

Electrically Functional Photopolymer Resins for Vat Photopolymerisation: A Compact Framework for System-Dependent Performance

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Abstract

Background. Vat photopolymerisation (VPP) is increasingly used to fabricate electrically functional structures in which electrical behaviour must coexist with photochemical cure, geometric fidelity, rheological processability and service stability. The literature spans electrostatic-control materials, carbon-based percolation composites, conducting-polymer systems, metallic-particle composites, high-permittivity dielectric composites and multi-material workflows. A recurrent interpretive problem is that electrical values are often reported without sufficient description of the cured-system configuration that produced them.

Scope and approach. This compact narrative review synthesises peer-reviewed literature, current standards and selected application studies relevant to electrically functional VPP. It is a framework-driven review, not a PRISMA systematic review, and therefore does not claim exhaustive database coverage or numerical screening completeness. The review separates established literature observations from review-specific engineering classifications and from industrial interpretation.

Framework. A System-Dependent Conductivity Framework (SDCF) is used to organise seven process stages - chemistry, dispersion/loading, printer optics, exposure history, geometry/orientation, post-cure, and storage/service - that condition the electrical response of the cured part. A four-level reporting hierarchy (intrinsic, effective, realised and operational performance) is used to distinguish constituent properties, coupon values, part-specific measurements and in-service trajectories.

Implications. The principal recommendation is methodological: electrically functional VPP materials should not be characterised by an isolated conductivity or resistance value. Reports should state the electrical figure of merit, measurement method and units, specimen geometry, print platform, exposure and post-cure history, ambient condition and time after manufacture. The framework is descriptive, not a closed-form predictive model.

Keywords: vat photopolymerisation; conductive photopolymer; system-dependent electrical performance; printed electronics; PEDOT:PSS; carbon nanotube composite; electrostatic control; dielectric composite

1. Introduction

Functional additive manufacturing extends AM beyond inert geometry into parts that deliver electrical, optical, biological or actuation functions. Electrically functional VPP is particularly demanding because the desired electrical response must be achieved without losing the optical penetration, rheology and cure fidelity needed for layerwise photopolymerisation [1,7,8,24-29].

Three constraints recur across the field. First, electrically active phases can attenuate or scatter the curing light. Second, conductive or dielectric fillers can raise viscosity, create yield stress, sediment or aggregate. Third, the electrical network formed after cure can depend on orientation, conversion, post-cure and environmental history. These constraints are well established in the literature on CNT and graphene composites, conducting polymers and dielectric composites [2-4,9,17,19,21,25-29].

A useful distinction is therefore required between the electrical property of a constituent and the value realised in a printed part. This review uses four reporting levels. Level 1, intrinsic, refers to the conductive or dielectric constituent itself. Level 2, effective, refers to a model composite or reference coupon under defined conditions. Level 3, realised, refers to a specific printed part on a specific platform and geometry. Level 4, operational, refers to the response during service and ageing. The levels are interpretive categories introduced for reporting clarity; they are not standardised metrology classes.

2. Literature methodology and evidentiary boundaries

Relevant literature was identified through targeted searches of Scopus, Web of Science and Google Scholar using combinations of vat photopolymerisation, stereolithography, DLP, LCD/MSLA, conductive photopolymer, conductive composite, carbon nanotube, graphene, PEDOT:PSS, conductive hydrogel, silver, dielectric composite, high permittivity and multi-material printing. Foundational pre-2014 literature was retained where it provides percolation, conducting-polymer, dielectric or printed-electronics background that remains directly relevant [2-6,9,12,13,18-21].

The present document is a narrative engineering review. Numerical search-flow claims from the earlier compact version have been removed because an auditable search log was not included with the manuscript. References were retained only when they could be bibliographically verified against publisher or standards-body records. Manufacturer-specific mechanisms are not inferred from product naming or commercial positioning.

