

Review

From Proxy to Impact: Evidence Translation in Functional Photovoltaic Cover Glass Coatings

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Abstract

Functional coatings for photovoltaic (PV) cover glass are often supported by optical, photocatalytic, wettability, or dust removal measurements, but these endpoints do not by themselves establish PV performance, field persistence, maintenance reduction, or environmental benefit. This critical conceptual review uses a structured, non-comprehensive evidence map of 56 primary studies published from 2006 to 2026 (46 PV-targeted and 10 boundary cases; 24 Si-Ti-containing studies) to examine how evidence moves from coating characterization to system-level outcomes. Optical and surface-functional evidence occurred in 51/56 (91.1%) and 50/56 (89.3%) studies, durability in 30/56 (53.6%), field or outdoor evidence in 24/56 (42.9%), PV performance evidence in 23/56 (41.1%), and coating-specific environmental outcomes in 3/56 (5.4%). Fifteen studies (26.8%) contained both field/outdoor exposure and PV performance evidence. Within the mapped corpus, PV performance evidence was positively associated with publication year (odds ratio 1.30 per year, 95% CI 1.10–1.53; $p = 0.002$), whereas the field/outdoor association was weaker (odds ratio 1.11, 95% CI 0.98–1.26; $p = 0.095$). The expanded map therefore supports a diagnosis of uneven, rather than absent, evidence translation. A two-track Evidence Translation Framework separates outcome evidence from mechanistic attribution and is used as a claim–audit architecture rather than a numerical quality score. The map is not presented as a prevalence census of the entire literature. Records without full-text verification are treated conservatively, and no formal inter-rater reliability is claimed.

Keywords: photovoltaic cover glass; anti-soiling coating; antireflective coating; self-cleaning; evidence translation; field validation; life-cycle assessment; structured evidence map



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1. Introduction

Soiling and front-surface optical losses reduce the energy delivered by photovoltaic modules, while cleaning requires water, labor, equipment, or all three. The burden is strongly climate-dependent: arid locations can experience severe dust accumulation, whereas rainfall, humidity, particle mineralogy, tilt, and cleaning practice alter both the

rate of loss and the value of mitigation [1–3]. Transparent coatings are therefore investigated as antireflective, photocatalytic, hydrophilic, hydrophobic, or combined anti-soiling surfaces [4,5]. Their laboratory performance can be technically meaningful, but the meaning is endpoint-specific: a transmittance spectrum establishes an optical property; a dye degradation test establishes activity under that protocol; a contact angle describes wetting; and a dust removal test describes a particular contamination and cleaning condition. None of these measurements alone establishes annual PV energy gain, reduced maintenance, or net environmental benefit.

Recent reviews show that PV coating research has moved beyond simple laboratory characterization toward consideration of durability, outdoor reliability, passive soiling mitigation, and multifunctional surfaces [4,6,7]. Elsafi et al. [6] synthesized anti-soiling and antireflective coatings for desert PV systems with emphasis on characterization, durability, and standardized testing, while Hooshyar et al. [7] reviewed soiling impacts and active/passive mitigation strategies. These reviews establish the technological landscape but do not explicitly code, study by study, whether a broader claim is supported by a directly corresponding endpoint or whether a measured outcome can be mechanistically attributed to a defined coating architecture. The present review addresses this narrower methodological gap. It asks not only what functions have been reported, but how far the evidence for each study travels from material design to PV operation and environmental consequence.

The term proxy inflation is used here for the upward promotion of a narrower measurement into a broader claim without measurement of the intervening endpoint. Examples include treating dye degradation as demonstrated anti-soiling, contact angle as maintenance reduction, or reduced cleaning as sustainability without accounting for coating manufacture and service life. Proxy inflation does not imply that the original measurement is weak; it identifies a mismatch between the measured endpoint and the scope of the claim. Earlier drafts also used the term ‘graphability effect’ as a possible explanation for why visually convenient laboratory endpoints appear frequently. Because this map contains no author survey, publication bias analysis, or causal test of endpoint selection, that explanation is not used as a finding in the revised manuscript.

This paper is therefore framed as a critical conceptual review with a structured, non-comprehensive evidence map. The map contains 56 primary studies covering functional PV cover glass and front-surface coatings, including a predefined 24-study Si-Ti subgroup. The objectives are to (i) quantify evidence distribution within the mapped corpus, (ii) separate PV performance evidence from mechanistic attribution, (iii) examine whether system-level evidence is associated with publication year within the mapped corpus, (iv) compare the Si-Ti subgroup with the remaining coating studies, (v) distinguish real field operation from outdoor exposure, and (vi) examine the small set of coating-specific environmental studies in greater methodological detail. No claim is made that the 56 studies constitute a statistically representative census of the entire field.

