

Algae-Containing and Photosynthetic Printed Materials: Light Delivery, Gas Exchange, Growth and Mechanical Stability

Qualification of light, carbon transport, cell distribution and structural evolution in photosynthetic living materials

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Abstract

Photosynthetic living materials couple a hydrated matrix to algae or cyanobacteria that require light and gas exchange while modifying their local environment through growth and metabolism. Geometry, optical attenuation, cell aggregation and carbon transport therefore determine both biological productivity and mechanical evolution. This review defines a qualification framework for printed photosynthetic materials in which light delivery, gas exchange, growth distribution, leakage and structural stability are measured together. It distinguishes cell viability from photosynthetic productivity and avoids treating bulk irradiance or nominal CO₂ exposure as proof that internal cells experience equivalent conditions.

Keywords: photosynthetic living materials; microalgae; cyanobacteria; hydrogel; light transport; gas exchange; growth; mechanical stability

1. Significance and scope

Photosynthetic engineered living materials can convert light and carbon dioxide into biomass or target products while retaining a designed three-dimensional shape. The critical distinction from conventional cell-laden hydrogels is that photons are a consumed process input whose spatial distribution changes as biomass accumulates. Oh and co-workers showed that *Chlamydomonas reinhardtii* in three-dimensional hydrogels grows preferentially near regions with favourable light and gas access, directly linking geometry to biological distribution [1].

The relevant optical state is wavelength-dependent because photosynthetic pigments, matrix chromophores and scattering structures do not attenuate all wavelengths equally. Thus a single broadband irradiance value cannot describe the usable photon field. The matrix should be characterized both before inoculation and after biomass accumulation, since growth can transform a transparent construct into an optically heterogeneous one without any change in external illumination.

As biomass accumulates, the optical boundary condition changes with time. A construct qualified only at inoculation can later develop a high-absorption peripheral layer that protects or starves the interior depending on spectrum and geometry. Oh and co-workers showed that cells preferentially grow near hydrogel peripheries where light and gas exchange are more favourable [1]. Thickness, channel spacing and exposed area should therefore be treated as design variables that determine whether growth remains distributed or becomes surface-dominated.

2. Light delivery must be measured inside the construct

Incident irradiance is not the same as cellular light dose. Absorption and scattering by the matrix, pigments and growing aggregates reshape the optical field. Chua and co-workers demonstrated that algal aggregation changes light management in living photosynthetic hydrogels and that optical scattering can alter internal illumination [2].

Qualification should therefore report wavelength spectrum, incident intensity, thickness and an internal-light metric or validated optical model. Overexposure at the surface and underexposure in the core are different failure modes. Internal-light qualification can use embedded microsensors, calibrated fluorescence proxies or radiative-transfer models, but the method and its assumptions must be stated.

A model should be validated against at least one measured depth profile or transmitted/reflected-light dataset. The Chua study is especially relevant because aggregation itself changes light redistribution [2], so a homogeneous-cell optical model can become invalid as the culture develops.

3. Gas exchange and carbon supply couple to geometry

Photosynthesis consumes inorganic carbon and produces oxygen, while respiration and dark periods reverse parts of that balance. Diffusion from the surrounding gas or liquid phase can become limiting when cells are embedded deeply. Surface-to-volume ratio, pore architecture and boundary-layer conditions must therefore be recorded.

Static and perfused systems are not directly comparable unless gas-transfer conditions are normalized. Gas transport has the same moving-boundary problem. Dissolved inorganic carbon, oxygen and pH can vary through the construct and around dense cell clusters.

When bicarbonate supplementation, aeration or perfusion is used, the delivery mode is part of the process specification; reporting only the nominal medium composition does not establish the concentration available to cells inside the printed object.

Photosynthesis also couples carbon uptake to oxygen evolution and local pH change. Bulk medium measurements can therefore mask strong internal gradients. Qualification should include at least one spatially resolved or geometry-sensitive measurement of dissolved oxygen, inorganic carbon, pH or a validated proxy under illumination. Dark controls are necessary because respiration continues when photosynthesis stops, so a material that performs well under continuous light may experience a different gas balance during realistic light-dark cycling.