3. Route taxonomy and operating directions

The field can be organised into seven practical routes. The taxonomy is a review framework rather than a formal standard. In particular, the functional-conductive and high-conductivity labels used below are application-oriented descriptors; they should not be presented as IEC material classes. Electrostatic-control materials must be specified using the applicable test method and standard, with the measured quantity and units stated explicitly [S1,S2,S7].

Route 1 - ESD-targeted photopolymers. These systems are designed for electrostatic-control applications such as fixtures, handling tools and housings. The exact conductive mechanism of a commercial formulation may be proprietary and should not be inferred without public compositional evidence. Compliance claims require testing under the applicable ESD control and material-characterisation framework [S1,S2].

Route 2 - matrix-integrated conductive photopolymers. In this route, electrical transport is intended to arise from the cured matrix or a molecularly integrated conducting phase rather than from a conventional high-loading discrete filler. The route is best treated as an emerging design direction unless a specific formulation has peer-reviewed compositional and electrical validation.

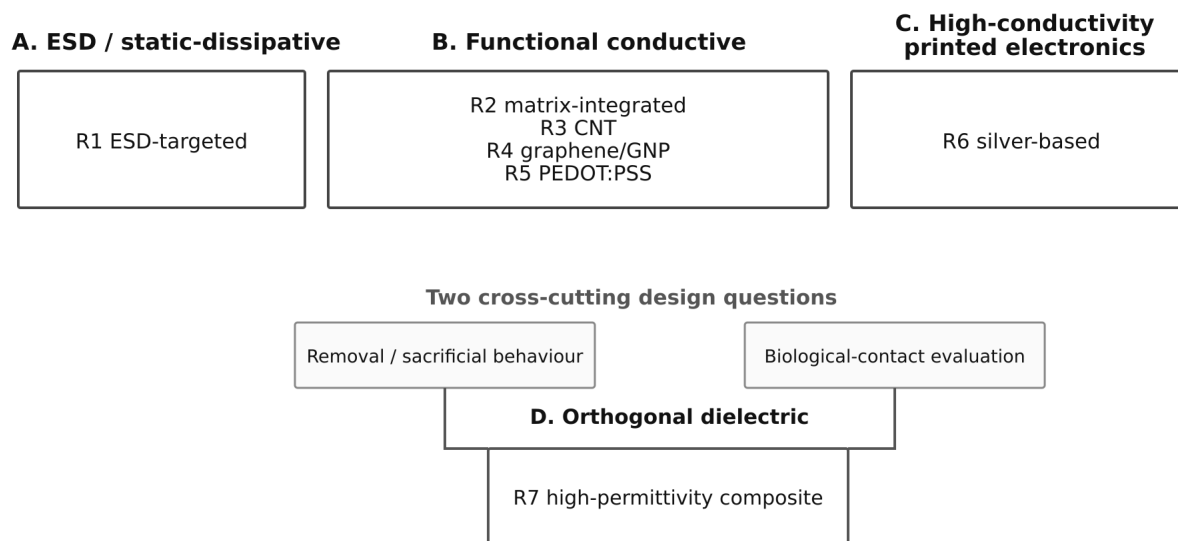
Routes 3 and 4 - carbon percolation composites. CNT and graphene-based systems rely on a connected conductive network within a photocurable matrix. Percolation threshold and realised conductivity depend on filler aspect ratio, dispersion state, matrix chemistry and orientation [2,3,9,19,25-29]. Recent VPP-specific work demonstrates that electrical and rheological percolation can be decoupled and matrix-dependent [25,26].

Route 5 - conducting-polymer systems. PEDOT:PSS is the principal documented conducting-polymer platform relevant to printable bioelectronics. Its solution processability, electronic/ionic transport and compatibility with hydrated systems have motivated work in bioelectronic interfaces and photopolymerisable conductive inks [4,11,13,16,22,30-33,38]. PEDOT:PSS is commonly supplied as an aqueous dispersion, which creates host-compatibility challenges but does not imply that only one class of hydrophilic host chemistry is possible.

