SEMARAK ILMU PUBLISHING

Semarak Engineering Journal

Journal homepage:
https://semarakilmu.my/index.php/sej/index
ISSN: 3036-0145



From Photosynthetic Quantum Energy Transfer to Verifiable Bio-inspired Energy Devices

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ARTICLE INFO

Article history:
Received 12 August 2026
Received in revised form 13 October 2026
Accepted 15 October 2026
Available online 25 October 2026

Keywords:
Quantum Biology; Photosynthetic Energy Transfer; Bio-inspired Photovoltaics; Energy Conversion; Measurement and Verification

ABSTRACT

Photosynthetic pigment–protein complexes suggest design principles for light harvesting, but quantum coherence or strong coupling alone does not establish improved electrical output in an engineered device. This review reframes quantum biology as an energy engineering problem: which molecular energy-transfer mechanisms can be translated into a reproducible photonic architecture and tested against a matched control? The source search reported 314 candidate records and 50 shortlisted studies, of which 49 were tabulated, 48 were unique, and 44 fell within the 2018–2024 window. No common device-output endpoint exists, so the evidence is synthesized descriptively without pooled effects. The study contributes a design specification rather than a fabricated prototype or validated model: a pigment-based absorber in an optical microcavity, an otherwise identical control with the cavity detuned or omitted, and acceptance gates based on external quantum efficiency (EQE), power conversion efficiency (PCE) and aging. A planning calculation shows that five devices per arm resolve a relative power difference of about 10% only when device scatter is near or below 5%. These are design criteria, not measured gains, and no efficiency improvement or emissions saving can be inferred. The framework gives engineers testable gates for prototype decisions.

1. Introduction

Photosynthetic pigment–protein systems motivate an applied energy question: can a measured molecular mechanism be reproduced in a manufactured light-harvesting architecture and improve useful electrical output? Laboratory studies of energy transfer and light–matter interactions establish physical phenomena [1–4]. Energy engineering, however, evaluates an assembled device by photon-to-charge conversion, power conversion efficiency, stability, manufacturability and cost. The gap between molecular observation and device-level verification is the central problem of this review.

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https://doi.org/10.37934/sej.16.1.149171

Quantum coherence, tunnelling and strong coupling appear in different experimental and theoretical contexts, and their observation cannot be treated as proof that a photovoltaic device will outperform a classical design. Candidate designs must specify the absorber or coupling structure, operating illumination and temperature, a physically matched control, and an output metric with uncertainty. The source manuscript spans imaging, medicine and education as well as photosynthesis, and the reference audit reported below shows that 27 of 55 bibliography entries concern photosynthetic light harvesting directly, while the remainder address general quantum biology, medicine, bioinformatics, protein folding, magnetic sensing and quantum computing. These contextual entries are retained to define the boundary of the field but are not used as evidence for device benefit, and the present revision focuses on photosynthetic energy transfer as the primary route to a bio-inspired energy-harvesting prototype.

Quantum coherence, tunnelling and strong coupling appear in different experimental and theoretical contexts. Their observation cannot be treated as proof that a photovoltaic device will outperform a classical design. Candidate designs must specify the absorber or coupling structure, operating illumination and temperature, a physically matched control, and an output metric with uncertainty. The source manuscript spans imaging, medicine and education as well as photosynthesis; the present revision focuses on photosynthetic energy transfer as the primary route to a bio-inspired energy-harvesting prototype.

We use a mechanism-to-device chain: characterize pigment absorption and excited-state dynamics; fit a physical transport model with identifiable parameters; fabricate or simulate a defined photonic/absorber architecture; and compare device output with a matched reference. An acceptance gate at each step prevents a spectroscopy result from being mistaken for a system-efficiency gain. Relevant molecular quantities include transfer time (fs or ps), transfer yield (%), dephasing time and spectral overlap. Relevant device quantities include external quantum efficiency (EQE, %), power conversion efficiency (PCE, %), output power density (W/m²), and retained performance after controlled ageing.

The real literature cases include vibrational strong coupling applied to photosynthetic energy transfer and experiments on biological light–matter coupling [3,5,6]. They establish test environments and candidate mechanisms, not a measured commercial photovoltaic benefit. Quantum biological tunnel-junction imaging serves as a contrasting instrumentation case; its imaging resolution should not be converted into a light-harvesting efficiency claim.

The contribution is an engineering evaluation framework that distinguishes direct observations, model-dependent inferences and untested device predictions, and it should be read as a synthesis and specification study rather than as an original design, simulation or prototype. We retain reported search counts and descriptive case evidence, identify the missing information needed to reproduce the synthesis, and define a prospective controlled test of a bio-inspired energy-conversion architecture. Its novelty relative to existing practice lies in coupling molecular acceptance gates to established photovoltaic characterisation, namely current–voltage measurement under a reference spectrum, spectral-mismatch correction and stability reporting based on the International Summit on Organic Photovoltaic Stability (ISOS) procedures, and not in proposing a new measurement standard [7,8]. The only calculation is a planning analysis of the smallest power difference that a given number of independent devices can resolve, and it is reported as a design aid rather than as a measured result.

The practical case for photosynthesis-inspired designs must be stated conditionally because conventional photovoltaics remain the stronger benchmark on measured output. Natural photosynthesis performs its primary energy-transfer steps near theoretical quantum limits in efficiency [57], yet an annual-average comparison with photovoltaic-driven water electrolysis favours

the photovoltaic route, although short-term photosynthetic yields under optimal conditions come within a factor of two to three of that benchmark [9,10]. A photosystem-I solar cell reported in 2012 delivered 81 μW/cm² under standard sunlight, which is about 0.08% of a 100 mW/cm² input if that irradiance is assumed and more than two orders of magnitude below the detailed-balance ceiling for a single junction [11,12]. A defensible rationale therefore rests on niches where photosynthetic design rules may add value, namely spectral extension through far-red antennas, optically engineered coupling and low-embodied-energy absorbers, and on the unresolved question of whether coherence has any functional relevance at all [13,14].

2. Purpose and scope

The review asks which photosynthetic energy-transfer mechanisms are supported by experimental evidence; which parameters can be carried into a model and prototype specification; and which measurements would demonstrate useful device-level gain. The chosen subject area is Energy and Mining Engineering, specifically energy-conversion design. Biotechnology and STEM education are discussed only as supporting knowledge-transfer contexts, not as separate application outcomes.

The objectives are to classify mechanistic evidence, map it to measurable design parameters, and specify a fair engineering comparison, and they are deliberately limited to what a literature-based study can deliver. A successful future claim would require a positive difference in PCE or output energy under identical illumination and operating conditions, exceeding the combined measurement uncertainty and reported together with durability data. This review contains no new fabrication, current–voltage curves, field operation or lifecycle inventory, and it presents no original numerical transport model, so it cannot quantify achieved energy or emissions savings. Its only quantitative additions are counts and ratios derived from the supplied records and a planning calculation of detectable power differences, both labelled as derived or illustrative rather than measured.

