

Antifouling and Biofilm-Resistant Photopolymer Surfaces: Hydration Layers, Topography, Leaching and Durability

A mechanism-separated qualification framework from conditioning-film exposure to repeated biofilm challenge

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Abstract

An antifouling claim for a printed photopolymer cannot be established by a clean initial surface, a short planktonic kill test or one percentage reduction. Protein and organic conditioning, initial cell attachment, growth, extracellular-matrix development and mature biofilm are different stages. Hydration layers, surface charge, designed topography, contact-active chemistry, leaching agents and photocatalytic surfaces act by different mechanisms and require different controls.

This review defines a qualification architecture for antifouling and biofilm-resistant photopolymer surfaces. It requires the printed and post-cured state, conditioning medium, organism or consortium, exposure time and endpoint to be declared; separates non-adhesive, fouling-release, contact-killing, leaching and photocatalytic functions; and repeats biological assessment after cleaning, abrasion, sterilisation or ageing. Direct evidence from vat-printed dental resins and photocurable PEGDA composites is combined with bounded adjacent evidence from zwitterionic coatings, combinatorial topographies, degradable photocurable coatings and microstructured photocatalytic surfaces. The framework joins surface-state, biological, release and cytocompatibility evidence without allowing one layer to substitute for another. No commercial recipe, universal graft density, topographic pitch, efficacy threshold, cleaning interval or service lifetime is established.

Keywords: antifouling; biofilm; printed photopolymer; hydration layer; zwitterionic coating; surface topography; leaching; durability; repeated challenge

1. Significance and scope

Biofouling begins before a mature biofilm becomes visible. Molecules from the surrounding medium adsorb, cells approach and attach, attached populations grow, extracellular material accumulates and a structured community develops. A surface can reduce one stage without preventing another. A treatment may reduce attachment by hydration, promote removal under shear, kill cells on contact, release an active agent or produce reactive species under illumination. These outcomes cannot share one unqualified label.

ER-228 addresses attachment prevention and biofilm resistance on printed-photopolymer surfaces. Its central decision is whether the claimed mechanism, surface state and biological endpoint remain demonstrated after representative conditioning and durability challenges.

1.1 Corpus boundary

ER-014 retains antimicrobial bulk formulations, kill mechanisms, efficacy testing and general leaching and durability. ER-022 retains ophthalmic-material requirements. ER-040 retains general tribology and wear. ER-086 retains extractables and leachables study design and risk interpretation. ER-088 retains general topography and finishing. ER-104 retains fluorinated photopolymer chemistry and PFAS boundaries. ER-168 retains general coating adhesion and barrier qualification. ER-192 retains hearing-device biofilm in its application context. ER-208 retains general surface-chemistry mapping. ER-227 retains friction and lubricity. ER-228 is restricted to nonfouling, fouling-release and biofilm-resistance claims and to the durability of the responsible surface state.

2. Define the printed surface before biological exposure

Record resin or controlled formulation family, printer and orientation, exposed face, layer thickness, wash, drying, post-cure, support removal, polishing, cleaning, sterilisation, storage and preconditioning. ER-042 retains sterilisation-method qualification for vat-printed photopolymers; ER-228 records sterilisation only as a defined surface-state or durability variable. Printed-resin surface chemistry and roughness can differ with build direction and finishing. Residual species, polishing debris and sterilisation can alter both cell response and analytical measurements.

Direct studies of vat-polymerised dental resins and printed denture materials demonstrate that surface state, orientation and processing covary with microbial outcomes [1-3]. These application-specific systems do not define general performance, but they establish that biological comparison without matched printed-state controls is incomplete.

3. Separate mechanism classes before selecting endpoints

At least five surface functions should be distinguished:

- 1 **antifouling or nonfouling**, which suppresses adsorption or attachment;
- 2 **fouling release**, which allows attached material to be removed under a declared force or flow;
- 3 **contact-active killing**, which requires cell-surface contact and a viability endpoint;
- 4 **leaching or degradative release**, which introduces an exposure pathway into the surrounding medium; and
- 5 **photocatalytic action**, which depends on illumination, environment and reactive-species access.

A surface may combine mechanisms, but each requires its own controls. A reduction in viable recoverable cells could reflect less attachment, greater detachment, killing or inhibited recovery. A low biomass signal does not identify which process occurred. The zwitterionic-coating study supports repeated nonfouling challenge [4]; the degradable photocurable coating supports distinguishing whole-coating degradation from active-agent release [6]; the printed PEGDA/ZnO study supports measured ZnO leaching and the distinction between embedded-particle antimicrobial activity and passive nonfouling [7]; and the microstructured TiO₂ study supports coupled topography and photocatalysis under declared illumination [8].

4. Treat conditioning films as part of the test system

The outermost surface presented to cells in service may be a conditioning film of proteins, salts, lipids or organic matter rather than the pristine polymer. Hydration, charge and topography can change after adsorption. A result obtained in simple buffer cannot be transferred to saliva, serum-containing medium, seawater or another service fluid.