Route 6 - silver-based composites. Silver nanoparticles, microflakes and nanowires provide high conductivity in printed electronics, but morphology, loading, sintering or contact formation, sedimentation, electromigration and environmental ageing all affect the realised response [6,12,18,39]. High-aspect-ratio fillers can reduce the volume fraction required for network formation, but the specific loading required is formulation- and process-dependent.

Route 7 - high-permittivity dielectric composites. Ceramic fillers such as TiO₂, CaCu₃Ti₄O₁₂ and BaTiO₃ can raise the relative permittivity of photocurable composites, while filler loading, scattering, loss tangent and temperature dependence constrain VPP processing and RF/microwave use [17,20,21]. This route is electrically orthogonal to the conductive routes: its primary figures of merit are permittivity, loss and dielectric stability rather than conductivity.

Two cross-cutting questions should be kept separate from the seven-route classification. First, does the workflow require a removable or sacrificial material? Multi-material VPP has demonstrated water-soluble, conductive and structural resin combinations in microfluidic fabrication [14,15,34,40]. Second, is biological contact relevant? If so, product-specific biological evaluation must be planned within the current ISO 10993 risk-management framework; a resin label or material-level test does not by itself constitute medical-device approval [S3-S6,S8].



Regime B and C boundaries are review-specific engineering descriptors, not IEC material classes.
Electrical values must always be reported with measurement method, geometry and units.

Figure 1. Review taxonomy for electrically functional VPP. Routes are grouped by intended electrical function. The functional-conductive and high-conductivity groupings are review-specific engineering descriptors, not IEC material classifications. The removal and biological-evaluation questions are cross-cutting design requirements.

4. System-Dependent Conductivity Framework (SDCF)

The SDCF formalises a simple interpretive position: the electrical response measured on a printed photopolymer part is conditioned by the complete resin-process-geometry-history system. The framework does not replace percolation theory, electromagnetic materials models or electrical metrology; it organises the variables that must be reported so that values can be compared meaningfully.

The seven stages are: (1) matrix and electrical-component chemistry; (2) dispersion state and loading; (3) printer optics; (4) exposure history; (5) part geometry and build orientation; (6) post-cure protocol; and (7) storage and service environment. Literature on

CNT/graphene composites, PEDOT:PSS systems, dielectric composites and multi-material VPP shows that several of these variables can materially alter measured electrical behaviour [17,22,25-29,31-33].

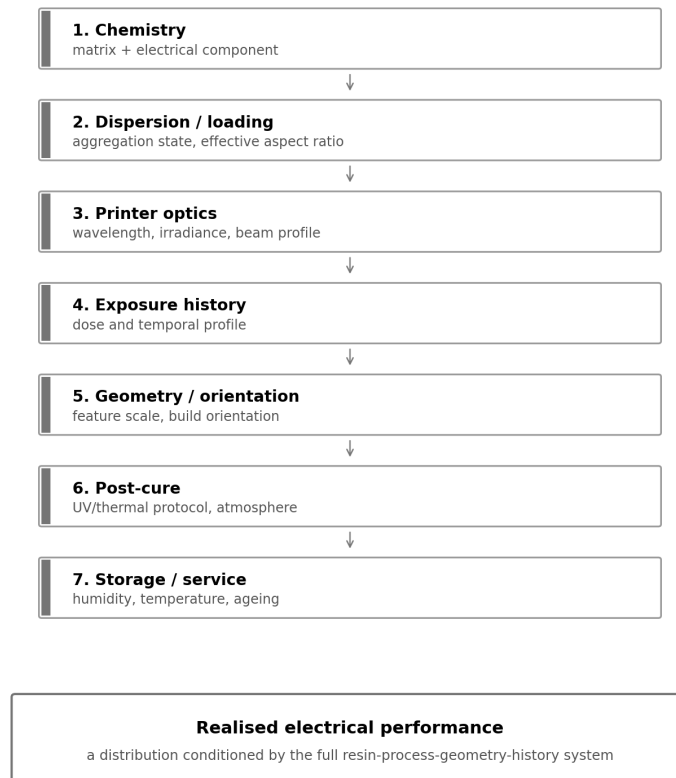


Figure 2. System-Dependent Conductivity Framework. The framework is descriptive: it identifies process and history variables that condition the measured response, but it does not provide a universal closed-form prediction of conductivity or resistance.