2. Review Design and Evidence Map

2.1. Scope, Identification, and Eligibility

The review was designed as a critical conceptual review with a structured evidence map [8], not as a completed systematic review or meta-analysis. Evidence was assembled through backward and forward citation chaining from established PV cover glass and Si-Ti studies, targeted title and DOI searches, and publisher site verification. Search concepts combined photovoltaic or solar module terms with cover glass, front surface, antireflective, anti-soiling, self-cleaning, hydrophilic, hydrophobic, TiO₂, SiO₂, field exposure, durability, power output, energy yield, water use, and life-cycle assessment. The search log and DOI-linked registry are supplied in Supplementary Data S1. Because the evidence assembly was

targeted rather than a database census, an initial search-hit denominator is not used and no representativeness threshold was selected a priori. Figure 1 therefore reports the evidence assembly routes, eligibility structure, final mapped corpus, and verification depth rather than presenting a PRISMA flow with retrospectively reconstructed counts.

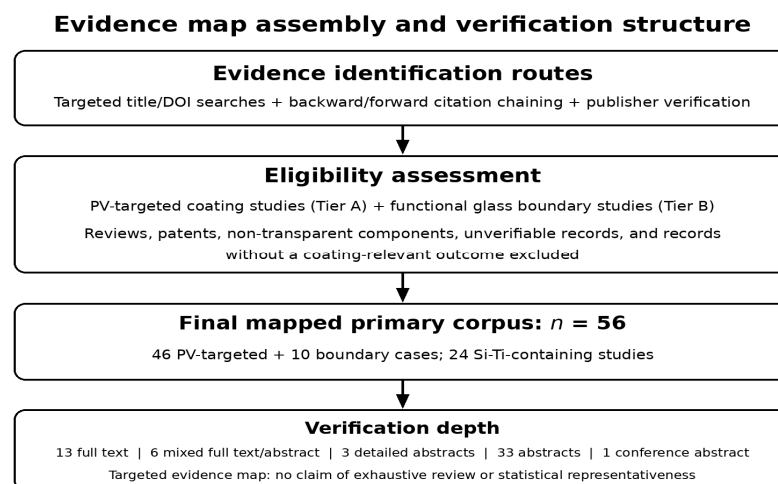


Figure 1. Evidence map assembly and verification structure. The figure documents the search routes, eligibility tiers, final 56-study primary corpus, and verification depth. Because the search was targeted rather than census-based, unidentified initial hit counts were not reconstructed retrospectively.

Tier A comprised primary studies explicitly targeting PV cover glass, modules, or solar cell front surfaces. Tier B comprised primary functional glass boundary studies with directly transferable optical, surface, durability, outdoor, or environmental methods. Reviews, patents, commercial reports without primary experimental data, non-transparent module components, unverifiable bibliographic records, and papers without a coating-relevant outcome were excluded from primary coding. The 2025 review by Elsafi et al. [6], which was mistakenly included as a primary record in the previous map, was reclassified as background literature and removed from all study-level counts. The final corpus therefore contains 56 primary studies: 46 PV-targeted and 10 boundary studies. The evidence identification and verification process used to assemble the final 56-study corpus is summarized in Figure 1.

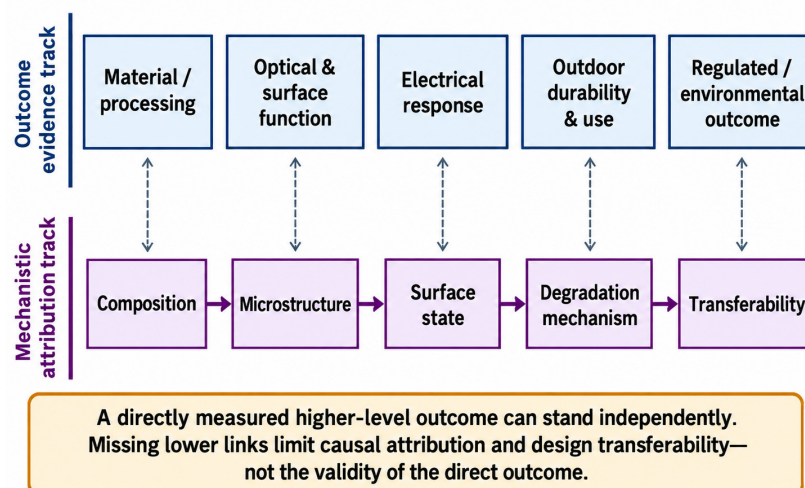
The scope and coding rules applied in the evidence map are summarized in Table 1.

Table 1. Scope and coding rules used in the expanded evidence map.

