

Antimicrobial Photopolymers for Vat Photopolymerisation: Mechanisms, Efficacy Testing, Leaching and Durability

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Statement of Significance

Antimicrobial performance in a vat-photopolymerised material is not a single property. A printed specimen may reduce planktonic bacterial counts through release of an active species, inhibit attachment without killing cells, kill microorganisms only at the surface, show activity only under illumination, or lose function after extraction, ageing or abrasion. These mechanisms require different experiments and support different claims. This review therefore treats antimicrobial qualification as an evidence chain linking mechanism, printing state, test method, organism, contact conditions, leaching behaviour, durability and biological response. The central proposition is that antimicrobial activity should be reported as a condition-dependent functional result rather than as an intrinsic label attached to a resin. The framework is designed to prevent common over-extensions such as converting an agar-diffusion screen into a universal surface claim, treating antibacterial data as antiviral evidence, or describing short-term activity as durable performance without ageing and re-testing.

Keywords: vat photopolymerisation; antimicrobial photopolymer; antibacterial; antifungal; antiviral; biofilm; silver; copper; zinc oxide; quaternary ammonium; chitosan; photodynamic therapy; leaching; durability; ISO 22196; ASTM E2149; DLP; SLA

Abstract

Vat photopolymerisation (VPP) enables digitally fabricated polymer parts with controlled geometry, but antimicrobial function introduces an additional set of coupled variables. Metal and metal-oxide fillers can provide ion-mediated or contact-associated activity; covalently incorporated cationic groups can create contact-active surfaces; releasable agents can generate sustained or transient antimicrobial effects; zwitterionic chemistries can reduce fouling without necessarily killing microorganisms; and photosensitising systems can create on-demand activity under a specified illumination protocol. Each route interacts with resin viscosity, optical attenuation, conversion, surface composition, post-curing and ageing. Published VPP studies demonstrate antimicrobial activity using silver, copper, cuprous oxide, zinc-containing fillers, quaternary ammonium chemistry, chitosan derivatives, cetylpyridinium chloride and photo-responsive additives, but they also show trade-offs in mechanical properties, optical behaviour, cytotoxicity and durability. This review organises the field around six qualification questions: what mechanism is intended; what microbial endpoint is measured; whether the activity depends on release; whether the printed state preserves the mechanism; whether efficacy survives realistic ageing or cleaning; and whether the biological and chemical profile is compatible with the intended use. Standards including ISO 22196, ISO 21702 and ASTM E2149 are positioned according to what they do and do not establish. A minimum reporting framework is proposed for antimicrobial VPP studies, with explicit separation of antibacterial, antibiofilm, antifungal and antiviral claims. The objective is not to rank formulations, but to provide a defensible architecture for evidence-based antimicrobial claims in printed photopolymer systems.

1. Introduction

Antimicrobial materials are frequently described with compact terms such as antibacterial, antimicrobial, antibiofilm or infection-resistant. In additive manufacturing, those labels can obscure the physical mechanism and the test conditions that produced the result. A VPP material is manufactured from a liquid formulation whose components influence light transport, reaction kinetics and network formation. After printing, washing and post-curing change the surface and the amount of mobile species. During service, extraction, abrasion, cleaning, humidity, temperature and biological fluids can further modify the antimicrobial state. The relevant engineering question is therefore not whether an ingredient is known to be antimicrobial, but whether the final printed and conditioned article exhibits a defined effect under a reproducible method.

The direct VPP literature already spans several mechanism families. Silver-containing systems have been printed as antimicrobial hydrogels, grafted nanoparticle resins and polymeric ionic-liquid constructs [7-9]. Copper and cuprous-oxide fillers have been incorporated into SLA/VPP resins and evaluated against representative Gram-positive and Gram-negative bacteria [10-12]. More recent work has extended the field to copper/zinc systems with bactericidal, fungicidal and virucidal testing [13], quaternary ammonium methacrylates whose activity changes with concentration and thermal ageing [14], phosphorylated chitosan and silanized chitosan nanoparticle systems [15,16], silver-containing denture resins with repeated-use ageing [17], and ZnO/SiO₂ dental composites [18]. These studies establish feasibility, but they also demonstrate that antimicrobial function is coupled to printability, conversion, mechanical performance and surface state.

A second line of evidence concerns the mechanism itself. Covalently tethered cationic surfaces can kill microorganisms by direct surface contact, as demonstrated in classical work on polymer-bound quaternary ammonium surfaces [26]. Release-based systems operate differently: the active species must migrate from the network into the surrounding phase, so activity depends on diffusion, concentration, environmental chemistry and depletion. Antifouling surfaces form a third category because reduced protein adsorption or microbial attachment is not identical to microbicidal activity. Lee and co-workers, for example, used a zwitterionic MPC-containing DLP resin to reduce biofouling while simultaneously evaluating rheology and mechanics [19].