Table 1 summarises the most important variables and deliberately avoids universal influence rankings. A variable that dominates one route may be secondary in another. For example, humidity is particularly relevant to PEDOT:PSS and ionic/hydrogel systems, whereas filler orientation and dispersion are central to CNT and graphene composites.

Stage	Variable	Mechanistic relevance	Reporting requirement
1 Chemistry	Matrix and electrical component	Sets intrinsic transport mechanism, compatibility and potential percolation behaviour	Identify matrix family and electrical component when disclosure permits
2 Dispersion/loading	Filler content, aggregation, effective aspect ratio	Controls conductive-network formation and rheology in filler routes	Report nominal loading and dispersion protocol
3 Printer optics	Wavelength, irradiance profile	Sets optical penetration and cure kinetics in absorbing/scattering systems	Report wavelength and platform
4 Exposure history	Exposure time, irradiance, cumulative dose	Controls conversion and can interact with filler motion and attenuation	Report both time and irradiance/dose where available
5 Geometry/orientation	Feature size, build direction, electrode geometry	Can create anisotropy and alters the electrical measurement geometry	Report CAD geometry and build orientation
6 Post-cure	UV/thermal treatment and atmosphere	Changes conversion, matrix state and in some systems contact formation	Report protocol, duration and atmosphere
7 Service history	Humidity, temperature, bias, ageing time	Can produce reversible drift, hysteresis or irreversible degradation	Report conditioning and time after manufacture

5. Chemistry and design principles

5.1 Conductivity-printability-biological-evaluation trade-off

Electrically functional VPP is a multi-objective formulation problem. Increasing the fraction of an electrically active phase can improve a target electrical response but can also increase viscosity, optical attenuation and mechanical discontinuity. Biological-contact applications add a separate requirement: the complete cured system and its processing residues must be evaluated for the intended contact scenario, not inferred from the identity of one constituent [S3-S6]. The trade-off is an engineering design problem, not a universal physical law.