3. Methods

3.1 Search record and evidence boundary

The source manuscript reports searches in eight bibliographic sources, namely Google Scholar, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis, IEEE Xplore, PubMed and Scopus. The query concepts combined quantum biology, photosynthesis, pigments, coherence, tunnelling, coupling and engineering applications. These concepts are summarised in a concept-level template, (quantum biology OR photosynthesis) AND (pigment OR coherence OR tunnelling OR coupling) AND (engineering OR application), which documents the logic of the search rather than the verbatim syntax of each database. The temporal boundary of the review was set at 2018–2024, and in this revision it is applied to the publication year printed in each reference entry. Database-specific syntax and execution dates were not archived with the source manuscript, and they were not reconstructed retrospectively because a reconstructed record would not describe what was actually done. The study-selection record is therefore anchored on the totals reported by the source and on bibliographic evidence that can be audited directly, as consolidated in Table 1. This approach separates the reported procedure from the checks added during revision, and it means that compliance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guideline is not claimed.

The search produced 278 database records and 36 records from citation tracking, giving 314 candidate records, as shown in Figure 1. Fifty studies were reported as shortlisted, whereas the

evidence table contains 49 reference-labelled study rows, so one shortlisted study cannot be identified. Five bibliography entries are dated 2025 and one is dated before 2018, which departs from the stated 2018–2024 window. Because an exported search log and a final included-study list are unavailable, these discrepancies are handled by an explicit decision rule. Under this rule, the 49 tabulated rows form the traceable inventory, and the unidentified fiftieth study is excluded from all counts. Entries that fall outside the window or are duplicated are flagged and retained with a label instead of being removed silently. All conclusions are therefore restricted to the tabulated records, and the figure of 50 shortlisted studies is retained only as a source-reported value.

Table 1 consolidates the study-selection record and states the handling adopted for each element in this revision. Duplicate handling relies on the bibliographic fields of the reference list, namely the Digital Object Identifier (DOI), the title and the author sequence, and this comparison identified three duplicate pairs among the 55 bibliography entries. Each pair is counted once, so the 49 tabulated rows reduce to 48 unique studies, of which 44 fall inside the 2018–2024 window and four lie outside it. The window functions as a flagging rule rather than an exclusion rule, because the original screening decisions cannot be reconstructed from the source. Relevance to energy conversion was assigned from reference titles, and the 27 of 55 bibliography entries that concern photosynthetic light harvesting, energy transfer or photonic coupling form the primary mechanistic evidence. The remaining entries provide context only and carry no weight in the energy-conversion argument. Online-first dates should still be checked against publisher records, since an entry dated 2025 may have appeared online earlier, as the volume field of reference [23] indicates for August 2024.
[NOTED – Reviewer Comment 5: database-specific search strings, search dates, duplicate removal, exclusion criteria and study-selection record not provided; Reviewer Comment 6: stated 2018–2024 review period conflicts with several 2025 references]

Table 1
Study-selection record that can be documented from the supplied material, and its handling in this revision

Record element	Handling in this revision
Databases searched	Google Scholar, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis, IEEE Xplore, PubMed and Scopus, as reported by the source manuscript
Query concepts	Quantum biology, photosynthesis, pigments, coherence, tunnelling, coupling and engineering applications
Search logic	(quantum biology OR photosynthesis) AND (pigment OR coherence OR tunnelling OR coupling) AND (engineering OR application), applied at concept level
Search period	Publication years 2018–2024, applied to the year printed in each reference entry
Records identified	278 database records + 36 citation-tracked records = 314 candidates
Duplicate removal	Matching of DOI, title and author sequence; three duplicate pairs identified, each counted once
Eligibility criteria	Publication year within 2018–2024 (flagging rule) and direct relevance to photosynthetic light harvesting, energy transfer or photonic coupling; other entries classed as contextual
Exclusion handling	No record removed for publication year; out-of-window entries flagged and retained; the unidentified fiftieth study excluded from all counts
Shortlisted studies	50 reported by the source manuscript (provisional)
Final analytic set	49 tabulated rows, 48 unique studies, 44 inside the 2018–2024 window and four flagged outside it

3.2 Coding and engineering translation

Each tabulated record is read for system studied, direct measurement or simulation, mechanism, experimental conditions and potential energy-conversion relevance. Direct spectroscopy or imaging is separated from model prediction, device demonstration and educational discussion. The core

translation matrix is mechanism → measurable molecular parameter → proposed design variable → device performance measure → comparator. No pooled effect size is computed because studies do not report a common endpoint, variance and intervention contrast.

3.3 Prospective validation protocol

A future prototype study should preregister its pigment or photonic architecture and matched control, measure both on the same calibrated illumination apparatus following IEC 60904-1 and IEC 60904-3 practice, and report EQE spectra and current–voltage curves from independent devices on independent operating days [61,62]. PCE is maximum electrical output divided by incident optical power under a defined test condition, the absolute efficiency difference is $PCE_{prototype} - PCE_{control}$ in percentage points, and device yield, temperature, ageing, absorber loading and fabrication batch must be recorded. For mechanistic support, time-resolved spectra are fitted with identical model selection rules in the intervention and control, with parameter uncertainty reported and a second illumination intensity or temperature held out for validation. To plan the number of devices, the smallest detectable relative power difference is computed from a two-sided two-sample t test at a 5% significance level and 80% power for stated device-to-device coefficients of variation, and a claimed gain still requires concordant device-output evidence, not coherence alone.

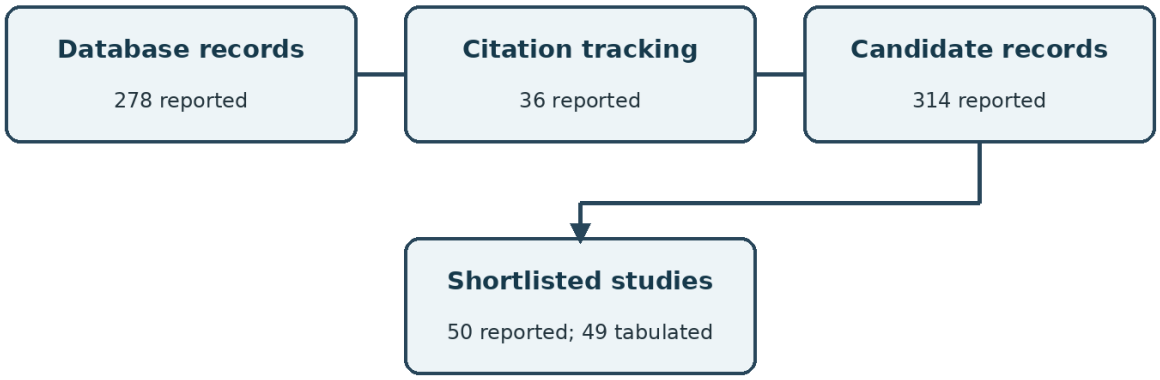


Fig. 1. Reported identification and selection totals; screening and eligibility details require reconciliation

4. Results

4.1 Evidence inventory

The source manuscript reports 50 shortlisted publications, whereas the evidence table in Table 2 identifies 49 entries, which corresponds to 98% of the reported total. This ratio is a completeness check and does not measure the effectiveness of any intervention. One tabulated row duplicates another reference, which leaves 48 unique studies in the analytic set. Of these 48 studies, 44 carry a bibliographic year inside 2018–2024 and four lie outside it, namely three dated 2025 and one dated 2014. The reference list holds 55 entries, six of which are absent from Table 2, and two of those six duplicate tabulated studies. Three duplicate pairs are identified across the full list, so the 55 entries correspond to 52 unique entries. Consequently, the fiftieth shortlisted study cannot be assigned to a single entry, and it is excluded from all counts in this review.