This literature-first engineering review is restricted to mechanism, efficacy testing, leaching, durability and claim boundaries. It does not provide proprietary recipes, universal dosage windows, broad untested organism claims, infection-prevention claims or regulatory shortcuts.

2. Terminology and evidence boundaries

2.1 Antimicrobial is an umbrella term

Antimicrobial can encompass antibacterial, antifungal and antiviral activity, but evidence for one category does not automatically support another. Bacteria, fungi and viruses differ in cell structure, replication strategy and susceptibility to ions, surface charge, oxidative stress and desiccation. A material tested against *Staphylococcus aureus* and *Escherichia coli* is therefore antibacterial under those test conditions; it is not automatically antifungal or antiviral. ISO 21702 exists specifically for measurement of antiviral activity on plastics and other non-porous surfaces [2], illustrating why antiviral claims require their own test architecture.

Antibiofilm is also not interchangeable with antibacterial. A surface may reduce initial adhesion or disrupt extracellular matrix development without producing a large reduction in planktonic viability. Conversely, a strongly bactericidal release system may show diminished performance inside a mature biofilm because transport and physiological state differ from a planktonic suspension. Vetsch et al. showed that *Candida albicans* colonisation can differ among denture-resin fabrication routes even without adding an antimicrobial agent [25], reinforcing the importance of separating baseline surface colonisation from active antimicrobial function.

2.2 Contact-active, release-active, antifouling and photoactivated systems

Four descriptors are particularly useful. Contact-active systems require microbial contact with a functional surface and ideally minimise dependence on bulk release. Release-active systems intentionally deliver ions, molecules or other active species into the surrounding phase. Antifouling systems primarily resist adsorption or adhesion rather than killing organisms. Photoactivated systems require an external illumination condition to generate the antimicrobial state. These categories can overlap: a composite may combine surface-bound functionality with some release, or a photoactivated material may also possess baseline contact activity. The mechanism should therefore be demonstrated experimentally rather than inferred only from ingredient identity.

Claim class	Primary endpoint	Minimum evidence	What it does not establish
Antibacterial surface	Viable bacterial recovery from treated versus control surface.	Defined bacterial strain, inoculum, contact time, recovery and quantitative enumeration; ISO 22196 where applicable [1].	Antifungal, antiviral, biofilm or in-use infection reduction.
Dynamic-contact antimicrobial	Change in viable count during agitated contact.	ASTM E2149-style dynamic exposure with controls and neutralisation [3].	Whether the active species is immobilised or leaching.
Antibiofilm / anti-adhesion	Attached biomass, CFU, metabolic signal or architecture after defined biofilm protocol.	Surface-conditioned specimens, biofilm growth conditions and quantitative endpoint.	Rapid killing of planktonic organisms or antiviral activity.
Antifungal	Viability or adhesion of a defined fungal species.	Fungal species/strain, growth phase, exposure and quantitative recovery.	Bacterial or viral activity.
Antiviral	Reduction in infectious virus recovered from surface.	Virus-specific protocol such as ISO 21702 where applicable [2].	Bacterial/fungal efficacy or clinical decontamination performance.
Durable antimicrobial	Retention of a defined antimicrobial endpoint after ageing/stress.	Predefined ageing, cleaning, immersion, abrasion or sterilisation followed by the same efficacy assay.	Universal lifetime outside the tested stress history.
Biologically acceptable antimicrobial	Antimicrobial effect plus appropriate biological/chemical evaluation.	Application-specific cytotoxicity and chemical characterisation, e.g. relevant ISO 10993 framework [4-6].	Regulatory approval or medical-device status by itself.

Table 1. Antimicrobial claim classes and the evidence needed to support them.

3. Mechanism families in VPP photopolymers

3.1 Silver-containing systems

Silver is one of the most established antimicrobial additives in printed photopolymers, but the mechanism and state of the silver vary substantially. Wang et al. incorporated silver-decorated lignin nanoparticles into a methacrylated hemicellulose hydrogel for DLP printing and explicitly measured Ag⁺ release together with antimicrobial performance [7]. In that system, release is part of the functional mechanism. Idriss et al. chemically grafted silver nanoparticles into a printable resin and reported controlled silver-ion release from printed microstructures [9]. Wales et al. used polymeric ionic-liquid materials to form and stabilise Ag nanoparticles after printing, decoupling the primary photopolymerisation step from later nanoparticle generation [8]. These examples should not be collapsed into a single silver-resin category: particle location, ion release, matrix water uptake and post-processing determine the operative antimicrobial state.