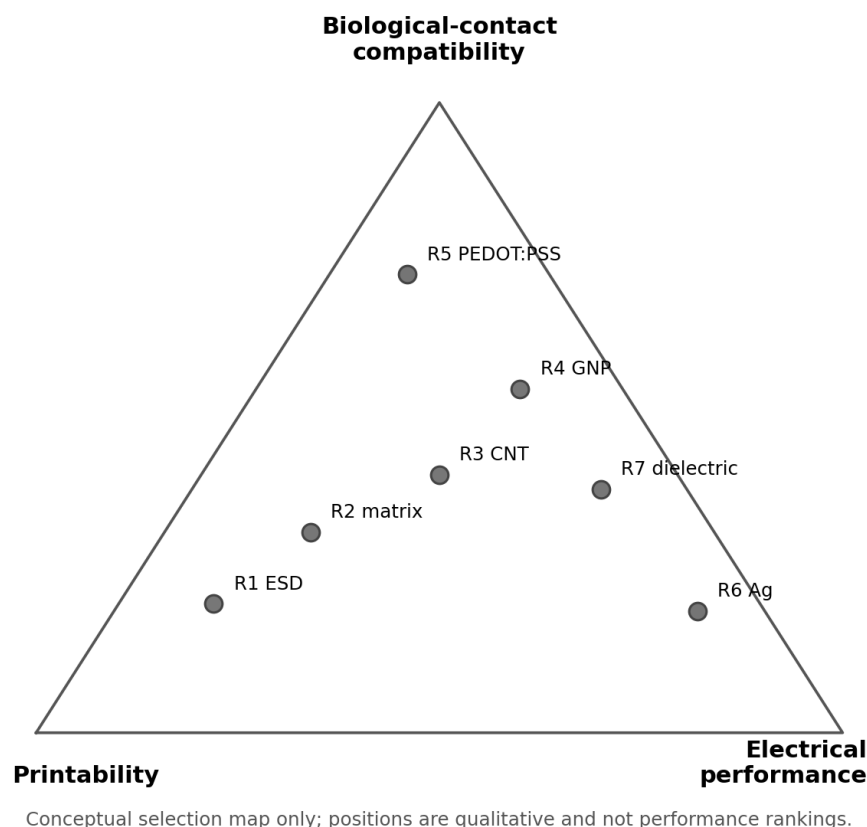


Figure 3. Qualitative route-selection triangle. Positions are conceptual and intended only to illustrate competing design priorities. They are not quantitative rankings or product specifications.

5.2 Percolation and rheology in carbon-filled systems

Percolation theory provides the basic explanation for the sharp transition between insulating and conducting behaviour in filler composites [2,5,9,19]. Aspect ratio, dispersion and orientation are critical. High-aspect-ratio CNTs can form connected networks at lower loading than low-aspect-ratio particles, but aggregation reduces the effective aspect ratio and may raise both the electrical and rheological thresholds.

The VPP-specific observation from Seviugina et al. is particularly important: the rheological percolation threshold and electrical percolation threshold need not coincide, and their separation depends on matrix type and dispersion protocol [25]. This means that a formulation can become difficult to print before it reaches a useful conductive network, or conversely can achieve conduction while remaining processable. A conductivity value therefore cannot be transferred from one matrix-dispersion system to another without recalibration.

5.3 Dielectric composites

High-permittivity polymer-ceramic composites are more appropriately interpreted with effective-medium and interfacial-polarisation concepts than with a conductive percolation threshold [17,20,21]. Malas et al. demonstrated visible-light VPP of TiO₂- and CCTO-loaded resin composites and characterised morphology, thermal, dynamic-mechanical and dielectric properties [17]. The engineering challenge is to increase permittivity while retaining acceptable loss, optical cure depth and rheology.

5.4 Conducting polymers and bioelectronics

PEDOT:PSS is well established in bioelectronics and conducting-polymer research [4,11,13,16,30,31]. DLP-printable PEDOT-based photopolymerisable inks have been demonstrated for ECG and EMG biosensing [38]. Separate studies have shown highly conductive 3D-printed PEDOT:PSS hydrogel interfaces by extrusion-based printing [32] and PEDOT:PSS-coated microstructures fabricated using two-photon lithography plus electrodeposition [33]. These examples should not be conflated as a single VPP mechanism: they represent different fabrication routes and matrix architectures.

Humidity, ionic content, additives and morphology can strongly affect PEDOT:PSS conductivity and mechanical response [13,16,31]. The compact compact version previously generalised specific humidity-driven changes and host limitations as universal values; those numerical generalisations have been removed. Route-specific measurements should instead be reported under defined conditioning.

6. Process, cure-state and time dependence

Printer irradiance, exposure time and optical attenuation are separate process variables. The earlier version presented generic DLP and LCD irradiance bands and implied a universal relationship between power-time decomposition and electrical-network architecture. Those claims are too platform- and formulation-dependent for a general review and have been removed. The defensible engineering statement is narrower: exposure conditions should be reported and calibrated for each resin-platform combination because conversion, cure depth and conductive-network formation can be coupled [1,7,8,24-29].

Geometry and build orientation can influence filler alignment and electrical anisotropy, particularly for high-aspect-ratio CNTs, nanowires and platelets [2,9,19,25-29]. The magnitude and even direction of the effect depend on the flow field, process architecture and measurement geometry; no universal correction factor is available.