Element	Operational Rule	Purpose
Primary scope	Transparent coating or surface treatment for PV cover glass, module fronts, or solar cell cover surfaces	Defines the 46-study PV-targeted set
Boundary scope	Functional glass with transferable optical, surface, field, durability, or environmental evidence	Tests framework transfer without treating all records as PV evidence
Study-level domains	Optical; surface/self-cleaning; PV performance evidence; field/outdoor; durability; environmental/LCA	Counts explicit presence only; no imputation
Decision-proximal endpoint	Most decision-proximal outcome supported by the accessible record	Orders claim directness, not experimental quality or technology readiness
Mechanistic attribution	Degree to which composition, structure, surface state, and outcome are connected	Separates explanation from proof of outcome
Verification depth	Full text, mixed full text/abstract, detailed abstract, abstract, or conference abstract	Makes source access and certainty visible
Synthesis	Descriptive counts, temporal logistic regression, and exploratory subgroup comparisons; no pooled effect size	Respects heterogeneity in chemistry, climate, test design, and outcome

2.2. Evidence Translation Framework

The framework contains two linked but non-identical tracks (Figure 2): The Outcome Evidence Track asks whether the following claimed endpoints were measured directly: optical response, surface function, PV electrical performance, field behavior, durability, and environmental outcome. The Mechanistic Attribution Track asks whether the outcome can be connected to a defined composition, coating architecture, process, microstructure, surface state, or degradation mechanism. The central rule is deliberately asymmetric: lower-level evidence does not inherit upward, but a directly measured higher-level outcome can stand on its own. Missing lower links restrict causal attribution, optimization, and transferability; they do not invalidate a higher-level outcome that was actually measured.



Proxy inflation occurs when a claim moves upward without a corresponding direct measurement.

Figure 2. Two-track Evidence Translation Framework. The upper track records the outcome demonstrated by the measurement; the lower track records how securely that outcome can be attributed to coating design or mechanism. The framework is a claim–audit architecture, not a numerical score or a technology readiness scale. Dashed vertical arrows indicate correspondence between the outcome-evidence and mechanistic-attribution tracks; they do not imply that lower-track evidence is required to validate a directly measured higher-level outcome.

The operational definitions and interpretation rules for the two-track framework are summarized in Table 2.

Table 2. Operational definitions and interpretation rules for the two-track framework.

Framework Component	Operational Question	Interpretive Rule
Outcome evidence	Was the claimed optical, surface, PV, field, durability, or environmental endpoint directly measured or explicitly modeled?	A higher-level measured outcome may stand independently; a modeled estimate is identified as modeled rather than as a direct measurement.
Mechanistic attribution	Can the outcome be traced to a defined composition, process, structure, surface state, or degradation mechanism?	Missing lower links limit causal attribution and transferability, not the validity of a directly observed higher-level outcome.
Decision proximity	How close is the reported endpoint to the practical claim being advanced?	Categories order claim proximity only; they are not weights, TRL scores, or ranks of experimental quality.

2.3. Coding and Analysis

Each primary record was coded as present or not identifiable for six evidence domains: optical, surface/self-cleaning, PV performance evidence, field/outdoor, durability, and environmental/LCA. ‘PV performance evidence’ includes measured electrical outcomes

and explicitly modeled PV performance estimates; modeled values are not described as direct measurements in the revised text. ‘Field’ is reserved for real PV operation under site conditions with an operating device or module, whereas ‘outdoor’ denotes exposure outside the laboratory that may not include an operating PV system. The combined field/outdoor flag is retained only as a broad coverage variable because several abstract-only records do not permit a more granular distinction. For records assessed without full text, a zero means that the domain was not identifiable in the accessible abstract or metadata, not that it was proven to be absent from the article.

The final map contains 13 records verified from full text, 6 from combined full-text and abstract information, 3 from detailed abstracts, 33 from abstracts, and 1 conference abstract. No effect size pooling was attempted because coating chemistry, substrate, exposure, climate, comparator, optical metric, electrical endpoint, and duration were not commensurable. Two exploratory analyses were added in response to reviewer comments. First, logistic regression tested the association between publication year and the presence of PV performance or field/outdoor evidence. Second, two-sided Fisher exact tests compared the 24-study Si-Ti subgroup with the 32 non-Si-Ti studies across the six evidence domains; Bonferroni correction was applied across these six subgroup comparisons. These analyses describe structure within the mapped corpus and are not used to infer prevalence in the complete literature. Formal inter-rater reliability was not measured and remains a limitation. Supplementary Data S1 provides the fixed codebook and a blinded recoding sheet for future independent replication.

3. Results

3.1. Corpus Composition

The revised structured map comprises 56 primary studies published between 2006 and 2026. Of these, 46 are PV-targeted and 10 are functional glass boundary cases. Twenty-four studies contain both silicon- and titanium-based components or directly comparable Si-Ti architectures. The evidence base broadened after 2013 from predominantly sol-gel and photocatalytic studies toward hydrophobic, hybrid, commercial anti-soiling, durability, outdoor, and environmental work. The mapped primary studies are listed chronologically in Supplementary Data S1 and in Refs. [9–64]. Figure 3 summarizes the temporal distribution of PV performance, field/outdoor, and environmental evidence.