Figure 2 shows the publication-year distribution of the 55 bibliography entries relative to the stated 2018–2024 window, with entries outside the window shown in grey. Of the 55 entries, 53 carry a printed year, and 47 of them fall inside the window. Five entries are dated 2025 and one is dated 2014, which together depart from the stated eligibility period. The remaining two entries are preprints without a printed year, so their position relative to the window cannot be determined from the reference list. Most dated entries are concentrated in 2023 and 2024, which indicates a rapidly developing literature, but a recent publication date does not imply greater readiness for engineering use. The six entries outside the window are therefore flagged and retained instead of being removed, because the original screening decisions cannot be reconstructed. Their online-first dates should be verified against publisher records, since an entry dated 2025 may have appeared online earlier, as an entry with an August 2024 volume field illustrates.

The thematic composition of the reference list shows that 27 of the 55 entries (49%) address photosynthetic light harvesting, energy transfer or photonic coupling directly. The other 28 entries concern general quantum biology (7), medicine, bioinformatics, protein folding and DNA (7), magnetic sensing and spin dynamics (6), quantum computing and algorithms (6), and cellular imaging or unrelated materials science (2). These entries are retained because they belong to the source record and mark where quantum-biological claims have been made. They carry no weight in the energy-conversion argument and are not cited as evidence for any device-level benefit. One entry, an atomistic study of Al–Cu alloy solidification, has no demonstrable connection to light harvesting and is flagged as outside the scope of the argument. The mechanism-to-device argument therefore rests on the 27 directly relevant entries, supplemented by the energy-conversion and measurement literature added in this revision. The entries span spectroscopy, biological imaging, theoretical transport, quantum simulation and educational discussion, and only records reporting a device output and a suitable control could directly support an engineering performance comparison, which the supplied synthesis does not provide in any consistent set.

The available numerical results are selection counts and ratios derived from them: 278 database records, 36 citation-tracked records, 314 candidates, 50 reportedly shortlisted studies, 49 tabulated references, 48 unique tabulated studies, 44 unique studies inside the stated window and 27 of 55 bibliography entries directly concerned with light harvesting. No common device PCE, EQE or output-power dataset is presented, so none of these quantities is a measured or calculated engineering outcome. Proposed impact indicators are absolute PCE difference (percentage points), relative output-energy change (%), device-to-device coefficient of variation (%), retained PCE after ageing (%), and energy yield (kWh/m^2/year) in a future field trial, and none is an observed improvement in this review. The only engineering calculation, a planning analysis reported below, converts the coefficient of variation and the number of independent devices into the smallest relative power difference that can be resolved, which indicates how large a future gain must be before it can be distinguished from fabrication scatter.

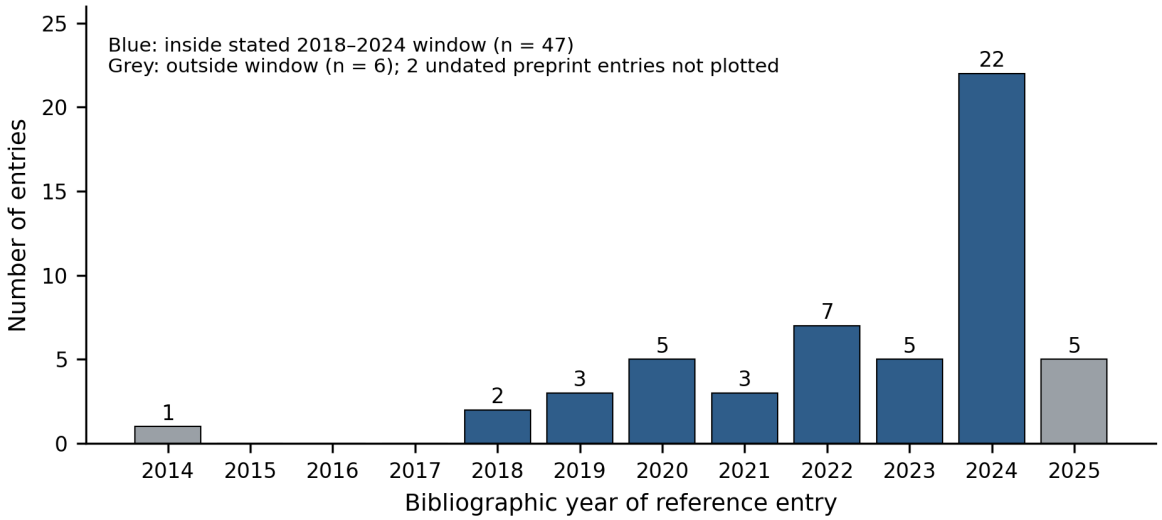


Fig. 2. Publication-year distribution of the 55 bibliography entries; entries outside the stated 2018–2024 window are shown in grey

Table 2
Forty-nine reference-labelled studies in the supplied review, with original mechanism and validation descriptions

Study	Quantum Phenomena Representation	Educational Integration Approaches	Empirical Validation
[5]	Demonstrates polaritonic states in photosystem 2 with strong light-matter coupling	Limited focus on education; primarily experimental physics	Strong in vivo evidence of quantum coherence in cyanobacteria
[15]	Real-time imaging of quantum electron tunneling in live cells using QBET junctions.	No direct educational integration; methodological innovation	High rigor with live cell electron transfer imaging
[16]	Quantum simulation of tunneling in biomolecules via IBM quantum computer	Theoretical quantum computing approach; no direct curriculum design	Simulation-based validation of quantum tunneling models
[3]	Biological cavity QED with chlorophyll a showing strong coupling and polariton formation	No educational framework; focus on nanophotonics and quantum biology	Experimental demonstration of room-temperature strong coupling
[17]	Mathematical quantum chemical modeling of chlorophyll photoexcitation	Theoretical analysis; no educational application	Theoretical validation of quantum transitions in chlorophyll
[18]	Theoretical manipulation of photosynthetic energy transfer via vibrational strong coupling	No educational integration; theoretical physics focus	Model-based predictions of energy transfer efficiency control
[19]	Open quantum systems approach to exciton energy pathways in LH2 complex	No curriculum design; computational physics study	Computational evidence of quantum coherence under physiological conditions
[20]	Single-photon quantum light spectroscopy probing photosynthetic light harvesting	Experimental quantum optics applied to photosynthesis	Direct experimental observation of single-photon events in vitro
[21]	Quantum electrodynamics behavior of chlorophyll in a plasmonic nanocavity	No educational focus; experimental quantum optics	Experimental evidence of cavity QED effects in chlorophyll
[22]	Electrodynamic interactions in light-harvesting proteins influenced by temperature and light	Experimental biophysics on collective modes; no education	Empirical evidence of long-range electrodynamic interactions