Release can be beneficial when sustained exposure is required, but it introduces a depletion problem. The initial activity of a freshly printed specimen can differ from the activity after extended immersion, cleaning or ageing. A quantitative antimicrobial result should therefore be paired with release or extraction information whenever the mechanism depends on a mobile species. Without that pairing, a study cannot distinguish a stable contact surface from an initially active reservoir that is progressively exhausted.

3.2 Copper and metal-oxide routes

Copper, cuprous oxide and zinc-containing fillers provide another major route. Petousis et al. incorporated Cu₂O into an SLA resin and reported antibacterial activity together with mechanical characterisation [10]. Vidakis et al. studied copper nanoparticles in a medical-grade VPP resin and found that antibacterial performance and mechanical properties depended on the nanofiller concentration [11]. A related study used combinations of cellulose nanofibres and antimicrobial nanoparticle agents in a VPP biomedical-grade resin [12]. More recent copper/zinc nanoparticle work extended testing to multiple bacterial, fungal and viral species and included accelerated ageing and keratinocyte cytotoxicity [13].

These studies illustrate two important qualification rules. First, a metal-containing formulation should not be described only by nominal loading. Dispersion, particle size, sedimentation, surface exposure and conversion state can determine how much active surface is actually presented in the printed part. Second, antibacterial efficacy and mechanical reinforcement are not necessarily aligned. A loading that maximises one endpoint can reduce another, and the apparent optimum is formulation- and application-specific rather than a transferable dosage rule.

3.3 Covalently incorporated and cationic contact-active chemistry

Cationic polymer chemistry can create antimicrobial functionality without relying on the same release mechanism as metal ions. Tiller et al. demonstrated that covalently attached alkylated poly(vinylpyridine) surfaces can kill bacteria on contact [26], providing a mechanistic foundation for later immobilised cationic systems. In VPP-relevant dental photopolymers, Jin et al. incorporated dimethylaminohexadecyl methacrylate into a urethane-acrylate resin and showed that antibacterial effectiveness, flexural strength, hardness and cytotoxicity changed with both concentration and thermal ageing [14]. The study is valuable precisely because it does not treat antimicrobial function in isolation: the active chemistry changes the network and the ageing response.

A contact-active claim nevertheless requires more than the absence of an inhibition zone. No visible halo can be consistent with a non-diffusing mechanism, but it does not prove that no species leach under other conditions. Extraction or release testing should be used when immobilisation is central to the claim. ASTM E2149 explicitly notes that the method itself cannot determine whether an antimicrobial compound is leaching or immobilised [3].

3.4 Chitosan, zwitterionic and anti-adhesion strategies

Chitosan-derived additives and zwitterionic polymers illustrate why reduced microbial burden can arise through different surface mechanisms. Garibaldi Otavio et al. incorporated phosphorylated chitosan into short- and long-term 3D-printed dental resins and observed reduced *Streptococcus mutans* recovery without inhibition halos, alongside changes in roughness, wettability and mechanical behaviour [15]. Azeez and Mudhir used silanized chitosan nanoparticles in a directly printed clear-aligner resin and assessed bacterial adherence, biofilm formation, transparency, conversion and tensile/flexural properties [16]. Lee et al. used MPC, a zwitterionic component, to reduce biofouling in a DLP dental composite while investigating rheology, photopolymerisation and mechanical performance [19].

For engineering reporting, the distinction between killing and adhesion resistance should be preserved. A hydrated, low-fouling surface can reduce initial attachment and therefore lower recovered CFU without being a classical bactericide. This can be a highly useful function, but it supports an antifouling or anti-adhesion claim unless direct killing has been demonstrated independently.

3.5 Controlled release and photo-responsive systems

Releasable organic agents can also be integrated into VPP resins. Nishikawa et al. developed a cetylpyridinium-chloride-containing photocurable resin and evaluated viscosity, cure depth, conversion, mechanical properties, antibacterial activity and CPC release [21]. Jin et al. developed a fluoride-releasing urethane-acrylate resin and coupled antimicrobial testing with long-term fluoride release and cytotoxicity evaluation [20]. These studies show the importance of measuring the active-species reservoir instead of assuming that nominal formulation concentration predicts long-term surface exposure.

Photo-responsive antimicrobial systems add a further condition: activity depends on illumination. Leite et al. evaluated photosensitiser-containing dental resins under blue-light photodynamic conditions and demonstrated that antimicrobial performance must be reported together with wavelength, irradiance or dose, exposure duration and formulation state [22]. The correct claim is therefore photoactivated antimicrobial activity under a defined optical protocol, not continuous antimicrobial function in darkness unless that has also been measured.