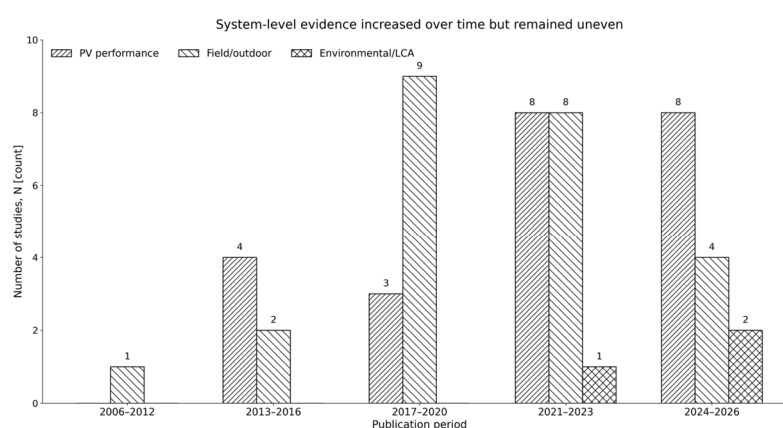


Figure 3. Temporal distribution of PV performance, field/outdoor, and environmental evidence in the 56 mapped primary studies. Bars are descriptive counts within the structured map; they are not prevalence estimates for all relevant literature. Within each publication-period group, the three adjacent bars represent PV performance, field/outdoor, and environmental/LCA evidence, respectively. The revised figure uses en dashes in year ranges and separates the groups to avoid label overlap.

The expanded corpus changes the substantive diagnosis. System-level evidence is present, but its distribution differs strongly by endpoint and by coating family. The earlier three-study appraisal overstated absence because it sampled a narrow chemistry. The present map instead tests where translation occurs, how it has changed over time, and whether the focal Si-Ti family follows the same pattern as the rest of the mapped literature.

3.2. Distribution of Evidence Domains

Optical outcomes were identifiable in 51/56 studies (91.1%) and surface or self-cleaning outcomes in 50/56 (89.3%). Durability evidence occurred in 30/56 (53.6%), field or outdoor evidence in 24/56 (42.9%), PV performance evidence in 23/56 (41.1%), and coating-specific environmental outcomes in 3/56 (5.4%) (Figure 4). The temporal analysis adds depth to these descriptive counts. Publication year was positively associated with PV performance evidence (odds ratio 1.30 per year, 95% CI 1.10–1.53; $p = 0.002$), whereas the increase in field/outdoor evidence was weaker and did not reach the conventional 0.05 threshold (odds ratio 1.11, 95% CI 0.98–1.26; $p = 0.095$). Within the mapped corpus, PV performance evidence was more common in later publications, whereas field/outdoor evidence showed a weaker temporal pattern. Because the corpus was assembled through a targeted, non-systematic process, this association should not be interpreted as a field-wide temporal trend. No causal explanation for the temporal shift is inferred from these data.

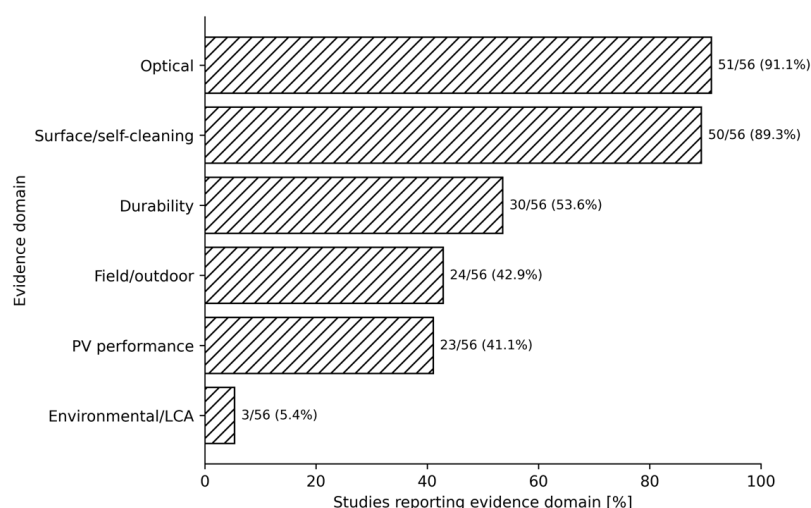


Figure 4. Evidence domain coverage across all 56 mapped primary studies. Presence indicates that an accessible source explicitly reported the domain; for abstract-only records, non-identification is not proof of absence from the full article.

3.3. Most Decision-Proximal Supported Endpoint

The most decision-proximal supported endpoint was a laboratory functional proxy in 10 studies and laboratory durability in 14. Six studies achieved PV performance evidence under laboratory conditions or through an explicit model, nine reported a field/outdoor proxy without PV performance evidence, 14 had field/outdoor exposure plus PV performance evidence as their most decision-proximal endpoint, and three reached a coating-specific environmental outcome (Figure 5). These categories order claim proximity, not scientific merit or technology readiness. The non-exclusive domain flags show that 23 studies contained PV performance evidence, 24 reported field/outdoor exposure, and 15 contained both.

