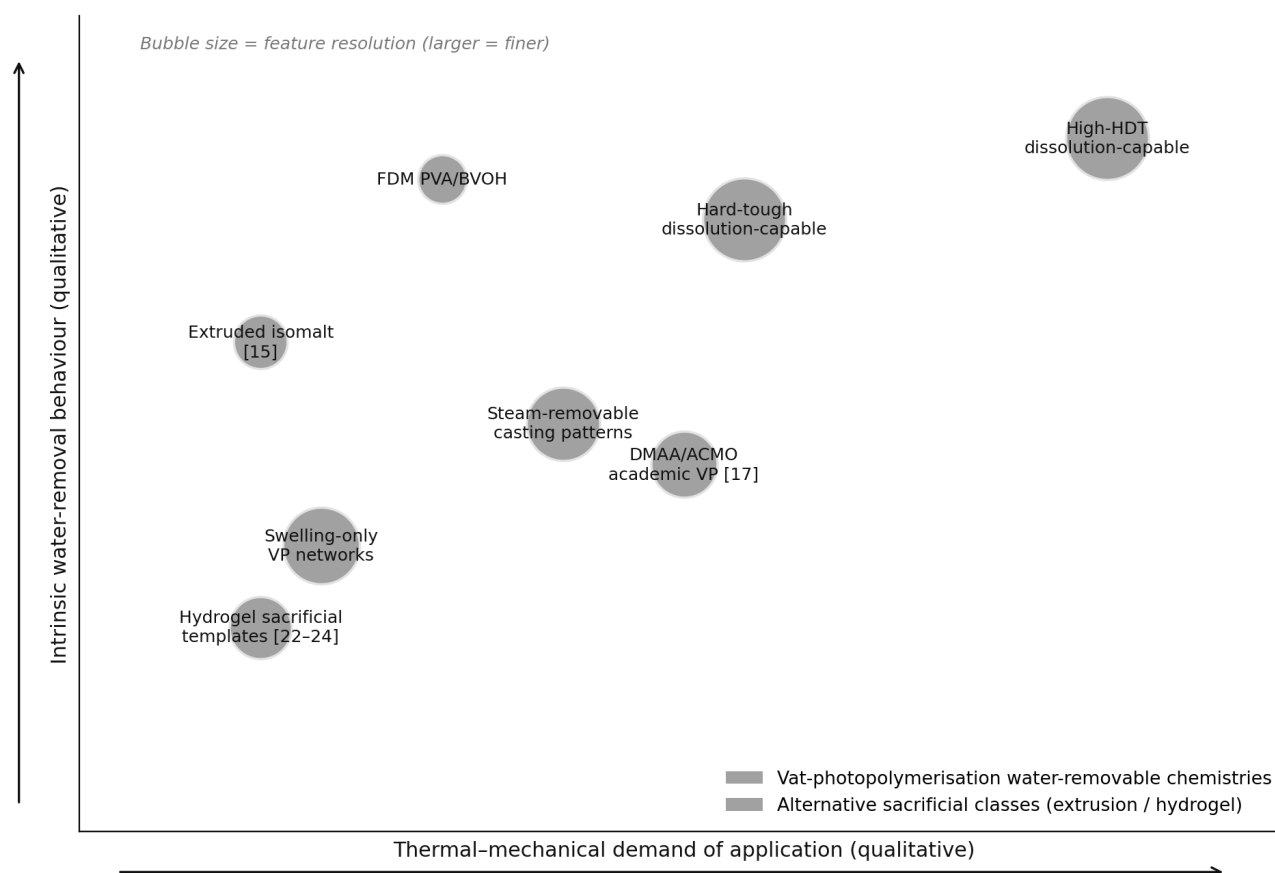


Figure 8. Conceptual design-space map for sacrificial materials, using thermal-mechanical demand, water-removal behaviour and relative feature-resolution capability as qualitative axes. Bubble positions are illustrative examples based on the systems discussed in the review and are not a quantitative benchmark. Cure state and application-specific processing can shift realised behaviour; direct calibration is required.

Vat-photopolymerisation water-removable sacrificial routes and extrusion-based water-soluble routes occupy complementary regions of the design space. Peer-reviewed comparisons show that DLP can provide finer small-feature resolution than FDM in specific ceramic sacrificial-mould workflows [29], while FDM water-soluble materials can offer practical advantages for larger or less resolution-sensitive cores [14,29,30]. Exact feature size, thermal envelope, cost and removal time are platform-, resin- and geometry-dependent. Consequently, Figure 8 should be read as a qualitative selection map rather than a technology-wide performance ranking.