Mechanism family	Representative VPP evidence	Critical VPP coupling	Qualification risk
Ag / Ag+ release	Silver-lignin hydrogel, grafted AgNP resin, PIL/Ag systems [7-9].	Particle dispersion; cure attenuation; water uptake; ion diffusion; post-print activation.	Fresh-sample efficacy may decline as releasable reservoir is depleted.
Cu / Cu ₂ O / Zn-containing fillers	Cu ₂ O and Cu VPP nanocomposites; Cu/Zn SLA systems; ZnO/SiO ₂ composites [10-13,18].	Sedimentation; scattering; cure depth; filler surface exposure; ageing.	Nominal loading is not equivalent to active surface concentration.
Cationic contact-active network	Quaternary ammonium and related polymer-bound chemistry [14,26].	Conversion; surface segregation; hydration; post-cure; abrasion.	No inhibition halo does not by itself prove zero leaching.
Chitosan-derived function	Phosphorylated and silanized chitosan systems [15,16].	Dispersion; optical clarity; roughness; wettability; network conversion.	Reduced adhesion may be confused with direct bactericidal action.
Zwitterionic antifouling	MPC-containing DLP composite [19].	Surface enrichment; hydration; filler/resin balance; polish state.	Antifouling is not automatically antimicrobial killing.
Controlled organic release	CPC and fluoride-releasing VPP resins [20,21].	Diffusion; porosity; conversion; fluid exposure; recharge/depletion.	Short-term release profile cannot define service lifetime.
Photoactivated antimicrobial	Photosensitiser-loaded photocurable resin under PDT [22].	Absorption spectrum; light dose; depth; oxygen; ageing.	Activity may exist only under the stated illumination protocol.

Table 2. Mechanism families relevant to antimicrobial VPP materials.

4. VPP-specific coupling between antimicrobial function and print state

Antimicrobial modification changes the VPP problem before microbiological testing begins. Nanoparticles and coloured or absorbing molecules can alter penetration of the curing light. Increased scattering or absorption can change cure depth, lateral over-cure and feature fidelity. Fillers can also increase viscosity or sediment during a long print. Reactive antimicrobial monomers can change network conversion and crosslink density. Surface-active components may segregate toward an interface before or during cure. Consequently, a formulation can display strong antimicrobial activity in a cast coupon yet behave differently when built layer-by-layer and post-cured.

The printed specimen must therefore be treated as the test article. Formulation-level antimicrobial screening can be useful during development, but performance claims should be based on specimens manufactured with the intended VPP process, washing route and post-cure state. Recent studies support this principle by jointly reporting printability or conversion together with antimicrobial performance [14-22]. In practical terms, microbiological test coupons should not be manufactured under a simplified cure condition that is substantially different from the functional part unless the relationship between those states has been established.

Surface preparation is equally important. Sanding, polishing, plasma treatment, solvent washing and prolonged post-cure can expose or remove antimicrobial species and can change roughness and wettability. In dental materials, roughness and water interaction directly influence microbial attachment. A study comparing only formulation composition without documenting polishing and ageing can therefore attribute a surface-topography effect incorrectly to chemistry.

5. Efficacy testing architecture

5.1 Surface antibacterial tests

ISO 22196 specifies measurement of antibacterial activity on antibacterial-treated plastics and other non-porous surfaces [1]. It provides a structured surface-test framework, but its result remains conditional on the organisms, inoculum, contact conditions and recovery procedure specified by the test. It is not a general certification that every microorganism or every real-world exposure will be controlled. For additively manufactured parts, the surface state used in the test should match the intended post-processing and should be reported explicitly.

ASTM E2149 uses dynamic contact and can be valuable for screening substrate-bound antimicrobial systems [3]. However, the standard itself states that the method cannot determine whether a compound is leaching or immobilised. This limitation is central to VPP materials because mobile species can be extracted from incompletely converted or deliberately release-active networks. Dynamic-contact efficacy should therefore be supplemented with release or extraction data whenever the mechanistic claim depends on immobilisation.

5.2 Agar diffusion and inhibition zones

Agar diffusion is simple and visually persuasive, but it favours agents that diffuse into agar. A strong inhibition zone demonstrates migration plus activity under the test conditions. The absence of a zone does not mean that a contact-active surface is inactive, and the presence of a zone does not establish durable non-leaching function. Several copper and cuprous-oxide VPP studies used agar-based screening [10,11]. Those results are useful as mechanism-oriented screens but should not be treated as equivalent to quantitative surface-contact or biofilm assays.

5.3 Biofilm, fungal and antiviral endpoints

Biofilm assays should define attachment period, growth medium, species composition, conditioning film, incubation time and the chosen endpoint. CFU, crystal-violet biomass, metabolic assays and microscopic architecture answer different questions. Recent chitosan and quaternary-ammonium studies have explicitly included bacterial adherence or biofilm endpoints [16,23]. For fungal claims, *Candida* adhesion and biofilm tests are particularly relevant to denture materials, and current work shows that fabrication route and ageing can alter *Candida* colonisation even in the absence of a specific antimicrobial additive [24,25].