Study	Quantum Phenomena Representation	Educational Integration Approaches	Empirical Validation
[23]	Quantum model of light-suppressed photosynthetic charge transfer	Theoretical quantum model; no educational content	Theoretical insights into photochemical regulation in plants
[2]	Mathematical and computational modeling of photosynthetic systems	Review of computational models; no direct pedagogy	Theoretical and computational validation of photosynthetic energy transfer
[24]	Quantum simulation of FMO complex dynamics on an NMR quantum computer	Quantum computing simulation; no curriculum design	Simulation results validating quantum transport models
[25]	Quantum algorithm for photosynthetic excitonic transport simulation	Quantum algorithm development; no educational framework	Quantum computer simulation with theoretical validation
[14]	Quantum coherence in photosynthesis of living cyanobacteria	Experimental demonstration of quantum coherence in vivo	Substantial empirical evidence of polaritonic states in living cells
[26]	Review of quantum models in biology, including photosynthesis and magnetoreception	Broad theoretical review; no educational integration	Theoretical synthesis of quantum biological models
[27]	Quantum coherence effects in photosynthesis and quantum simulation (Chinese)	Theoretical and simulation approaches; no curriculum design	Review of quantum coherence and simulation methods
[28]	Coupling and slips in photosynthesis across timescales	Theoretical perspective on quantum and thermodynamic interplay	Conceptual analysis of photosynthetic efficiency
[29]	Ultrafast photosynthesis behavior in nanostructured photosystems	Experimental ultrafast spectroscopy of chlorophyll	Empirical data on coherent light emission in photosystems
[30]	Quantum theory of radical pair mechanism in flavin adenine dinucleotide	Detailed quantum model with molecular dynamics	Model predictions consistent with experimental data
[31]	Digital quantum simulation of radical pair spin dynamics	Quantum computing simulation; no educational design	Simulation validated against master equation approaches
[32]	Review of magnetic field effects in biology via the radical pair mechanism	Comprehensive review; no curriculum framework	Synthesis of experimental and theoretical evidence
[33]	Quantum biology for therapeutic and technological control	Discussion of quantum spin control in cells; educational implications	Emerging experimental control of spin states in vivo
[34]	Engineered magneto-sensitive fluorescent proteins for quantum sensing	Experimental development of quantum biosensors; no pedagogy	Demonstrates ODMR in living cells at physiological conditions
[35]	Quantum theory applications in biology, including microtubules and superradiance	Theoretical applications; no educational integration	Theoretical and experimental applications in biological quantum optics
[36]	Review of quantum biology and its biological contexts	Broad interdisciplinary review; no curriculum design	Synthesizes quantum effects across biological systems
[37]	Review of quantum biology's impact on medicine and pharmacy	Discusses ethical and educational aspects	Highlights interdisciplinary collaboration needs
[38]	Classification of quantum bioinformatics fields	Theoretical classification; educational implications	Discusses challenges in interdisciplinary education
[39]	Quantum computing in life sciences: complexity	Theoretical framework for integrating quantum computing in biology	Discusses computational advances for biological complexity
[40]	Mathematical modeling of living systems with quantum dynamics	Theoretical model emphasizing quantum measurement in biology	Proposes quantum dynamical models for living cells

Study	Quantum Phenomena Representation	Educational Integration Approaches	Empirical Validation
[41]	Quantum biology, spectroscopy, and sensing review	Reviews quantum sensing technologies and biological applications	Discusses state-of-the-art quantum biological sensing
[42]	Intersection of chronobiology and quantum biology	Theoretical exploration of rhythmic quantum phenomena in biology	Discusses quantum effects in biological rhythms
[43]	DNA as a quantum computer: a theoretical study	Theoretical quantum informatics model of DNA	Proposes quantum computational mechanisms in DNA
[44]	Quantum trajectory model of single photon absorption in photosystem II	Theoretical and numerical quantum modeling	Provides quantum trajectory analysis of photosynthetic excitation
[45]	Magnetic response of chlorophyll self-assembly in hydrogel	Experimental evidence of spin coupling and exciton delocalization	Empirical magnetometry and spectroscopy data
[46]	Singular value decomposition quantum algorithm for quantum biology	Quantum algorithm applied to excitonic transport and radical pairs	Simulation results on quantum simulators
[47]	Quantum phase synchronization sustaining coherence in photosynthetic antennas	Experimental ultrafast spectroscopy demonstrating vibronic coherence	Empirical evidence of long-lived quantum coherence
[48]	Exciton-vibrational coupling in chlorophyll binding protein	Theoretical multilevel fluorescence line-narrowing spectroscopy	Provides spectral density extraction of exciton-vibrational coupling
[49]	Bio-inspired quantum energy harvesting with collective effects	Theoretical overview of quantum coherence in light harvesting	Discusses quantum coherence as a design principle
[50]	Quantum coherence measure in radical-pair biological sensing	Theoretical measure linking coherence and biological uncertainty	Proposes physiological measures of quantum coherence
[51]	Quantum-based spectroscopy and energy transport with biomolecules	Thesis on quantum optics applied to photosynthetic energy transport	Combines quantum optics and biological experimental data
[1]	Fundamental aspects of quantum biology review	Conceptual review bridging quantum mechanics and biology	Discusses quantum effects in photosynthesis and other processes
[52]	Quantum theory of radical pair mechanism in flavin adenine dinucleotide (duplicate of 20)	Duplicate of (Sotoodehfar et al., 2024)	Duplicate of (Sotoodehfar et al., 2024)
[53]	Quantum transport and free energy utilization in protein α-helices	Theoretical modeling of quantum solitons and tunneling in proteins	Computational simulations supporting quantum transport
[54]	Quantum protein folding theory	Theoretical quantum mechanics applied to protein folding	Bioinformatics comparison with experimental data
[55]	Transient synchronization and quantum coherence in vibronic dimer	Theoretical study of quantum synchronization in biomolecules	Computational modeling of vibronic coherence
[56]	Quantum computing in computational biology review	Review of quantum computing applications in molecular biology	Discusses quantum algorithms for protein folding and molecular dynamics
[57]	Fluorescence noise measurement in photosynthetic systems	Experimental fluorescence noise analysis revealing quantum effects	Empirical data on quantum fluctuations in chlorophyll

Study	Quantum Phenomena Representation	Educational Integration Approaches	Empirical Validation
[58]	Resonant tunneling in natural photosynthetic systems	Theoretical and numerical modeling of quantum tunneling in thylakoids	Simulation of resonant tunneling matching photosynthetic wavelengths

4.1.1 Mechanisms relevant to energy conversion

Photosynthetic energy-transfer studies describe excitonic transport and its sensitivity to pigment arrangement, vibronic interaction and the optical environment [3,6,10]. Strong coupling and coherence must be interpreted using the measurement timescale and experimental conditions. The engineering transfer hypothesis is that a deliberately controlled optical environment could improve the probability that absorbed energy reaches a charge-separation interface. That hypothesis remains unverified until a device comparison measures charge or power output.

4.1.2 Supporting education and simulation evidence

Computational studies can explore transport-parameter sensitivity and guide device geometry, but a fitted or simulated transfer pathway is not itself an efficiency improvement [7]. The educational literature may help engineers learn the distinction between spectroscopy, modelling and performance testing. Its effects on student competence and prototype success were not measured by the review and are outside the primary energy-conversion endpoint.

4.1.3 Experimental validation boundary

The supplied manuscript reports approximately 15 strongly empirical studies, but it does not state the coding rubric or identify all 15 records unambiguously. We therefore do not treat that number as an independently verified proportion. Experimental cases such as photosynthetic coupling [3,9,18] demonstrate observables at a molecular or biological boundary, while quantum tunnel-junction imaging [8] demonstrates instrumentation at a cellular boundary. None of these observations establishes a percentage PCE gain for a fabricated bio-inspired photovoltaic module in the supplied dataset.

4.1.4 Design-readiness assessment

A candidate mechanism reaches the modelling gate if the source specifies sample composition, temperature, illumination or excitation, instrument resolution and uncertainty. It reaches the prototype gate only if the engineer can state a controllable design variable and a plausible charge-extraction route. It reaches the performance gate only with calibrated electrical output, a comparable control and stability data. These gates identify a reproducible path from basic research to applied energy engineering without assuming that all shortlisted studies meet them.