12. Challenges and future directions

Seven open challenges define the research agenda for the coming decade. (i) Higher thermal resistance with retained removability. More demanding injection and casting workflows would benefit from sacrificial materials that retain dimensional stability at elevated processing temperatures while still permitting controlled aqueous removal. Because thermal stability and water removability can impose competing molecular-design requirements, this remains an important formulation and validation problem. Quantitative target temperatures should be defined by the specific feedstock and process rather than assigned universally.

(ii) Faster and better-characterised removal kinetics. Published examples show that removal times can differ substantially with geometry and process: Nilsson et al. used ultrasonic-assisted aqueous removal in a cerebral-artery workflow [19], while Soloukey et al. report complete dissolution after a longer circulating-water step [26]. Industrial optimisation therefore requires geometry-specific kinetic data rather than a universal 3–6 h assumption. Relevant variables include wall thickness, exposed surface area, cure state, temperature, water chemistry, flow and agitation.

(iii) Peer-reviewed consolidation of CIM and MIM applications. The broader CIM concept is supported by the independent sacrificial-mould study of Wick-Joliat et al. [29], while direct peer-reviewed validation of the specific commercial MIM routes discussed here remains absent from the reviewed literature. The gap should be closed with studies reporting complete resin–feedstock–geometry process chains and final-part characterisation.

(iv) 4D sacrificial behaviour. Current water-removable sacrificial resins remove their mechanical contribution in a single dissolution event. Some applications could benefit from sacrificial materials that release stress, change shape, or expose features in a programmed sequence as the dissolution proceeds — sacrificial mandrels that deflate to release internal pressure on the cast geometry, sacrificial scaffolds that dissolve in stages, sacrificial templates that change shape under water exposure to allow demoulding of geometries that would otherwise be locked by undercuts.

(v) Bioprinting integration. Sacrificial biofabrication has generated vascular and perfusable structures using removable or fugitive templates [21–25,36,39,41]. Vat-photopolymerised water-removable sacrificial templates could potentially extend the available geometric toolkit, but their suitability for cell-containing systems cannot be assumed. Biocompatibility of the removal conditions, residual species and surrounding bioink must be established experimentally for each formulation and workflow.

(vi) Sustainability. Aqueous removal can reduce reliance on organic solvents in some workflows, but it transfers polymer or degradation products into the water stream. The environmental benefit therefore depends on formulation, water consumption, treatment and disposal. Future work should quantify waste-water composition, treatment requirements, opportunities for closed-loop water management, and the feasibility of biodegradable or recoverable sacrificial chemistries rather than assuming that water-based removal is inherently low-impact.

circular-economy strategies.

(vii) Long-term storage and humidity stability. Hydrophilic materials may interact with ambient moisture, but the public literature reviewed here does not establish a universal humidity threshold or storage lifetime for commercial water-removable sacrificial photopolymers. Controlled studies of mass uptake, dimensional drift, mechanical properties and removal behaviour as functions of humidity, temperature, time and post-cure history would provide directly useful engineering data.

12.1 Limitations of the proposed framework

The framework proposed in this review — direct molecular dissolution, swelling-dominated behaviour and hydrolytic disintegration as three operational removal pathways — has clear scope limitations. The further proposition that cure conditions can shift the realised removal behaviour by modifying polymer architecture is a mechanistic hypothesis motivated by general photopolymerisation science and manufacturer observations, not a resin-specific molecular mechanism established by direct characterisation.

Empirical anchoring. The application analysis combines one documented commercial family [M1–M5] with a limited number of peer-reviewed water-removable or sacrificial systems, including DMAA/ACMO investment-casting resin [17], isomalt [15], water-soluble microfluidic/phantom routes [14,19,20,26,27], ceramic sacrificial moulds [29] and related biofabrication templates [21–25,36]. The framework should not be extrapolated to untested chemistries without direct measurement.

Qualitative rather than quantitative. Figures 2, 3, 6, 7 and 8 are conceptual engineering diagrams unless explicitly tied to measured data in the accompanying text. Their positions, trajectories and scales are not derived from a unified experimental dataset. Production decisions should therefore be based on direct calibration and measured properties for the specific resin, printer, geometry and downstream process.

Architecture argument requires direct characterisation. Predominantly monofunctional formulations may favour less densely crosslinked structures, but monomer functionality alone does not prove the molecular architecture of a cured photopolymer. Gel fraction, soluble fraction, molecular-weight distribution of extractable species, swelling ratio, spectroscopic conversion measurements and dynamic-mechanical analysis would be needed to establish the proposed architecture for representative formulations.

Cure-kinetics coupling is a hypothesis, not a quantified transition. General free-radical polymerisation literature supports cure-rate-dependent phenomena such as autoacceleration, diffusion-controlled termination and branching reactions [5,9–12,37]. However, dose-response curves linking irradiance or power-time decomposition to gel fraction, molecular-weight distribution, water diffusivity and removal mode have not been published for the commercial sacrificial families discussed. Figure 3 therefore identifies a research question and calibration framework rather than a validated universal trend.