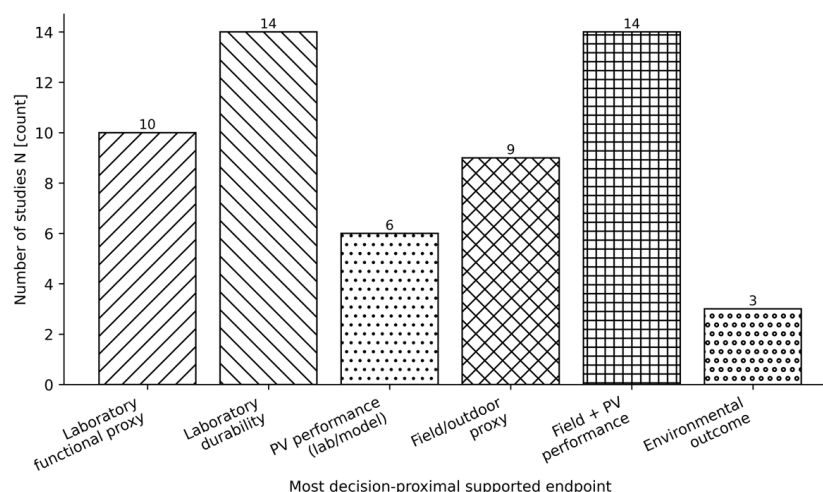


Figure 5. The most decision-proximal supported endpoint for each mapped primary study. Categories are mutually exclusive and do not rank intrinsic experimental quality. Modeled PV performance estimates are retained as modeled evidence and are not described as direct electrical measurements.

Study-level evidence coverage across the full map and the predefined subgroups is summarized in Table 3.

Table 3. Study-level evidence coverage in the full map and predefined subgroups.

Set (n)	Optical	Surface	PV Performance	Field/Outdoor	Durability	Environmental
All mapped studies (56)	51/56 (91.1%)	50/56 (89.3%)	23/56 (41.1%)	24/56 (42.9%)	30/56 (53.6%)	3/56 (5.4%)
PV-targeted studies (46)	43/46 (93.5%)	40/46 (87.0%)	23/46 (50.0%)	22/46 (47.8%)	23/46 (50.0%)	3/46 (6.5%)
Si-Ti-containing studies (24)	22/24 (91.7%)	22/24 (91.7%)	8/24 (33.3%)	5/24 (20.8%)	13/24 (54.2%)	1/24 (4.2%)

3.4. The Si-Ti Subgroup: From Multifunctional Design to Incomplete System Translation

The 24-study Si-Ti-containing subgroup provides the most direct test of whether the corpus-level pattern also holds for the focal material family. Optical evidence and surface-functional evidence were each identifiable in 22/24 studies, durability in 13/24, PV performance evidence in 8/24, field/outdoor evidence in 5/24, and a coating-specific environmental outcome in 1/24. Compared with the 32 non-Si-Ti studies, field/outdoor evidence was substantially less frequent in the Si-Ti subgroup (5/24, 20.8%, versus 19/32, 59.4%; Fisher exact odds ratio 0.18; unadjusted $p = 0.006$; Bonferroni-adjusted $p = 0.036$). By contrast, PV performance evidence did not differ significantly (8/24, 33.3%, versus 15/32, 46.9%; $p = 0.412$), and no adjusted difference was detected for optical, surface, durability, or environmental domains. This exploratory comparison identifies a material family-specific field validation deficit within the mapped corpus without implying a causal chemistry effect. A hydrophobic-versus-photocatalytic binary comparison was not imposed because these functions overlap in several multifunctional coatings and are not mutually exclusive study classes; forcing that dichotomy would create classification error rather than a defensible correlation analysis.

The exploratory comparison between the Si-Ti and non-Si-Ti subgroups is summarized in Table 4.

Table 4. Exploratory comparison of Si-Ti and non-Si-Ti studies. *p* values are two-sided Fisher exact tests; multiplicity correction was applied across six domain comparisons.

Evidence Domain	Si-Ti (<i>n</i> = 24)	Non-Si-Ti (<i>n</i> = 32)	Fisher Exact <i>p</i>	Interpretation
Optical	22/24 (91.7%)	29/32 (90.6%)	1.000	No detectable difference
Surface/self-cleaning	22/24 (91.7%)	28/32 (87.5%)	0.691	No detectable difference
PV performance	8/24 (33.3%)	15/32 (46.9%)	0.412	No detectable difference
Field/outdoor	5/24 (20.8%)	19/32 (59.4%)	0.006	Lower in Si-Ti; Bonferroni-adjusted <i>p</i> = 0.036
Durability	13/24 (54.2%)	17/32 (53.1%)	1.000	No detectable difference
Environmental/LCA	1/24 (4.2%)	2/32 (6.3%)	1.000	No detectable difference

Earlier Si-Ti studies established multifunctional design through layered, nanoporous, and particle-based architectures. Zhang et al. [9], San Vicente et al. [12], Li and He [13], Miao et al. [15], Ye et al. [18], and Wang et al. [21] emphasized antireflection, photocatalysis, hydrophilicity, and related self-cleaning functions. These studies are mechanistically valuable because they connect composition, layer arrangement, porosity, or particle architecture to function. Their typical endpoint, however, remains at coating or coupon scale rather than applying to module operation.