Report medium identity, composition, renewal, temperature, preconditioning time and whether the surface was rinsed before inoculation. If a hydration-layer mechanism is claimed, demonstrate resistance to the relevant conditioning material rather than relying on water contact angle alone. Zwitterionic chemistry can retain a strongly hydrated interface, but its performance remains dependent on coating integrity and the challenge medium [4].

5. Resolve attachment, viability, biomass and matrix

Attachment count, colony-forming units, metabolic activity, total biomass, viable/dead imaging and extracellular-matrix measurements are not interchangeable. Each samples a different part of the process and can be affected by recovery or staining efficiency. Mature biofilm claims require time-resolved evidence beyond initial adhesion.

The Candida study on printed denture-base resins directly separates microbial adhesion and biofilm formation over the tested conditions [3]. The vat-photopolymer dental-resin study combines surface characterisation with microbiological analysis [1]. These sources support paired surface and biological measurements, but one organism and one oral model cannot represent bacterial, fungal or multispecies biofilms in other environments.

6. Distinguish hydration-layer antifouling from killing

Hydrophilic or zwitterionic layers can reduce nonspecific adsorption and attachment by maintaining an energetically costly, water-rich interface. Such a mechanism does not require cell death. Demonstrating it therefore needs adsorption or attachment evidence, surface chemistry and hydration-related state controls. If killing is also claimed, add viability and mechanism-specific controls.

The sulfobetaine-containing PMMA coating study evaluates antifouling performance over repeated biomass-producing challenges [4]. It is adjacent evidence because the substrate and organisms differ from printed photopolymers. It supports repeated challenge and hydration-layer interpretation, not a transferable composition, graft density or lifetime.

7. Treat designed topography as organism- and scale-dependent

Surface features can alter available attachment area, local shear, cell orientation, nutrient transport and community signalling. Their effect depends on feature geometry relative to the organism and on chemistry and conditioning. A single arithmetic roughness value cannot define the topographical landscape.

Combinatorial microtopography work demonstrates that different landscapes can produce different biofilm responses and that the effect can involve organism-mediated behaviour rather than a simple “smoother is cleaner” rule [5]. Microstructured TiO₂ coatings further show that topography can coexist with photocatalytic chemistry [8]. These studies do not establish a universal pitch, height or roughness for vat-printed resins. ER-088 retains the general metrology; ER-228 requires only the feature description needed to interpret the biological result.

8. Separate leaching, depletion and surface retention

An embedded or coating-bound active component may remain fixed, migrate slowly, be released by degradation or be lost during cleaning. Apparent efficacy can decline as the surface depletes, or remain while exposure accumulates in the surrounding medium. Antifouling and safety therefore require separate evidence.

The photocurable boron-containing coating chemically anchors its bactericidal component to prevent continuous release; the coating nevertheless degrades as a whole, with degradation measured by total coating mass loss and chemical comparison before and after hydrolysis [6]. No active-agent release measurement is reported in [6], so it is not evidence for leaching. The vat-printed PEGDA/ZnO system combines photocurable printing, embedded particles, antibacterial assessment and measured ZnO leaching [7]. ER-014 retains general antimicrobial efficacy, leaching and durability interpretation, while ER-086 retains analytical release-study design and risk interpretation. ER-228 uses these results only to require mechanism-specific release and retained-surface evidence; they do not permit safety, cytocompatibility or service lifetime to be inferred from efficacy.

9. Preserve illumination and oxygen conditions for photocatalytic claims

Photocatalytic surfaces require the relevant spectrum, irradiance, exposure, oxygen and fluid environment. Dark controls and substrate-only controls are essential. If topography and photocatalysis are both present, the experimental design must separate their contributions.

The microstructured TiO₂ study addresses bacterial adhesion and biofilm development in a declared marine-pathogen system [8]. It supports mechanism-specific light and dark controls. It cannot establish efficacy on a printed resin, under another spectrum, or against another organism. A photocatalytic label without delivered optical conditions is incomplete.

10. Test durability by repeating the biological challenge

Durability should challenge the feature responsible for performance. Candidate operations include abrasion, wiping, flow, cleaning chemistry, sterilisation, immersion, ageing and light exposure. ER-042 retains sterilisation-method qualification; here sterilisation is only one declared challenge to the antifouling surface state. After challenge, repeat surface-state measurements and the same mechanism-matched biological endpoint. A surface that remains visually intact may have lost hydration, charge, active-agent content or nanoscale coverage.

Repeated-challenge evidence is especially important for hydration layers and degradable coatings [4,6]. Printed denture-resin evidence also shows why orientation and finishing state must remain controlled when comparing biological outcomes [2,3]. A one-time unaged reduction does not establish durable antifouling.

11. Pair efficacy with cytocompatibility and exposure where relevant

For medical, dental or skin-contact use, reduced attachment cannot substitute for cytocompatibility, extractables, irritation or sensitisation evidence. ER-006 retains biological-response qualification in dental and biomedical photopolymer work. A leaching antimicrobial can reduce recoverable cells while creating unacceptable exposure. A strongly hydrated nonfouling layer may also alter desired mammalian-cell attachment. Application-specific biological safety requirements remain separate gates.