4.2 Mechanism-to-device synthesis

The principal technical bottleneck is parameter transfer across scales. A spectral signature measured in a pigment–protein assembly may depend on a controlled nanocavity or biological environment that is difficult to manufacture or operate in a solid-state device. A systems comparison should therefore include optical absorption, parasitic loss, interfacial charge separation, fabrication

yield and operating stability. Without these terms, improved energy transfer within an isolated complex need not improve net electrical output.

4.3 Thematic pattern in the supplied literature

Figure 3 retains the source manuscript's descriptive thematic map. It shows why photosynthetic transfer is a practical focus for this review: the mechanism has direct links to optical design and energy transport. The figure should be interpreted as an author-coded overview, not as a quantitative technology-readiness scale or a device performance result. Other themes, such as medical imaging and general STEM integration, provide context but do not enter the proposed PCE comparison.

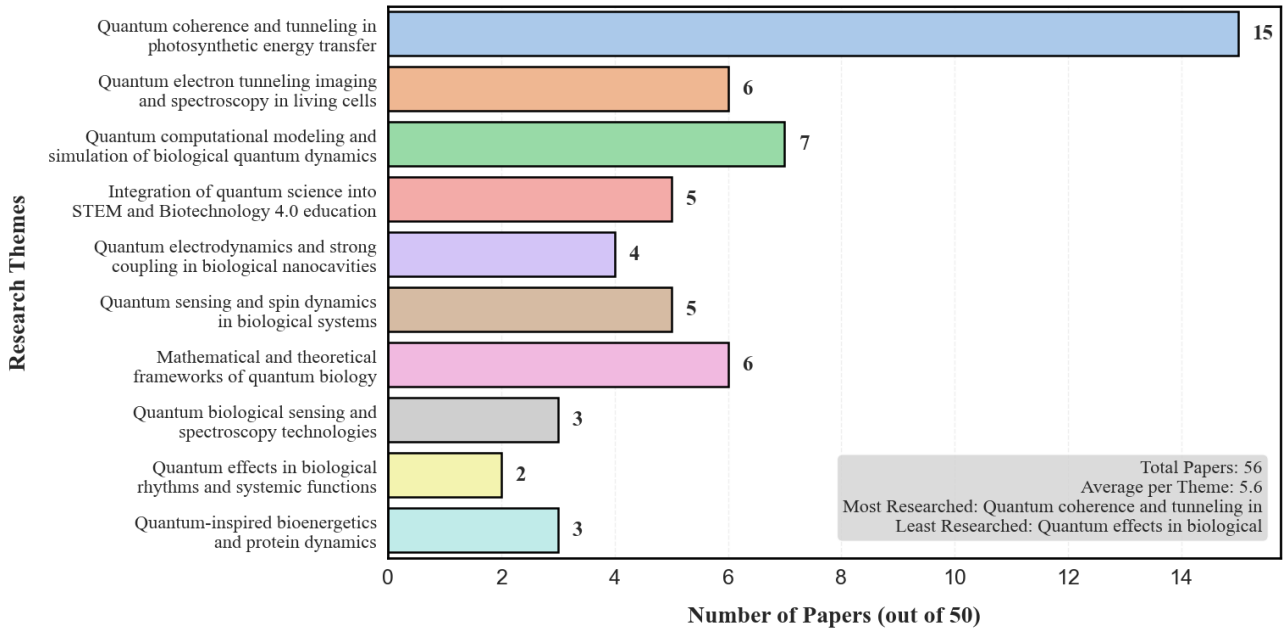


Fig. 3. Descriptive themes of the source review; theme frequency does not measure device performance

4.4 Chronological context

Figure 4 provides the original narrative chronology of modelling and experimental themes. A more recent publication date does not imply greater engineering readiness. Device relevance instead depends on whether a study reports a controlled comparison, reproducible conditions and an output metric that can inform the prototype specification.

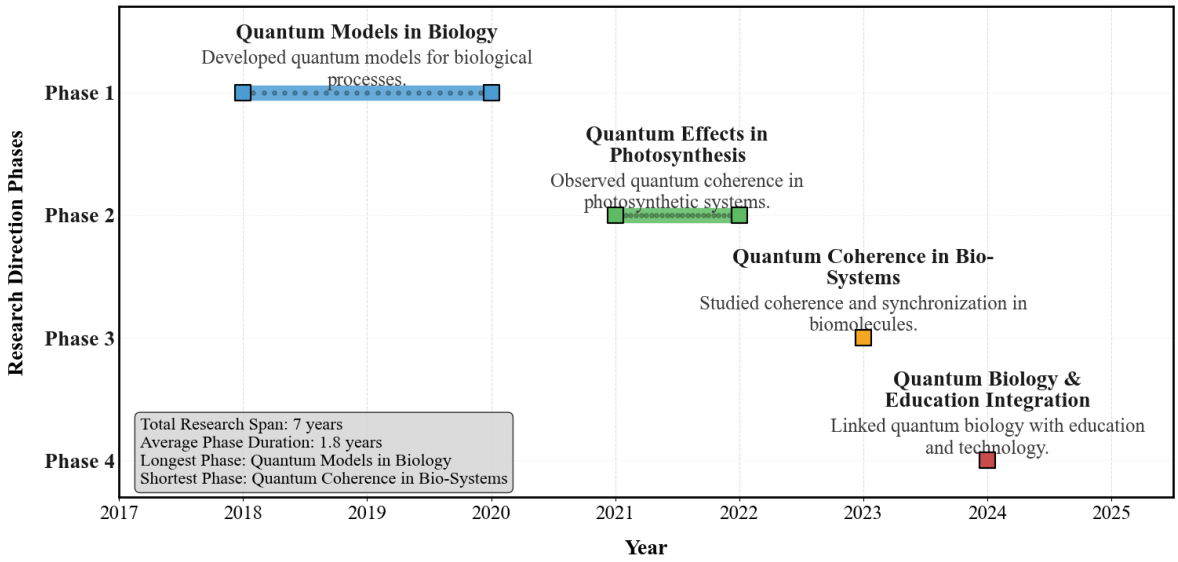


Fig. 4. Source manuscript chronology of research topics, shown as descriptive context

4.5 Translation requirements and decision criteria

The decision matrix for an energy-harvesting pilot has four requirements: (i) an experimentally characterised mechanism with stated uncertainty; (ii) a fabrication variable that can be changed while keeping the control otherwise matched; (iii) a predicted and measurable output pathway to charge or power; and (iv) a durability and cost envelope. Table 3 translates these requirements into a prospective specification, and for each element it states the proposed criterion together with the engineering rationale for adopting it. The preferred architecture is a pigment-based absorber placed in an optical microcavity, motivated by the strong-coupling and cavity cases [3,18]. The technically justified control is an otherwise identical device whose cavity is detuned from the absorption band or omitted, so that only the optical environment differs. This design matters because pigment loading, interfacial charge extraction and stability can change device output for reasons unrelated to coherence, and only a control that isolates the optical environment can attribute a difference to the mechanism. The specification is a design proposal and not a measured result, and the architecture remains a hypothesis until a device comparison measures charge or power output.

The primary acceptance criterion is a positive PCE difference whose confidence interval excludes zero and whose size exceeds the minimum detectable difference for the measured device scatter. This criterion is supported by EQE, stability and cost criteria, which together define engineering feasibility. Reference illumination and measurement follow IEC 60904-1, -3 and -7, so the molecular acceptance layer sits above established characterisation and does not replace it. The threshold is defined relative to measured scatter and not as a fixed percentage, because the supplied material provides no consensus value for these gates. Replication across independent devices, fabrication batches and test days captures variability that repeated scans of a single specimen would conceal. A project that fails any criterion should return to measurement or design before claims of energy impact are made, and a failed test should be reported as a negative result. The external benchmarks, namely the photosystem-I cell and the detailed-balance ceiling, serve as reference points for interpreting output density and not as targets to be exceeded.