The next step in translation occurred along two partially separate routes. Li et al. [14] and Soklič et al. [20] moved toward PV performance evidence, while de Jesus et al. [22], Mazur et al. [23], Fardo et al. [39], Guo et al. [46], and Lai et al. [57] strengthened durability or multifunctional characterization. Outdoor exposure was introduced in other studies without always being paired with operating module electrical measurements. This split helps explain why the Si-Ti family can be mechanistically rich yet comparatively sparse in field evidence.

Recent work has begun to reduce this separation. Ismail et al. [53], Walz et al. [54], Batool et al. [55], and Yang et al. [58] extend PV relevance through device-level or outdoor testing, but the designs remain heterogeneous in formulation, duration, climate, and comparator. Two technical features may contribute to the slower accumulation of field evidence in Si-Ti systems: multifunctional formulations, which often vary several design variables simultaneously, and photocatalytic/hydrophilic performance, which can evolve under UV exposure, contamination, abrasion, and repeated wet–dry cycling. These mechanisms make long-duration attribution harder than a single laboratory optical or surface test. The present map supports the existence of the field validation gap; it does not by itself establish these mechanisms as its cause.

The subgroup therefore clarifies the distinction between mechanistic richness and system validation. Most Si-Ti studies explicitly connect composition or processing to structure or surface response, but binary TiO₂-SiO₂ systems coexist with Zr-, V-, PAA-, B4C-, and mixed-oxide formulations. This diversity can improve function while weakening cross-study transfer when composition, layer thickness, porosity, substrate, and process change together. A field or PV outcome can be valid in its own right, yet, without a controlled design axis, it cannot identify which material variable produced the gain.

Carvalho et al. [59] provide the only coating-specific environmental outcome within the 24-study Si-Ti subgroup. Their TEOS/TTIP coating study links primary process data to a prospective carbon footprint analysis and then models the consequence for a 16.4 MW PV plant. This is an important advance because it connects coating manufacture to system benefit, but it also demonstrates why coating lifetime, reapplication frequency, electricity

mix, and modeled energy gain must be stated explicitly before a net-benefit claim can be transferred to other formulations or climates.

3.5. Environmental Evidence Is Emerging, Not Absent

Three primary studies reach coating-specific environmental outcomes, but they use different functional units and system boundaries. Laopreecha et al. [49] used life-cycle assessment with the CML method for a sprayed nano-silica coating, defined the functional unit as 1 kWh of electricity over a 25-year PV lifetime, and reported a 2.08% reduction in total environmental impact relative to an uncoated system while noting a small increase in photochemical oxidation from additional coating chemicals. Carvalho et al. [59] quantified primary material and energy flows for a two-layer TEOS/TTIP coating, calculated coating production greenhouse gas emissions, and linked an experimentally observed 4.5% efficiency increase to a 16.4 MW plant simulation with lifetime sensitivity analysis. Fonseca et al. [60] evaluated a nano-silica-coated 16.4 MW system using LCA and greenhouse gas payback, reporting lower modeled lifetime emissions and a shorter environmental payback than the uncoated reference. Table 5 compares these studies directly.

Table 5. Comparative analysis of the three coating-specific environmental studies in the mapped corpus.

Study	Coating/Method	Functional Unit/Boundary	Main Environmental Result	Key Transfer Limitation
Laopreecha et al. [49]	Sprayed nano-silica; CML LCA	1 kWh electricity; 25-year PV lifetime	2.08% lower total environmental impact than uncoated PV; photochemical oxidation slightly increased	Thailand-specific operation and assumed lifetime; chemistry differs from Si-Ti
Carvalho et al. [59]	TEOS + TTIP two-layer coating; prospective process carbon footprint + plant simulation	One coating batch/process inventory linked to a 16.4 MW PV scenario	Coating production emissions quantified; 4.5% experimental efficiency gain propagated through lifetime simulations	System benefit depends on coating lifetime, reapplication, electricity mix, and modeled scaling
Fonseca et al. [60]	Nano-silica coating; PV system LCA + GHG payback	16.4 MW reference PV system including manufacturing, operation, replacement, and disposal	Modeled coated system emitted about 5% less GHG and shortened GHG payback relative to reference	Performance benefit is scenario-dependent and linked to modeled system assumptions

Together, these studies show that environmental assessment is feasible but not yet routine. The main barriers are not a lack of LCA methodology; they are the need to connect coating-scale inventory with a defensible field lifetime, reapplication schedule, cleaning baseline, and energy yield effect. Coating papers are often produced in materials laboratories that do not routinely collect process inventories or long-term operational data, while LCA studies require precisely those inputs. A practical route forward is to predefine a functional unit, meter coating process energy and materials, retain a matched uncoated control, measure coating persistence and cleaning demand under site conditions, and carry those measurements into ISO 14040/14044-compliant [65,66] scenario and sensitivity analyses rather than appending a qualitative sustainability claim after the experiment.