Electrical performance can also evolve with time. A practical reporting sequence is: as-printed state; post-cure state; environmental equilibration; service cycling; and long-term ageing. This sequence is a reporting framework, not a claim that all routes follow the same kinetics. PEDOT:PSS systems may respond strongly to humidity and ionic environment, whereas silver-based systems may be limited by electromigration, tarnishing or contact degradation under particular service conditions [12,13,16,18,31].

7. Manufacturing and metrology constraints

Filler sedimentation, agglomeration and viscosity are practical constraints in conductive and dielectric VPP. Stokes-type settling provides a first-order dilute-limit picture, but concentrated suspensions can show hindered settling, yield stress and non-Newtonian behaviour. Therefore generic shelf-life values, refrigeration benefits or heated-vat temperature windows should not be presented as universal properties unless tied to a specific formulation and validated source.

Aqueous PEDOT:PSS dispersions create compatibility challenges with hydrophobic photocurable matrices. Phase compatibility can be improved through formulation strategies such as solvent exchange, compatibilisation or selection of hydrophilic components; consequently, the earlier absolute statement that PEDOT:PSS requires only water-soluble hosts has been removed.

Electrical metrology must match the resistance regime and specimen geometry. Two-probe measurements include contact resistance and can become unsuitable for low-resistance specimens. Four-terminal methods reduce contact-resistance error for appropriate geometries. Surface resistance, sheet resistance, volume resistivity and bulk conductivity are not interchangeable quantities; the manuscript should state which one is measured, the electrode geometry and the test method [S2,S7].

8. Application mapping

Electrostatic-control fixtures and housings are a commercially established use case for dissipative polymeric materials, but dedicated VPP ESD systems are less extensively represented in peer-reviewed literature than carbon-nanocomposite and bioelectronic research. They should therefore be described as commercially established rather than as a peer-reviewed "mature" VPP literature class unless independent validation is available.

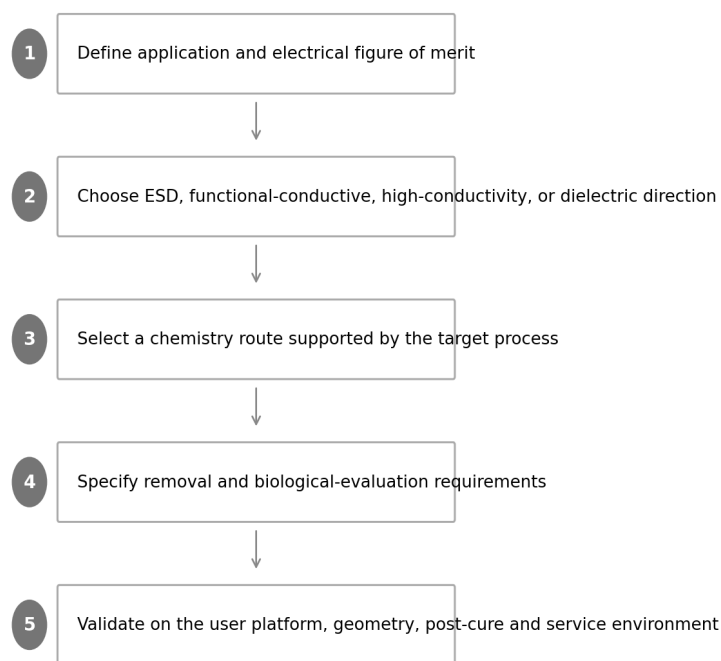
Functional prototypes and sensors are supported by the rapidly expanding literature on CNT, graphene and piezoresistive VPP composites [25-29]. Bioelectronics is supported by conducting-polymer and hydrogel literature, including DLP-printable PEDOT-based inks [38], broader conducting-hydrogel reviews [22,30,31], and complementary 3D fabrication routes [32,33].