Table 3
Prospective prototype specification, control device and feasibility criteria for a photosynthesis-inspired energy-harvesting test

Specification element	Proposed criterion	Engineering rationale
Preferred prototype architecture	Pigment-based absorber layer in an optical microcavity or nanocavity with charge-extraction contacts, fabricated within one substrate batch	Cavity and strong-coupling cases offer the only candidate route by which the optical environment could alter energy transfer, so the architecture is tested as a hypothesis and not assumed to deliver a gain
Control device	Identical absorber, thickness, contacts and substrate, with the cavity detuned from the absorption band or omitted; same batch and test day	Changing only the optical environment (requirement ii) allows an output difference to be attributed to the mechanism and not to loading, interfaces or batch effects
Reference illumination and measurement	Current–voltage curves and EQE under a stated reference spectrum, with spectral-mismatch correction, stated area and temperature, following IEC 60904-1, -3 and -7	Established characterisation keeps PCE comparable between laboratories, and transfer-yield data from spectroscopy cannot substitute for it
Primary endpoint	Absolute PCE difference (percentage points) and relative power change (%), prototype versus control	A device-level quantity ties the result directly to useful electrical output, and the relative change is the quantity whose detectability is assessed in **Table 4**
Target threshold	95% confidence interval of the difference excludes zero, and the observed relative gain exceeds the minimum detectable difference for the measured device scatter and number of devices	A threshold tied to measured scatter prevents a fixed percentage from being accepted when fabrication variation alone could produce the same difference
Replication	At least five independent devices per arm from two fabrication batches and two test days, revised once the pilot scatter is known, as supported by Table 4	Independent devices and days capture fabrication and measurement variability that repeated scans of one specimen would hide
Stability criterion	Aged-to-initial PCE ratio at a stated stress protocol and exposure time, with ISOS-type reporting items	Pigment-derived absorbers may have limited durability, so an initial gain without retained performance would not support a practical advantage
Mechanistic consistency	Transport model fitted with identical selection rules in prototype and control and validated on a held-out illumination or temperature	A model that reproduces spectra but fails to predict device behaviour is inadequate evidence, so identical rules in both arms test whether the mechanism explains the output difference
External benchmark	Output density reported against the photosystem-I cell (81 μW/cm²) and the detailed-balance ceiling [11,12]	The benchmarks place the prototype between a biological baseline and a physical upper bound, and no claim to exceed the ceiling is made without direct evidence
Feasibility gate	Proceed to cost and field assessment only if the threshold and stability criteria are met; otherwise return to measurement or design	Cost and energy-yield claims should not rest on a result that has not passed the earlier gates, and a failed test is reported as a negative result

4.6 Quantitative verification plan

4.6.1 Optical and electrical measurements

For each prototype and control, report calibrated incident photon flux, absorptance, wavelength-resolved EQE, maximum power point and active area, using IEC 60904-1 for current–voltage curves and the reference spectral irradiance and spectral-mismatch correction of IEC 60904-3 and IEC 60904-7 [61–63]. EQE(λ) equals collected electrons divided by incident photons at wavelength λ, and PCE equals maximum electrical power divided by incident optical power under a stated illumination standard. A transfer-efficiency parameter from spectroscopy is reported separately from both quantities because it is a molecular observable and not a device metric, so the protocol acts as a molecular acceptance layer placed above established characterisation and does not replace it. Confidence intervals should reflect independent fabricated devices rather than repeated scans of a

single specimen, and a device that cannot be stabilised for measurement should be reported with its preconditioning and scan protocol.

4.6.2 Model validation and uncertainty

Fit a transport model to time-resolved data with documented assumptions, instrument response and parameter bounds, and estimate the parameters with confidence intervals obtained from the fit covariance or from a bootstrap over independent measurements. Parameter identifiability should be checked by profiling the fit residual over each parameter, and a one-at-a-time sensitivity analysis of transfer yield to the dephasing time, the exciton–bath coupling and the spectral overlap shows which parameters must be measured rather than assumed. Validate against held-out conditions such as a second illumination intensity or temperature, and compare the same model structure between the candidate architecture and its control, reporting fit residuals and identifiability. A model that reproduces spectra but fails to predict device current–voltage behaviour is inadequate evidence of engineering impact, and because the supplied review contains no model of this kind, none is implemented or claimed here.

4.6.3 System performance and economics

Calculate relative power change as 100 × (Pprototype − Pcontrol)/Pcontrol under matched conditions, with an uncertainty interval. Track ageing as 100 × PCEaged/PCEinitial at a defined exposure time. A field study can then estimate annual energy yield and levelised cost per delivered kWh using a stated lifetime, financing assumption, fabrication yield and maintenance schedule. No monetary inputs or operational yield data are available here, so no payback or cost-benefit result is claimed.

4.6.4 Meta-analysis applicability

The original manuscript contains funnel, domain-effect and heterogeneity figures with effect values of approximately 0.61–0.78 and incompatible overall I^2 summaries. Study-level effect definitions, sample sizes, standard errors and analysis code are not supplied, while experimental quantum phenomena, educational outcomes and health applications have no shared natural effect scale. Those plots and pooled estimates have therefore been removed from the revised analysis. Publication bias and cross-domain pooled effects cannot be inferred from the present record.

4.6.5 Planning sensitivity of the verification protocol

Because no measured device scatter is available, the detectability of a prospective gain was explored as a planning calculation rather than as a result. For a two-arm comparison of independent devices, the smallest detectable relative difference in mean PCE was computed for a two-sided t test at a 5% significance level and 80% power, with equal numbers of devices per arm and device-to-device coefficients of variation (CV) of 2%, 5% and 10% as scenario values that span a range of fabrication scatter. The solution used the noncentral t distribution and was checked by Monte Carlo simulation with 20,000 draws per case, which reproduced 80% power within 0.5 percentage points for all four sample sizes. Table 5 lists the resulting minimum detectable differences, which depend only on the assumed scatter and the number of devices and not on any measured prototype performance.

As summarised in Table 4, with five independent devices per arm the minimum detectable relative difference is 4.0% at a CV of 2%, 10.1% at 5% and 20.2% at 10%, and it falls only to 2.4%, 6.0% and 12.0% when the number of devices is increased to twelve. These results indicate that a gain of about 10% in output power can be resolved with five devices only when fabrication scatter is near or below 5%, and that a gain of a few percent would require both a highly reproducible process and a larger device set. Consequently, the acceptance threshold in the prototype specification is defined relative to measured scatter and not as a fixed percentage, and a pilot batch should establish the CV before the confirmatory sample size is fixed. The calculation does not predict that any photosynthesis-inspired architecture will reach these differences, and it must be repeated with measured scatter once prototype data exist.