3.6. Integrated Results Summary

Across Sections 3.1–3.5, three findings are robust within the mapped corpus: First, optical and surface-functional measurements remain near-universal, while PV performance and field/outdoor evidence occurs in roughly two-fifths of studies, and environmental outcomes remain rare. Second, PV performance evidence is more common in later publications within the mapped corpus, but field validation is not uniformly distributed across chemistries: Si-Ti studies contain significantly less field/outdoor evidence than the non-Si-Ti group despite comparable optical, surface, and durability coverage. Third, the three environmental studies demonstrate multiple viable assessment routes but also show that

net-benefit conclusions depend on functional unit, lifetime, reapplication, operating climate, and system boundary. These results motivate the integrated discussion below rather than a separate theoretical argument.

4. Integrated Interpretation and Discussion

4.1. *The Revised Diagnosis: Uneven Translation*

The results support a narrower and more defensible diagnosis than the earlier manuscript. System-level evidence is not largely absent: within the revised 56-study map, 23 studies contain PV performance evidence, 24 contain field/outdoor evidence, and 15 contain both. The central weakness is uneven translation and incomplete integration. Optical and surface measurements are much more prevalent, and higher-level outcomes are frequently reported without the material, exposure, comparator, or lifetime information needed for transfer between coating architectures and climates.

This distinction is the practical value of the two-track framework. A measured field energy outcome does not become invalid because a microstructural link is missing; rather, the missing link limits causal attribution and design transferability. Conversely, a richly characterized coating does not inherit an operational claim from transmittance, contact angle, or dye degradation alone. The framework therefore orders claim proximity but deliberately avoids arbitrary weighting coefficients or a technology readiness score.

4.2. *Proxy Inflation Without a Causal Publication Claim*

The mapped distribution is consistent with proxy inflation as a claim-level risk, not with a demonstrated publication mechanism. Optical and surface-functional evidence appears in about nine of every ten mapped studies, whereas PV performance and field/outdoor evidence occurs in about four of every ten. This imbalance is descriptive. The revised manuscript does not attribute it to visual appeal, publication incentives, or investigator preference because no author survey, publication bias analysis, or cross-field causal comparison was performed. The previously proposed ‘graphability effect’ is therefore retained only as a hypothesis that would require independent empirical testing, and it is not used to explain the results. Quantitative comparison with adjacent coating fields was not used because no review identified in those fields employed the same six-domain coding definitions; comparing raw percentages across incompatible evidence taxonomies would therefore be misleading.

The actionable point is simpler: claims should remain aligned with the endpoint actually measured. Photocatalytic activity may be scientifically strong evidence for a surface reaction without being evidence of mineral dust removal; an anti-soiling effect may reduce transmittance loss without proving lower cleaning water demand; and a field performance benefit may still require an inventory and lifetime model before it supports a net environmental claim. This endpoint discipline is independent of why particular measurements are popular. Where methylene blue photocatalytic activity is used as a standardized surface endpoint, ISO 10678 [67] provides an appropriate test framework; it does not by itself demonstrate outdoor anti-soiling performance.

4.3. *Field Evidence Requires Climate and Duration Context*

Twenty-four studies contain field or outdoor evidence, but these terms are not synonymous. In this review, field evidence refers to operation of an actual PV device or module under site conditions, including controlled test sites; outdoor evidence refers more broadly to external exposure and may not include an operating PV system. The combined coverage flag is used only because several abstract-only records cannot be separated more finely. Transferability depends on duration, climate, dust type, rainfall, tilt, cleaning protocol,

comparator, module technology, and electrical normalization. Short outdoor exposures can show directional behavior without establishing seasonal persistence, while a coating aided by rain in a humid climate may behave differently under water-limited desert conditions.

Accordingly, field reporting should pair PV performance metrics with exposure meta-data and a physically meaningful control. IEC 61724-1 [68] provides a monitoring context for PV performance, while optical properties of PV glass should be measured using IEC 62805-2 [69]. Durability claims should identify the stress sequence, retained property, intermediate time points, and uncertainty. IEC 61215-2 [70] can inform stress test selection but does not convert coupon durability into a service life prediction.

4.4. Environmental Translation Must Couple Burdens and Benefits

The three environmental studies show that sustainability claims can be evaluated quantitatively, but they also expose strong dependence on system boundary and assumptions. Laopreecha et al. [49] couple a 1 kWh functional unit to a 25-year lifetime; Carvalho et al. [59] begin from coating process inventory and scale an experimentally observed efficiency change into a plant scenario; Fonseca et al. [60] evaluate whole-system greenhouse gas payback. These are complementary rather than interchangeable designs. Their small number means that the map supports the statement that environmental assessment is emerging, not a universal estimate of coating benefit.

Future environmental studies should therefore couple four quantities: burden per coated area or per functional unit, measured or transparently modeled effect on PV energy or cleaning demand, persistence over a declared service interval, and an explicit end-of-life/system boundary. Where coating lifetime is uncertain, reapplication frequency must be treated by sensitivity analysis. Water savings should be measured rather than inferred from wettability, and release should be tested from aged finished coatings rather than extrapolated from nanoparticle suspensions. ISO 14040 [65] and ISO 14044 [66] provide the LCA framework but do not replace the required primary inventories.