Antiviral testing requires separate evidence. ISO 21702 provides a method for antiviral activity on plastics and other non-porous surfaces [2]. Sandu et al. included viral testing in a copper/zinc nanoparticle 3D-printed material study [13], which is stronger evidence for an antiviral statement than extrapolation from bacterial assays. The practical rule is simple: antimicrobial breadth should never exceed the organisms or virus families actually tested.

Method / endpoint	Best use	Required controls / descriptors	Interpretation limit
Agar diffusion / inhibition zone	Screening of diffusible antibacterial activity.	Untreated resin; positive control; agar/media; inoculum; zone method.	Biased toward mobile agents; not a quantitative surface-contact test.
ISO 22196-type surface test [1]	Quantitative antibacterial activity on non-porous treated surfaces.	Specified bacteria, inoculum, contact film, time, recovery and viable count.	Does not establish antifungal, antiviral or mature-biofilm performance.
ASTM E2149 dynamic contact [3]	Screening antimicrobial-treated substrates under agitation.	Control substrate; inoculum; contact time; recovery/neutralisation.	Cannot itself distinguish leaching from immobilised activity.
Direct-contact CFU / metabolic assay	Mechanism-specific comparison of printed surfaces.	Surface area, conditioning, contact geometry, time, neutralisation.	Method-specific; cross-study comparison requires matched protocols.
Adhesion / biofilm assay	Attachment resistance and established biofilm behaviour.	Growth medium, conditioning film, incubation, biomass/CFU/metabolic endpoint.	Reduced biomass is not identical to rapid planktonic killing.
Fungal adhesion / CFU	<i>Candida</i> or mould interaction with printed material.	Species/strain, morphology state, surface conditioning, incubation.	Does not support antibacterial or antiviral claims.
ISO 21702-type antiviral test [2]	Infectious-virus reduction on non-porous surfaces.	Virus, host-cell system, contact time, recovery and infectivity endpoint.	Does not establish bacterial/fungal efficacy or clinical disinfection.
Ageing plus repeat efficacy	Retention of function after service-relevant stress.	Same efficacy assay before/after ageing; defined fluid, temperature, cycles or abrasion.	Supports only the tested ageing history and endpoint.

Table 3. Test-method hierarchy and interpretation for antimicrobial VPP articles.

6. Leaching, extraction and active-species balance

Leaching is not inherently a defect or inherently an advantage. For a controlled-release antimicrobial, migration of the active species is intentional and should be quantified. For a surface-bound contact-active material, uncontrolled release may undermine the intended mechanism and can create a biological or environmental exposure that requires separate assessment. The key is to state which behaviour is intended and to measure it under conditions relevant to use.

A useful mass-balance concept is to distinguish initial active content, accessible surface fraction, released fraction and retained fraction after conditioning. In silver hydrogel and grafted-resin studies, ion release was measured explicitly [7,9]. CPC and fluoride systems likewise coupled antimicrobial testing to release profiles [20,21]. This type of pairing is much more informative than a single efficacy measurement because it reveals whether performance is likely to be reservoir-driven. Where release is not intended, extraction studies can help determine whether observed activity is actually caused by mobile residuals or by the designed surface chemistry.

For biomedical applications, chemical characterisation becomes part of the evidence architecture. ISO 10993-18 addresses chemical characterisation of medical-device materials within a risk-management process [6], while ISO 10993-12 defines sample preparation and

reference-material principles [5]. These standards do not themselves certify antimicrobial suitability; they help frame how the material state and extract are characterised when biological evaluation is required.

7. Durability, ageing and repeated-use performance

A durable antimicrobial claim requires re-testing after a defined stress history. Ageing can reduce activity by depleting releasable agents, oxidising particles, covering the surface with adsorbed proteins, smoothing or roughening the surface, changing water uptake, or modifying polymer conversion. It can also increase exposure to residual components as the network relaxes or degrades. The direction of change cannot be assumed from formulation alone.

Recent studies show why ageing belongs inside the antimicrobial experiment rather than in a separate materials section. Jin et al. thermocycled a DMAHDM-containing 3D-printing resin and found coupled changes in antibacterial effectiveness, flexural strength, hardness, colour and cytotoxicity [14]. Eshetea et al. evaluated a silver-containing 3D-printed denture resin after repeated-use and accelerated ageing protocols [17]. Sandu et al. reported antimicrobial performance after accelerated ageing in copper/zinc-containing printed materials [13]. These designs are stronger than fresh-specimen comparisons because they test retention of function.

The ageing protocol should reflect the intended application. Dental materials may require water or artificial-saliva storage, thermal cycling, brushing or cleaning exposure. High-touch engineering surfaces may require disinfectant exposure, abrasion, UV ageing or repeated handling. Hydrogels may require prolonged aqueous incubation that can strongly alter release. The correct output is not a universal lifetime claim but a statement that a defined antimicrobial endpoint was retained after a specified stress history.