Table 4
Planning calculation: minimum detectable relative difference in mean PCE between prototype and control, for a two-sided t test at 5% significance and 80% power

Device-to-device CV (%)	3 devices per arm	5 devices per arm	8 devices per arm	12 devices per arm
2	6.1	4.0	3.0	2.4
5	15.4	10.1	7.5	6.0
10	30.7	20.2	15.1	12.0

5. Discussion

5.1 Engineering interpretation and practical use

5.1.1 Physical mechanism versus device benefit

Quantum transport models can motivate an absorber layout or optical cavity, but a mechanism observed under biological or laboratory conditions is only a design hypothesis for energy conversion, and Table 5 retains the source's theoretical implications as candidate mechanisms. The hypothesis is further weakened by the unresolved debate over whether long-lived electronic coherence has a functional role, since spectroscopic re-examinations report that the long-lived oscillations originate largely from vibrations and that inter-exciton coherences are too short-lived to be functionally significant [7,12]. Engineering translation therefore requires a measured path from absorbed photons through transport and charge separation to electrical output, with losses and operating constraints accounted for. A transport model that is calibrated and validated on held-out conditions, as specified in the verification protocol, is the minimum computational evidence needed before an optical environment is chosen as a design variable.

Table 5
Candidate quantum mechanisms and engineering hypotheses in the reviewed literature

Implication Type	Key Insights	Engineering Relevance	Representative Papers
Quantum Coherence & Tunneling	Coherence across complete complexes supports wave-like energy transfer	Provides principles for energy-transfer optimization and bio-inspired transport systems	[19]
Quantum Modeling	Spin-Boson Model and quantum computing validate biological tunneling	Supports multiscale computational modeling of molecular transport	[51]
Light–Matter Coupling	Strong coupling in nanocavities reveals polaritonic biological states	Enables design concepts for photonic, optical, and nanoscale devices	[59]

Vibrational Dynamics	Vibrational coupling enables long-lived coherence	Provides mechanisms for controlling energy-transfer efficiency in engineered systems	[28]
Quantum Spin Processes	Radical-pair dynamics explain magnetoreception	Supports development of quantum magnetic sensors and bio-inspired sensing systems	[50]
Computational Theory	Modeling requires integration of quantum physics and biology	Establishes a basis for coupled quantum–biological engineering simulations	[2]

5.1.2 Prototype design and trade-offs

Table 6 lists applications in the supplied review; for the chosen subject area, its bio-inspired energy-harvesting row is the direct application. Greater optical coupling may require a costly cavity or narrow spectral resonance and can reduce broadband performance or durability, while pigment-derived structures may pose stability and fabrication-yield problems. A fair decision weighs incremental PCE and energy yield against material cost, production repeatability and service life, and the benchmark is demanding because a photosystem-I cell reported in 2012 delivered 81 μW/cm² [59] and any single-junction absorber is bounded by the detailed-balance limit [64]. The review provides no comparable device dataset to resolve this trade-off numerically, so the advantage of photosynthesis-inspired designs remains conditional on spectral tailoring, operation under low or diffuse light, or material sustainability being demonstrated against a matched conventional control.

Table 6
Potential applications; energy harvesting is the primary engineering application assessed here

Application Area	Key Insights	Engineering Application	Representative Studies
Bio-Inspired Quantum Tech	Reported molecular transport motivates, but does not demonstrate, photovoltaic gain	Prototype hypothesis requiring controlled EQE, PCE and ageing comparison	[49]
Quantum Imaging	Quantum tunneling imaging enables real-time cellular monitoring	Design of high-resolution biological imaging and monitoring systems	[15]
STEM Education	Need for integrating quantum biology into curricula	Development of interdisciplinary engineering and Biotechnology 4.0 training modules	[26]
Quantum Simulation	Quantum computational models can explore molecular parameter sensitivity	Model predictions require experimental and device-level validation	[39]
Quantum Biosensing	Magneto-sensitive quantum biosensors support in vivo imaging	Development of biological sensing, monitoring, and diagnostic devices	[34]
Therapeutic Modulation	External quantum control enables modulation of biological systems	Engineering of controlled bio-interaction and therapeutic platforms	[47]

5.1.3 Comparison with established photovoltaic and bio-inspired approaches

Established photovoltaic development rests on standardised measurement and reporting: current–voltage curves under a reference spectrum, spectral-mismatch correction for non-ideal simulators, and stability protocols reported with enough procedural detail to be compared between laboratories [7,60]. Table 7 compares the proposed mechanism-to-device framework with these practices and shows that the framework adds a molecular acceptance layer, namely transfer time, yield, dephasing and spectral overlap, but does not replace any device-level measurement and

cannot be accepted on its own. Where the framework is silent, such as certified efficiency measurement, scan-protocol reporting and module-level qualification, the established standards apply without modification, and the framework should be judged by whether its prototype passes them. The comparison also exposes a genuine limitation, because the molecular gates have no counterpart in photovoltaic standards and their predictive value for PCE has not been demonstrated.

Among bio-inspired solar systems, dye-sensitised cells are often described as inspired by photosynthetic charge separation yet rely on synthetic sensitisers and electrolytes, whereas photosystem-I biophotovoltaics use the natural pigment–protein complex directly as light harvester and charge separator and have reached a power density of 81 μW/cm² at an open-circuit voltage of 0.5 V and a fill factor of 71% [61,62]. The proposed framework differs from both because it asks whether a specific photosynthetic energy-transfer mechanism, rather than the pigment alone, adds output relative to a matched control, which is a narrower and more falsifiable question. This distinction matters because a pigment-based device can perform well or poorly for reasons unrelated to coherence, such as loading, interfacial charge extraction or stability, and only a control that changes the optical environment alone can attribute a difference to the mechanism. The absence of such controlled comparisons in the supplied literature is the main reason why the framework stops at a specification and does not claim a performance gain.

Table 7
Critical comparison of the proposed mechanism-to-device framework with established photovoltaic characterisation, stability reporting and bio-inspired solar systems

Established or comparator approach	What it establishes	Relation to the proposed framework	Consequence for the prototype test
IEC 60904-1 current–voltage measurement [61]	Procedures for current–voltage curves of cells and modules in natural or simulated sunlight	Adopted unchanged for PCE and output power	PCE is reported only from current–voltage curves under a stated spectrum, temperature and area
IEC 60904-3 reference spectrum and IEC 60904-7 mismatch correction [62,63]	Reference spectral irradiance for terrestrial devices and computation of spectral-mismatch correction	Adopted; transfer-yield data cannot substitute for it	Mismatch correction reported separately for prototype and control
ISOS-based stability reporting [60]	Consensus procedures and reporting items for stability testing of perovskite photovoltaics, not intended to replace qualification standards	Used as a template for the ageing endpoint; not validated for pigment-based absorbers	Aged-to-initial PCE ratio at a defined stress and exposure time
Detailed-balance benchmark [64]	Efficiency ceiling for a single-junction absorber	External benchmark, not a target	No claim to exceed the ceiling without direct evidence
Dye-sensitised cells [65]	Molecular absorber with an engineered charge-transfer interface in a complete cell	Closest conventional analogue for device architecture	Architectural reference for contacts and charge extraction
Photosystem-I biophotovoltaics [59]	Natural pigment–protein complex as harvester and charge separator; 81 μW/cm² reported	Closest biological analogue	Baseline output density for biological absorbers
Photosynthetic versus photovoltaic efficiency [56]	Annual-average comparison of photosynthesis with photovoltaic-driven electrolysis	Frames expectations: gains must be shown against photovoltaic practice	Matched control and conventional reference reported together
Molecular acceptance layer (this framework)	Transfer time, yield, dephasing and spectral overlap with uncertainty	No counterpart in photovoltaic standards; predictive value untested	A gate before prototyping, never a performance claim

5.2 Limitations of the evidence

The search is not independently reproducible from the supplied record, one shortlisted study cannot be identified in Table 8, and five bibliography entries postdate the stated window, which the reference audit documents without being able to recover the missing search log. Source descriptions sometimes treat theoretical mechanisms as established technology benefits, and the source's pooled effect sizes and bias plots lack a defined common outcome and study-level inputs, so they cannot support quantitative conclusions about device efficiency or publication bias. Table 9 summarises the limitations that affect translation from biological observation to energy device, and the evidence-handling rules added here limit their effect by restricting conclusions to the unique tabulated records, flagging out-of-window entries and separating directly relevant from contextual references. The review is therefore a structured engineering interpretation of cited cases, not a validated statistical meta-analysis, and it contains no original numerical model, prototype or measured device output.