Multi-material microfluidic workflows are directly supported by Fernandes Quero et al., who demonstrated DLP multi-material fabrication with flexible, rigid, water-soluble, fluorescent, phosphorescent and conductive resins, including conductive PEDOT- or copper-nanoparticle-containing materials [14]. Broader multi-material VPP reviews confirm active development of resin-switching, orthogonal chemistry and spatial-control strategies [15,34].

RF/microwave dielectric components are supported by the high-permittivity VPP composite work of Malas et al. [17] and by the wider polymer-ceramic literature [20,21]. Printed antennas and high-conductivity interconnects remain dominated by adjacent technologies such as DIW, inkjet and aerosol jet; an example is the DIW EGaIn antenna reported by Guo et al. [39]. VPP-specific antenna claims should therefore distinguish direct conductive printing from dielectric-substrate-plus-metallisation workflows.

9. Selection framework

An engineering selection sequence follows directly from the SDCF. First define the application and electrical figure of merit. Second choose the functional direction: electrostatic control, functional conduction, high-conductivity printed electronics or dielectric response. Third select a chemistry route supported by the required VPP process. Fourth define removal/sacrificial and biological-evaluation requirements. Fifth validate the candidate on the actual printer, geometry, post-cure and service environment.



The final validation step is non-skippable: the route narrows the design space, but does not determine the realised value.

Figure 4. Five-step selection workflow. Route selection narrows the candidate space, but the realised electrical performance remains a system-level outcome requiring user-side validation.

10. Critical assessment: field-level gaps

Gap 1 - Cross-study reproducibility. Nominally similar filler-matrix systems can report different electrical responses because dispersion, conversion, geometry, post-cure and metrology differ. The literature needs more complete system descriptions and interlaboratory comparison.

Gap 2 - Storage and formulation stability. Long-duration stability data for conductive VPP formulations are sparse relative to proof-of-concept print data. Filler sedimentation, aggregation, flocculation and premature reaction need route-specific reporting rather than generic shelf-life assumptions.

Gap 3 - Environmental conditioning. Humidity and temperature are well recognised in conducting-polymer and dielectric systems, but conditioning protocols are inconsistent. Values should be reported after defined equilibration.

Gap 4 - Scale-up. Most peer-reviewed studies remain laboratory-scale. Vat residence time, repeated-print reproducibility, batch variability and QA/QC translation are under-reported.

Gap 5 - Optical cure-window reporting. Conductive and dielectric phases can attenuate the curing wavelength, yet absorbance/scattering spectra and cure-depth calibration are not consistently reported.

Gap 6 - Regime language. Terms such as conductive, antistatic, dissipative and metallic are used inconsistently. Authors should report the measured quantity and avoid converting a review-specific band into a standards claim.

Gap 7 - Single-time-point characterisation. Electrical behaviour may evolve after post-cure and during environmental equilibration or ageing. A time-dependent characterisation protocol would improve transferability.

A minimum near-term reporting convention is therefore proposed: state (i) the electrical figure of merit and method; (ii) specimen/electrode geometry; (iii) resin composition at the level permitted by disclosure; (iv) printer wavelength and exposure protocol; (v) layer thickness and build orientation; (vi) post-cure; and (vii) conditioning environment and measurement time. This convention is intentionally modest: it can be adopted without a new standard and would materially improve cross-study interpretation.

11. Conclusions

Electrically functional VPP is not a single materials class. Carbon percolation composites, conducting polymers, silver-based composites, ESD-targeted systems and high-permittivity dielectric composites rely on different physical mechanisms and fail in different ways. The compact route taxonomy is useful only if those differences remain explicit.

The central conclusion is methodological. A conductivity, resistance or dielectric value measured on a printed photopolymer part is meaningful only together with the system configuration that produced it. The SDCF provides a compact structure for reporting that

configuration, while the four-level hierarchy distinguishes constituent, coupon, part and service-level values. Neither construct is presented as a standard or universal predictive equation.

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Disclosure

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