8. Biological response and the efficacy-safety boundary

Antimicrobial activity and biological compatibility are independent axes. A formulation can be highly effective against microorganisms and still produce unacceptable mammalian-cell response under the intended exposure. Conversely, a cytocompatible material may have weak or transient antimicrobial function. The two endpoints should therefore be measured separately and interpreted together only at the final application-qualification stage.

ISO 10993-5 describes in vitro cytotoxicity methods for medical devices [4]. In VPP antimicrobial research, cytotoxicity is particularly relevant for release-active systems, nanoparticles and reactive cationic additives because the same species that damage microbial membranes or generate oxidative stress can interact with mammalian cells. Recent studies have explicitly combined antimicrobial endpoints with cell-viability testing [13,14,20,22,23]. These results are useful but remain formulation- and exposure-specific. They do not justify a blanket statement that a chemistry class is biocompatible.

Post-processing also matters. Under-cured surfaces and insufficient washing can introduce extractables unrelated to the antimicrobial additive. A biological-response study should therefore use the final validated post-cure state and should document the washing route. If the intended end use involves skin, oral tissue or another biological interface, extract preparation and exposure conditions should be justified for that use rather than copied automatically from a generic coupon test.

9. Reporting antimicrobial effect without overstating it

Log reduction, percentage reduction and absolute viable counts are mathematically related but communicate different aspects of the result. Percentage reduction can make moderate changes appear visually large when the initial count is high. Log reduction is useful for orders-of-magnitude comparisons but depends strongly on the denominator, detection limit and recovery method. Absolute CFU values preserve information about the starting burden. Strong reporting therefore provides the raw or transformed endpoint, the control level, the detection limit and the statistical treatment.

A result should also identify whether it measures killing, growth suppression, adhesion inhibition or a combined effect. For example, fewer recovered cells after 24 h can arise from rapid killing, slower growth, weaker attachment or easier removal during rinsing. Microscopy, time-course data or complementary assays can help distinguish these pathways. Mechanistic interpretation should remain proportional to the experiment actually performed.

Claims about resistance development require an even higher evidentiary bar. A single antimicrobial efficacy test does not show that a material does or does not select for resistance. Such a claim would require dedicated serial-exposure, adaptation or genomic/phenotypic studies designed around that question. Accordingly, this review makes no general claim that any antimicrobial route prevents resistance development.

10. Application-specific qualification

10.1 Dental and oral applications

Dental VPP currently provides the richest direct evidence base because plaque, *Streptococcus mutans* and *Candida* endpoints are clinically relevant to dentures, provisional restorations, aligners and related devices. However, the oral environment is chemically and biologically complex. Saliva proteins can condition surfaces, pH changes can alter release, brushing modifies roughness, and thermal cycling can affect both the polymer network and the antimicrobial agent. Recent VPP studies have therefore moved toward combined assessment of conversion, mechanical properties, ageing, biofilm or adhesion and cytotoxicity [14-25]. This integrated approach is more informative than a single antibacterial screen.

10.2 High-touch engineering and clinical surfaces

For high-touch surfaces, the relevant organisms, soil load, cleaning chemistry and contact time differ from dental use. Copper/zinc 3D-printed systems demonstrate that broad organism panels and virucidal testing are technically feasible [13], but a laboratory reduction result is not equivalent to a claim that a surface prevents infection in a hospital or public environment. Field exposure, cleaning frequency, organic contamination and wear can all change performance. The defensible claim remains laboratory antimicrobial activity under the stated protocol unless clinical or field evidence exists.

10.3 Hydrogels and aqueous biomedical constructs

Hydrogels can support high release rates because water uptake facilitates diffusion. The DLP silver-lignin hydrogel study illustrates this route [7]. For such systems, mechanical stability and antimicrobial release are tightly coupled to swelling. A change in crosslink density can simultaneously change shape retention, diffusion and cell interaction. Qualification should therefore combine swelling, release, mechanical integrity and antimicrobial testing rather than optimising any one variable in isolation.

11. Minimum reporting framework

A useful antimicrobial VPP paper should allow the reader to reconstruct the complete state of the specimen when the microbiological test was performed. Exact proprietary formulation percentages are not always required, but chemistry class, active-agent identity and the distinction between reactive, particulate and releasable components must be clear enough to interpret mechanism. Manufacturing and post-processing conditions should be reported at the same level as microbiological conditions because both determine the final surface.