4.5. A Concise Evidence Package for Future Coating Studies

The reporting package is intentionally compact and claim-dependent. It is not a regulatory checklist. A materials paper can remain at the mechanism level when its claims remain there. A PV performance claim requires an electrical measurement or an explicitly labeled model with assumptions; a field claim requires defined site exposure and a comparator; a sustainability claim requires a functional unit and burden–benefit accounting. This structure links Sections 3 and 4 directly and avoids treating every study as if it should satisfy the same endpoint hierarchy.

The concise reporting package aligned with claim level is summarized in Table 6.

Table 6. Concise reporting package aligned with the level of claim.

Claim Level	Minimum Evidence Needed For That Claim	Recommended Reporting
Coating/material mechanism	Composition/process linked to optical, structural, or surface response	Composition, thickness, process conditions, uncertainty/replication
PV performance	Measured electrical response, or an explicitly labeled model	Coated/uncoated comparator; I–V or energy metric; model assumptions if applicable
Field performance	Defined site exposure with retained optical/surface/PV endpoint	Climate, duration, tilt, cleaning history, comparator, normalization
Durability	Stress sequence plus retained property	Intermediate time/cycle points, failure criterion, uncertainty
Environmental benefit	Functional unit plus coating burden and operational benefit	Inventory, lifetime/reapplication, energy/water effect, end-of-life, sensitivity analysis

5. Limitations

This study is a critical conceptual review with a structured, non-comprehensive evidence map, not a completed systematic review. The 56-study corpus is substantially broader than the original three-study appraisal but is not claimed to contain every eligible coating paper. Evidence identification relied on citation chaining, targeted scholarly searches, and publisher verification rather than a reproducible multi-database census with dual screening. A conventional PRISMA denominator cannot be reconstructed from this targeted workflow without inventing search-hit counts; Figure 1 instead makes the evidence assembly structure and verification depth explicit. The number 56 is therefore the number of studies in final eligible mapped set, not a threshold chosen to imply representativeness.

Verification depth remains mixed: 13 records were assessed from full text, 6 from combined full-text and abstract information, and 37 from detailed abstracts, abstracts, or a conference abstract. For records not verified in full-text, a zero may represent non-reporting in the accessible abstract rather than non-measurement in the full article. The use of records without full-text verification may underestimate domain coverage, particularly for secondary outcomes that are not routinely reported in abstracts. Binary coding records presence rather than measurement quality or duration. No formal second reviewer agreement statistic was calculated; the blinded coding worksheet is intentionally unfilled, and reliability testing is deferred until an independent recoding is actually completed.

The exploratory logistic regressions and Fisher exact subgroup tests increase analytical depth but do not convert the map into a statistically representative sample of the full literature. The Si-Ti field evidence difference is robust to the stated six-comparison Bonferroni correction within this corpus, but causal explanations for that difference require dedicated comparative work. Environmental evidence remains based on three studies, and the magnitude or direction of net benefit cannot be generalized across coating families.

The observed association between publication year and PV performance evidence should be interpreted with additional caution. Because the corpus was assembled through targeted searches and citation chaining rather than systematic database sampling, the temporal pattern may partly reflect source selection, changes in terminology or abstract reporting over time, and preferential capture of more visible or highly cited studies. The regression therefore describes an association within the mapped corpus and should not be interpreted as evidence that the field as a whole has shifted toward system-level outcomes.

6. Conclusions

Expanding and auditing the evidence map changes the conclusion. After reclassifying a 2025 review that had been mistakenly coded as primary literature, the final map contained 56 primary studies: 23 contained PV performance evidence, 24 contained field/outdoor evidence, and 15 contained both. Within the mapped corpus, PV performance evidence was positively associated with publication year, while the field/outdoor association was weaker. The Si-Ti subgroup was substantially less likely than the non-Si-Ti group to include field/outdoor evidence (20.8% versus 59.4%; Bonferroni-adjusted $p = 0.036$), even though optical, surface, and durability coverage was similar.

The central finding is therefore uneven evidence translation, not a wholesale absence of real-world testing. Optical, wettability, photocatalytic, and dust removal measurements remain valuable within their domains, but they do not inherit upward into PV performance, maintenance, or sustainability claims. Conversely, measured higher-level outcomes can stand independently; missing mechanistic links limit causal explanation and transferability rather than invalidating the outcome itself. Modeled PV estimates are now explicitly distinguished from direct measurement.

The highest-value next step is integration: a traceable coating formulation tested with standardized PV glass optics, matched electrical controls, climate-resolved field exposure, retained properties during aging, and burden–benefit environmental analysis when sustainability is claimed. The Evidence Translation Framework and accompanying study registry are intended to make those links auditable rather than to rank technologies with an unvalidated score.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/solar6050068/s1>, Supplementary Data S1: The 56-study DOI-linked registry; the evidence-coding matrix; domain summaries; the codebook; the claim–evidence audit; the reference audit; the standards audit; the blinded second reviewer worksheet; and the search log.

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