Table 8
Limitations affecting translation from biological observation to energy device

Limitation Area	Description	Engineering Consequence	Representative Studies
Limited Real-Time Imaging	Reliance on indirect/simulated data limits external validity	Restricts validation of dynamic biological systems and device performance	[5,15]
Small Quantum Models	Simplified systems limit generalizability	Reduces scalability of computational models toward complex biological systems	[25,46]
Experimental Constraints	High-complexity setups reduce reproducibility	Increases implementation complexity, cost, and laboratory dependence	[3,16]
Photosynthesis Dominance	A narrow biological focus restricts the scope	Limits transferability of design principles to other biological technologies	[2,17]
Simulation Bias	Overreliance on theoretical methods	Creates gaps between computational predictions and experimental engineering validation	[24,35]
Limited Educational Studies	Minimal integration in STEM teaching	Delays development of engineering-ready quantum biotechnology competencies	[38,63]
Environmental Factors	Limited exploration of temperature/light effects	Restricts understanding of system robustness under variable operating conditions	[2,58]
Lack of Longitudinal Data	Few studies across species/time	Limits reliability assessment, durability analysis, and long-term engineering performance	[21,64]

5.3 Research priorities

A staged validation programme should first reproduce a selected photosynthetic measurement under documented conditions; second, implement and validate a transport model with parameter estimation and sensitivity analysis; third, design a matched absorber or cavity comparison; and fourth, test EQE, PCE and ageing across independent batches before comparing annual energy yield and lifecycle cost against a conventional device. Instrument calibration, raw spectra, device areas, model code and uncertainty should be archived so that the search, selection and measurement records become reproducible. Table 9 lists future research priorities in which direct device validation precedes broader translation claims, and the education-related priorities remain supporting

outcomes that need their own assessment. Education can support the programme through training on these measurement tasks, while remaining a separate outcome, and a bio-inspired device that fails the acceptance criteria of the prototype specification should be reported as a negative result.

Table 9
Future research priorities; direct device validation precedes broader translation claims

Gap Area	Future Research Directions	Engineering Justification	Priority
Learning Model Evaluation	Test quantum biology learning models in STEM	Establishes measurable competencies for future biotechnology and engineering workforce development	**High**
Curriculum Development	Build interdisciplinary frameworks	Connects quantum science, biology, computation, and engineering design	**High**
Pedagogical Tools	Develop simulations and laboratory modules for quantum effects	Converts abstract quantum mechanisms into measurable engineering learning activities	**High**
Terminology Standardization	Establish consensus definitions and taxonomies	Reduces ambiguity in interdisciplinary engineering communication	**Medium**
Empirical Expansion	Validate quantum effects across organisms	Determines whether observed mechanisms can support broader technological applications	**High**
Quantum Simulation in Education	Integrate quantum computing modules	Develops computational skills relevant to molecular engineering and Biotechnology 4.0	**Medium**
Translational Research	Link quantum biology to biotechnology and medicine	Accelerates conversion of biological mechanisms into functional technologies	**Medium**
Methodological Standardization	Develop unified protocols and meta-analyses	Improves reproducibility, benchmarking, and engineering validation	**Medium**
Coherence Quantification	Measure coherence efficiency in photosynthesis	Clarifies the functional contribution of coherence for engineered energy-transfer systems	**Medium**
Ethics in Quantum Biology	Address societal and ethical impacts	Supports responsible development and deployment of emerging quantum-biological technologies	**Low**

6. Conclusion

The source reports 314 candidate records and 50 shortlisted publications, of which 49 are tabulated, 48 are unique and 44 fall inside the stated 2018–2024 window. The analysis is restricted to these tabulated records, and the unidentified fiftieth study is excluded from all counts. Experiments on photosynthetic energy transfer and strong coupling offer physical design hypotheses for energy-conversion systems. The functional role of long-lived coherence, however, remains disputed. These observations do not establish improved photovoltaic efficiency, output energy or carbon savings. The review itself presents no original design, model or prototype result. The revised engineering contribution is a sequence of measurable gates from mechanistic spectroscopy through transport modelling to controlled prototype testing, aligned with established photovoltaic characterisation.

For a future prototype, the preferred architecture is a pigment-based absorber in an optical microcavity. Its technically justified control is an otherwise identical device with the cavity detuned or omitted, so that the optical environment is the only variable. The primary acceptance outcome should be the absolute PCE difference from this matched control. This outcome should be supported by EQE, output-power variation, retained performance after ageing and a documented cost

comparison. The target threshold is a difference whose 95% confidence interval excludes zero and whose magnitude exceeds the minimum detectable difference set by the measured device scatter and sample size. Feasibility further requires that the stability and cost criteria are met under the same conditions. Each result needs a physical boundary, operating condition and uncertainty interval, so that engineers can reject a promising molecular mechanism when it fails to improve useful system output.

The evidence base is defined as the 48 unique tabulated studies, of which four are flagged as outside the stated window. The 2018–2024 search period and the later references are reconciled by flagging rather than deletion, because the original screening decisions cannot be recovered. The online-first dates of the 2025-dated entries remain to be confirmed against publisher records. A complete search log, with database-specific strings and execution dates, was not archived with the source manuscript and was not reconstructed, so the review does not claim PRISMA-level reproducibility. Any future pooled analysis requires comparable endpoints and complete study-level estimates. Until those conditions are met, the practical impact is a testable energy-device development protocol rather than a quantified efficiency gain. Future work should therefore prioritise prototype fabrication and matched-control testing before any broader translation claim is made.

Author contributions

1. Hadi Suwono: Conceptualized the study, developed the research framework, undertook the literature review, and contributed to the writing and editing of the manuscript. Spearheaded the analysis of empirical studies and integration of findings into educational implications. **2. Marsya Aulia Rizkita:** Assisted in conducting the literature review and analyzed educational strategies for integrating quantum science into STEM curricula. Contributed to drafting the pedagogy and curriculum design sections, and helped refine the manuscript for clarity and coherence. **3. Chun-Yen Chang:** Participated in the critical literature analysis and provided expertise in earth sciences relevant to quantum biology. Aided in synthesizing findings related to interdisciplinary connections and reviewed the manuscript for scientific accuracy and comprehensiveness. All authors have read and approved the final manuscript.

Funding

The State University of Malang funded this research. The funding body had no involvement in the study's design, data collection, analysis, interpretation, or the decision to publish this article. Contract Number: 14.04.224/UN32.14.1/LT/2026.

Acknowledgements

The authors would like to sincerely thank the State University of Malang for the continuous academic and institutional support provided throughout the research process.

Conflicts of Interest

The authors declare that they have no conflicts of interest. The funders had no role in this manuscript's design, analysis, interpretation, or writing.

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