Reporting block	Minimum information	Why it matters	Claim boundary
Antimicrobial mechanism	Active chemistry/filler class; intended contact, release, antifouling or photoactivated mechanism.	Defines what experiment should verify.	Avoids inferring mechanism from ingredient name alone.
Resin / VPP process	Matrix class; VPP subtype; wavelength; layer thickness; exposure; build orientation.	Defines the polymerisation state and filler/light interaction.	Prevents results from being detached from the printing process.
Post-processing	Wash solvent/time; drying; post-cure wavelength/time/temperature; polish or surface treatment.	Controls conversion, extractables, roughness and surface composition.	Avoids comparing different cure states as one material.
Physical state	Conversion where relevant; roughness; wettability; filler dispersion/sedimentation; optical or mechanical changes.	Explains confounders in attachment and efficacy.	Separates chemistry effect from topography or under-cure.
Microbial challenge	Organism/strain; inoculum; medium; planktonic/biofilm state; contact time; temperature.	Defines the biological challenge.	Activity cannot be generalised beyond untested organism classes.
Efficacy endpoint	CFU, log/percentage reduction, metabolic assay, biomass or infectivity; recovery/neutralisation; detection limit.	Makes the reported effect interpretable and reproducible.	A photograph or inhibition halo alone is insufficient for broad quantitative claims.
Release / extraction	Active-species release, extractables or evidence of immobilisation where mechanism requires it.	Distinguishes contact-active from reservoir-driven behaviour.	A dynamic-contact assay alone does not prove non-leaching.
Durability	Ageing fluid; thermal cycles; abrasion/cleaning; sterilisation; storage time; repeat efficacy test.	Determines retention of function.	Supports only the stated stress history, not universal lifetime.
Biological response	Relevant cytotoxicity or other endpoint for intended biological contact; extract conditions.	Separates microbial efficacy from mammalian-cell response.	Does not by itself establish regulatory approval or clinical safety.

Table 4. Minimum reporting set for antimicrobial VPP studies.

12. Critical boundaries for common claims

12.1 “The resin is antimicrobial”

This phrase is too broad unless followed immediately by the organism class, method and conditions. A more defensible formulation is that printed specimens showed antibacterial activity against defined strains under a specified contact test after a stated post-processing condition. The scope can be widened only when additional bacteria, fungi or viruses have been tested.

12.2 “No inhibition zone means non-leaching”

This conclusion is not justified. Absence of diffusion into agar only shows that a detectable inhibition halo was not produced under that agar protocol. A compound can still leach under water, saliva, solvent, acidic or protein-containing conditions. Release or extraction testing is required when immobilisation is a central mechanism claim, and ASTM E2149 explicitly does not resolve that question by itself [3].

12.3 “High initial log reduction means long-term durability”

Initial efficacy says nothing about retention after depletion, abrasion, fouling or chemical ageing. Durable performance requires ageing followed by repetition of the same or a justified equivalent antimicrobial assay. The ageing studies in current quaternary-ammonium, silver and copper/zinc systems illustrate the stronger design [13,14,17].

12.4 “Antibacterial means infection-preventing”

Laboratory reduction of microbial viability is a material-performance endpoint. Infection prevention is a clinical or field outcome involving dose, transfer route, cleaning, host susceptibility and many other variables. Without appropriately designed clinical or environmental studies, a VPP material should not be described as preventing infection merely because it is antibacterial in vitro.

12.5 “Antimicrobial implies biocompatible”

The mechanisms that damage microorganisms can also affect mammalian cells, and the relevant exposure can change after ageing or leaching. Antimicrobial efficacy and biological response should therefore be qualified separately. Product or device suitability depends on the intended contact and a risk-based biological evaluation, not on antimicrobial performance alone.

13. Research priorities

The first priority is method harmonisation. Many current VPP studies use different organisms, contact geometries, media and endpoints, which makes numerical efficacy difficult to compare across materials. Greater use of standard surface methods, combined with clearly described biofilm protocols where needed, would improve comparability. The goal should not be to force every system into one standard, but to select a method matched to the proposed mechanism and application.

The second priority is mass-balance and durability. Release-active systems need longitudinal release profiles linked to repeated antimicrobial testing. Contact-active systems need extraction evidence where non-leaching is claimed, and all systems need relevant ageing. This would allow the field to distinguish early high activity from retained performance.

The third priority is explicit VPP process mapping. Studies should quantify how antimicrobial additives change viscosity, cure depth, conversion, dimensional fidelity and surface composition. The print process should be treated as part of the antimicrobial material design rather than as a neutral fabrication step. Sedimentation studies are especially important for nanoparticle systems used in long builds.

The fourth priority is more realistic biological challenge. Single-species planktonic assays are useful for screening, but many applications involve mixed biofilms, protein-conditioned surfaces or repeated contamination. Multi-species oral biofilms, repeated inoculation, cleaning cycles and clinically relevant ageing can provide stronger evidence without requiring premature clinical claims. For viral applications, breadth should be demonstrated with virus-specific infectivity assays rather than inferred from bacterial results.