The printed PEGDA/ZnO study is useful because a photocurable printed composite and biological activity are evaluated together [7]. Its formulation, particle state and endpoints remain study-specific. ER-228 does not convert antibacterial activity into general biosafety or mature-biofilm resistance.

12. Control the biological model and recovery method

Report organism identity and strain, single or multispecies design, inoculum preparation, growth phase, medium, conditioning film, temperature, atmosphere, exposure time, static or flow conditions and renewal. Define washing, detachment or sonication, dilution, plating, imaging or staining and detection limits. Include material blanks, no-cell controls and appropriate positive or reference surfaces.

Recovery efficiency can differ between smooth and textured surfaces or between strongly and weakly attached communities. A lower recovered count may therefore reflect incomplete removal. Orthogonal endpoints help distinguish attachment, viability and biomass. Any percentage reduction must identify its denominator, comparator, uncertainty and time point. ER-014 retains general antimicrobial efficacy-test design and validation; ER-228 uses these controls only to distinguish antifouling attachment, fouling-release, viability, biomass and matrix endpoints.

13. Build a non-compensatory qualification matrix

Gate	Required evidence	Unsupported shortcut prevented
Printed state	Resin, orientation, wash, post-cure, finishing, sterilisation and storage	Treating all printed surfaces as equivalent
Mechanism	Nonfouling, fouling release, contact killing, leaching or photocatalysis	Using “antifouling” as an undefined umbrella
Conditioning environment	Medium, adsorbed film, temperature and preconditioning	Testing only a pristine dry surface
Biological endpoint	Organism, time, attachment, viability, biomass and/or matrix	Equating planktonic kill with biofilm resistance
Durability	Cleaning, abrasion, sterilisation or ageing followed by repeated challenge	Declaring lifetime from one unaged exposure
Exposure and safety	Measured release, retained surface state and application-specific cytocompatibility	Inferring safety from efficacy

The gates are independent. A large initial reduction cannot compensate for an undefined mechanism, absent ageing, unmeasured release or a mismatched biological endpoint.

14. Minimum reporting set

Report resin or formulation family; printer, orientation and exposed face; layer thickness; wash, dry and post-cure; polishing, cleaning and sterilisation; storage and preconditioning; surface treatment or coating identity; chemistry, coverage, thickness and topography relevant to mechanism; conditioning medium and time; organism or consortium, strain and inoculum; static or flow conditions; exposure time and renewal; illumination for photocatalytic systems; attachment, viability, biomass and matrix methods as applicable; recovery efficiency and detection limits; comparators, replicates and uncertainty; cleaning, abrasion, ageing or sterilisation challenge; post-challenge surface state and repeated biological result; release measurements; and cytocompatibility or other application-specific safety evidence where required.

Every numerical result must retain the printed and post-cured state, surface treatment, conditioning medium, organism, exposure time, endpoint and durability challenge. No graft density, coating thickness, topographic pitch, efficacy percentage, contact time or cycle count becomes a universal target.

15. Knowledge boundary

The evidence supports linking printed-resin surface state and processing to microbial outcomes [1-3]; distinguishing hydration-layer antifouling from killing and assessing repeated challenge [4]; treating topography as feature- and organism-dependent [5]; distinguishing an anchored active agent and whole-coating degradation from measured agent release [6]; retaining direct photocurable-composite evidence, including measured ZnO leaching, without equating antibacterial activity to antifouling [7]; and separating topographical and photocatalytic mechanisms under declared illumination [8]. Dental and marine systems dominate the evidence. They support the qualification architecture but do not transfer organisms, media, efficacy, safety or lifetime to other printed-photopolymer applications.

16. Limitations

Three studies directly concern printed dental resins [1-3], and one concerns a vat-printed PEGDA composite [7]. The remaining studies concern coatings or structured surfaces on other substrates and are mechanistically adjacent. Two sources were available only at publisher-abstract depth in the frozen preflight: [2] and [8]. They support only bibliographic identity and their abstract-visible high-level experimental relation. The corpus has no common resin, conditioning film, organism, endpoint, cleaning challenge or service environment. It does not establish equivalence among protein adsorption, bacterial attachment, fungal biofilm, marine fouling and mammalian-cell response. It supplies no commercial recipe, universal percentage reduction, safety claim or service-life acceleration factor.

17. Conclusions

Antifouling and biofilm resistance on printed photopolymers must be qualified as mechanism-specific, state-dependent performance. Hydration layers, designed topography, contact activity, leaching and photocatalysis require different controls and endpoints. The printed orientation, wash, post-cure, finishing, sterilisation and conditioning medium belong to the test definition. Initial attachment, viability, biomass and mature biofilm are not interchangeable. Durability requires repeating the biological challenge after cleaning, abrasion, sterilisation or ageing and verifying that the responsible surface state remains. Efficacy cannot substitute for measured release, cytocompatibility or application-specific safety.

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