Unaccounted variables. Printer wavelength and spectral distribution, spatial uniformity, layer thickness, oxygen inhibition, initiator chemistry and concentration, temperature, resin history, environmental moisture and post-cure conditions can all affect cure state [5–8,38]. Their effects on water removability are not separated in the available datasets. The framework should therefore be used as a first-order organisational tool, not as a controlled-variable predictive model.

Metrology gap. The field currently lacks a standardised quantitative definition of 'effective water removability'. Dissolution time, residue mass after rinse, geometric fidelity of the cast part, optical clarity of the cast medium and operational ease of removal are all in use across the cited literature but rarely measured under comparable protocols. Comparison between published case studies and between commercial systems is therefore semi-qualitative even when individual studies report numerical values. A standardised metrology for water removability — protocol, water composition, agitation, geometry, sampling — would benefit the field disproportionately to its complexity.

13. Conclusions

Water-removable sacrificial photopolymers are supported by a growing but uneven peer-reviewed evidence base. Direct demonstrations exist for patient-specific and vascular phantoms [19,26,27], multi-material microfluidic printing [20], water-soluble investment-casting patterns [17], ceramic injection moulding with sacrificial water-soluble moulds [29], thermoplastic micro-injection moulding using IM-HDT-WS [30], and dual-material inkjet optics using a removable support [32]. These studies establish technical feasibility in specific workflows; they do not justify treating every commercial grade or every application as independently validated. In particular, the MIM route discussed in §8 remains supported primarily by manufacturer documentation and engineering rationale rather than a direct peer-reviewed process-chain study.

The central contribution of this review is an operational taxonomy and a testable formulation × cure-state hypothesis for organising water-removable sacrificial photopolymers. Formulation chemistry clearly influences water affinity and molecular/network architecture, while photopolymerisation conditions determine conversion and cure state [3–12,37]. Whether cure conditions cause a reproducible transition from dissolution-dominated to swelling-dominated removal in a given commercial resin remains to be quantified directly. The framework is therefore intended to guide experiments, calibration and reporting rather than to replace resin-specific measurements.

Seven open challenges define the agenda for the coming decade: higher HDT with retained removability, faster removal kinetics, peer-reviewed consolidation of CIM and MIM applications, 4D sacrificial behaviour, bioprinting integration at full vat-photopolymerisation resolution, biodegradable or circular-economy-compatible chemistries, and systematic characterisation of ambient-humidity storage stability. None blocks the current generation of applications; each represents a sustained research direction for the coming decade. The trajectory across the seven application areas reviewed here suggests that water-removable sacrificial photopolymers are moving beyond their original niche role toward broader use as indirect-manufacturing enabling materials.

Acknowledgements

The author thanks the international research community whose peer-reviewed publications form the technical backbone of this review, with particular acknowledgement of the groups whose independent characterisation work has anchored the analysis in §4 through §10. 3Dresyns by Resyner Technologies S.L. acknowledges the customers and academic partners worldwide whose collaboration has provided the application context that this review consolidates.

Disclosure

The author is the founder and Scientific Director of 3Dresyns by Resyner Technologies S.L. The commercial family discussed in this review is manufactured by 3Dresyns by Resyner Technologies S.L. and is used as a worked industrial example alongside independent academic systems. The main reference list combines direct application studies with foundational and review literature needed to support the polymer-physics and photopolymerisation discussion. Manufacturer documentation is isolated in Appendix A and labelled [M1]–[M7] so that manufacturer-reported specifications and application positioning are distinguishable from peer-reviewed evidence. No external funding was received for the preparation of this manuscript.

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Appendix A — Manufacturer documentation cited

The following sources are manufacturer documentation and an industry trade publication. They are cited as [M1]–[M7] to distinguish manufacturer-reported specifications, workflow guidance and application positioning from the peer-reviewed and foundational literature in the main reference list. Their inclusion does not constitute independent validation of manufacturer claims.

- [M1] 3Dresyns by Resyner Technologies S.L. (2026). 3Dresyn IM-HDT-WS High-Temperature Water-Soluble Sacrificial Resin. Product technical documentation. www.3dresyns.com
- [M2] 3Dresyns by Resyner Technologies S.L. (2026). 3Dresyn IM-UHT-WS High-Strength Rigid Water-Soluble Sacrificial Resin. Product technical documentation. www.3dresyns.com
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- [M4] 3Dresyns by Resyner Technologies S.L. (2026). Ceramic and metal slurries feedstock for Ceramic & Metal Injection Molding (CIM & MIM) and additive manufacturing of technical ceramics and metals. Technical workflow page. www.3dresyns.com
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