Finally, the field needs stronger negative claims discipline. Statements such as non-leaching, non-cytotoxic, resistance-proof, medical-grade or infection-preventing should be reserved for studies directly designed to establish those endpoints. A material can still be scientifically valuable when the claim remains narrow. In fact, narrow claims usually make comparisons more robust because they reveal which part of the mechanism has actually been validated.

3Dresyns implementation examples

Current 3Dresyns antimicrobial-related products illustrate two different functional categories that should not be conflated: an additive intended to create copper-containing printed parts, and a process-preservation additive intended to control contamination in liquid resin before printing. Neither product name alone establishes a specific antibacterial, antifungal or antiviral endpoint; efficacy remains conditional on organism, test method, contact conditions, printed state, ageing and, where relevant, release.

3D-ADD CuVK2C. A concentrated copper antimicrobial paste intended for mixing into compatible 3Dresyns before printing to produce copper-containing parts with controlled antimicrobial action. It is a commercial example of the copper-filled route discussed in Section 3.2; quantitative efficacy and durability require the organism- and method-specific validation architecture described in this review.

3D-ADD MGI1. A microorganism-growth-inhibition additive positioned for contamination control of liquid 3D resins before printing. It is a process-preservation product and should not be cited as evidence that the final printed part is antimicrobial unless that final part is tested independently.

Source basis: current 3Dresyns product and Technical Data Sheet documentation, August 2026. These commercial examples are included to connect the review framework to implementation and are not substitutes for independent application-specific validation.

14. Conclusions

- Antimicrobial function in VPP photopolymers is condition-dependent and should be defined by mechanism, organism, test method, post-processing state and exposure history rather than by ingredient identity alone.
- Contact-active, release-active, antifouling and photoactivated routes are mechanistically different. They require different evidence and should not be merged under one generic antimicrobial label.
- Silver, copper, cuprous oxide, zinc-containing fillers, quaternary ammonium chemistry, chitosan derivatives, CPC, fluoride and photosensitiser systems have all demonstrated viable routes to antimicrobial or anti-adhesion function in printed photopolymers, but each route introduces distinct printability and durability constraints.
- ISO 22196 provides a framework for antibacterial activity on treated non-porous surfaces, ISO 21702 addresses antiviral activity, and ASTM E2149 provides a dynamic-contact method. None of these standards alone establishes universal antimicrobial performance.
- Agar diffusion is best treated as a screen for diffusible activity. It cannot substitute for quantitative surface-contact or biofilm testing and does not define whether a system is durable.
- Leaching must be interpreted according to intended mechanism. It is necessary for some controlled-release systems but requires quantification; for contact-active systems, non-leaching claims require separate evidence.
- Durability requires the same antimicrobial endpoint to be re-measured after a defined stress history such as immersion, thermal cycling, cleaning, abrasion or accelerated ageing.
- Antimicrobial efficacy and biological compatibility are independent axes. Cytotoxicity and chemical characterisation must be evaluated according to intended use and cannot be inferred from microbial results.
- Claims should not extend from antibacterial to antifungal or antiviral performance without organism-specific evidence, and laboratory antimicrobial activity should not be converted into infection-prevention or regulatory claims without the appropriate evidence level.
- A minimum reporting framework linking VPP process, post-processing, surface state, microbial challenge, efficacy endpoint, release, durability and biological response would make antimicrobial photopolymer studies substantially more comparable and defensible.

Limitations

This manuscript is an engineering synthesis rather than a preregistered systematic review or meta-analysis. The VPP antimicrobial literature remains heterogeneous in resin chemistry, microbial challenge, post-processing, ageing and efficacy metrics, so numerical results are not pooled across studies. Several mechanism principles are supported by broader antimicrobial-surface literature and are used to define testing logic rather than to claim direct equivalence between all chemistries. Standards are cited for methodological boundaries, not as evidence that any specific material or application is certified or approved.

Author contributions

Juan Seguro: conceptualisation, literature synthesis, engineering framework, writing and critical review.

Competing interests

The author is affiliated with 3Dresyns by Resyner Technologies S.L. The review discusses antimicrobial photopolymers at a materials-engineering and test-method level and does not disclose proprietary formulation composition. Commercial or experimental materials are not treated as independently qualified outside the conditions reported in the cited literature.

Data availability

No new experimental dataset was generated for this review. Quantitative examples and mechanistic conclusions are attributed to the cited standards and published studies.

Company information

Legal company name: 3Dresyns by Resyner Technologies S.L. Registered tax address: General Etxague 15B, 20003 Donostia / San Sebastián, Gipuzkoa, Spain VAT number: ESB24827511 Contact email: info@3Dresyns.com Company website: www.3Dresyns.com

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