4. Growth redistributes both optics and mechanics

Cell proliferation is not a neutral outcome. Local growth increases pigment concentration, changes scattering and can generate swelling or stress in the matrix. Mechanical properties should be measured before and after the biological growth interval, not only after printing.

Taylor and co-workers showed that cyanobacteria-based living hydrogels can remain metabolically active while the living component and bioproduct accumulation alter material mechanics, demonstrating that function and stiffness can evolve together [3]. Mechanical evolution should be separated into matrix ageing and biology-driven change. Taylor and co-workers observed that the presence of cells and accumulated product altered compressive response [3].

For engineering qualification, an abiotic matrix aged under the same light, temperature and medium conditions is therefore necessary to determine whether a modulus change originates from hydrolysis or swelling of the matrix, biomass growth, or accumulated metabolites.

Growth can change not only modulus but also dimensional stability and residual stress. Cell clusters, extracellular material and gas pockets may redistribute local strain or initiate defects during repeated wetting and drying. Mechanical testing should therefore use the same hydration and illumination history as the biological measurements. If the intended service state includes partial drying, that transition should be qualified as a separate material state rather than extrapolated from fully hydrated data.

5. Species and metabolic state are part of material identity

Algae and cyanobacteria differ in size, motility, nutrient requirements, pigment systems and tolerance to confinement. Species, strain, culture age and pre-print light history should be reported. A matrix qualified for one photoautotroph should not be assumed transferable to another.

If engineered production pathways are used, product formation should be measured independently from photosynthetic activity.

Axis	Measurement	Failure mode
Light field	spectrum, incident intensity, internal map/model	incident irradiance treated as cell dose
Gas transfer	CO ₂ /O ₂ boundary condition and geometry	bulk atmosphere treated as internal concentration
Growth	spatial biomass distribution over time	total viability hides peripheral clustering
Mechanics	pre/post growth modulus or structural metric	fresh-print stiffness treated as lifetime stiffness
Function	photosynthetic or product output with controls	chlorophyll signal treated as productivity

Table 1. Domain-specific qualification matrix for algae-containing and photosynthetic printed materials.

6. Device-level verification

Testing should include continuous or cyclic illumination, the intended gas-transfer environment, hydration control, and the expected service temperature. Spatial imaging of biomass is valuable because a stable total chlorophyll or fluorescence signal can hide migration or peripheral overgrowth. Leakage, contamination and structural cracking must be assessed after growth, when internal stresses and porosity may differ from the freshly printed state. Sun and co-workers used a 3D-bioprinted artificial-coral platform to interrogate structural effects on microalgal photophysiology, providing a direct example of geometry being part of the biological forcing condition rather than a neutral container [4].

This review is bounded to photosynthetic material performance. ER-431 owns the general bacterial-living-material problem where light-driven autotrophy is not the defining function, while ER-436 owns calibrated biosensing. Photosynthetic productivity should therefore not be converted into a generic viability or sensor claim without the appropriate separate qualification.

7. Minimum qualification framework

The minimum dataset should include organism identity, initial loading, matrix chemistry, cure history, geometry, incident spectrum, internal light evidence, gas-transfer condition, spatial growth, photosynthetic output, mechanical property change and leakage. A productivity number should be normalized to a declared basis such as projected area, illuminated area, biomass or volume. Dark controls and abiotic controls are needed when attributing gas or product changes to photosynthesis.

8. Engineering conclusions

Photosynthetic printed materials are optically driven bioreactors embedded in a load-bearing or shape-retaining matrix. Their performance depends on maintaining a useful overlap between the illuminated volume, the gas-accessible volume and the mechanically stable volume

as cells grow. The key qualification question is therefore not whether the organism survives, but whether the construct maintains spatially distributed photosynthetic function without optical self-shading, transport starvation or structural loss.

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Competing interest

Juan Segurola is founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L., which develops and commercialises photopolymer materials and related additive-manufacturing technologies. This review is an engineering analysis and does not constitute a product-performance claim or a device qualification.