Clean Energy and Sustainability

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Review

Renewable Energy Systems and Indoor Environmental Quality: A Systematic Review of Co-Benefits, Trade-Offs, Feedback Loops and Evidence Gaps

Emmanuel Chongcicimmi Ibrahim [1,*], Andrew Mhya Stanley [2], Lekan Amusan [1], Paul Pate Isaac [1] and Edidiong Sunday Sam [3]

[1] Department of Building, Covenant University, Ota 112104, Nigeria; lekan.amusan@covenantuniversity.edu.ng (L.A.); paul.isaac@covenantuniversity.edu.ng (P.P.I.)
[2] Department of Building, Ahmadu Bello University, Zaria 810211, Nigeria; amstanley@abu.edu.ng (A.M.S.)
[3] Department of Chemistry, Covenant University, Ota 112104, Nigeria; edidiong.sam@covenantuniversity.edu.ng (E.S.S.)

* Corresponding author. E-mail: emmanuel.ibrahim@covenantuniversity.edu.ng (E.C.I.)

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ABSTRACT: Integrating renewable energy systems (RES) into buildings changes envelopes, airflow paths and control logic, yet indoor environmental quality (IEQ) is rarely assessed alongside energy and carbon performance. A systematic review was conducted using Scopus (n = 1200) and Web of Science (n = 890), covering literature published between 2016 and 2026 and yielding 50 studies. Most studies focused on thermal comfort (41), followed by air quality (21) and visual comfort (15). None assessed acoustics, particulate matter, or volatile organic compounds (VOCs). Evidence came primarily from simulated data (26 studies, 52%) and was geographically concentrated, with 88% of studies originating from four regions and only five studies (10%) covering hot-humid climates. Twenty-one studies reported co-benefits, 11 reported trade-offs, and 18 reported no relationship between IEQ and energy. Trade-offs were classified under four feedback loops, namely ventilation–hygrothermal, solar control–visual–thermal–lighting, seasonal thermal asymmetry, and economic–life-cycle. Studies reporting energy rarely measured IEQ, while studies measuring IEQ rarely reported energy. Co-benefits were also reported most frequently in the lowest-scoring categories, including hybrid and smart-control systems. The findings indicate insufficient evidence to support RES-based building decarbonization while maintaining acceptable indoor environmental conditions alongside energy and carbon performance. This study provides an input–process–output framework, a feedback-loop typology incorporating testable decoupling pathways and an evidence gap map. Future research should combine IEQ measurements with metered energy and calculated carbon emissions, particularly in tropical and low-income contexts, to support evidence-based building design, operation and policymaking.

Keywords: Indoor environmental quality; Renewable energy systems; Building-integrated photovoltaics; Solar chimney; Windcatcher; Feedback loops; Trade-offs; Occupant comfort

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1. Introduction

The integration of renewable energy systems (RES) into buildings is necessary for reducing operational energy consumption and carbon emissions. Globally, buildings and construction account for a substantial proportion of energy demand and carbon emissions, making building decarbonisation a priority for climate change mitigation [1,2]. However, energy and carbon performance alone cannot establish environmental sustainability, as building interventions can influence indoor environmental quality (IEQ), occupant comfort and wellbeing [3,4]. IEQ encompasses thermal comfort, indoor air quality, visual comfort and acoustic comfort. These conditions influence occupant satisfaction and productivity [5,6], while poor indoor air quality in schools has been linked to ill health in Europe [7]. The importance of energy performance is also evident in residential buildings, where appliance use and occupant behaviour influence energy demand and associated emissions [8,9]. Consequently, RES integration requires decarbonisation while maintaining acceptable indoor environmental conditions.

RES technologies can alter building envelopes, solar gains, ventilation pathways and indoor conditions. Photovoltaic (PV) shading and building-integrated photovoltaic (BIPV) façades influence solar gains and lighting requirements, while windcatchers, solar chimneys and earth-to-air heat exchangers affect ventilation, temperature and humidity [10–12]. Although PV shading can provide energy and comfort benefits [13–16], these outcomes depend on climate and operating priorities. A windcatcher improved comfort through evaporative cooling in a hot climate but caused overventilation and increased heating requirements in a mild, cold climate [12]. Similarly, kinetic PV shading for glare control increased lighting and winter heating demands [17]. Furthermore, studies on residential retrofits have established that energy efficiency measures can adversely affect indoor air quality when ventilation is inadequate [18].

These interdependencies create an evaluation problem because assessing energy and carbon benefits separately from IEQ may overstate the overall environmental performance of RES-integrated buildings. A previous study [19] identified competing objectives involving energy consumption, thermal comfort, and indoor air quality, while research on green buildings has reported differences between designed and actual energy performance and occupant satisfaction [3]. Therefore, energy and carbon assessments need to consider multiple IEQ domains and the conditions under which interventions operate.

While previous reviews on IEQ and RES provide relevant insights, they offer limited examination of the interactions and interdependencies across all four IEQ domains: thermal comfort, visual comfort, acoustic comfort, and indoor air quality. Perera et al. [20] examined IEQ guidelines and energy codes, while Irfeey et al. [21] focused on solar-powered approaches to thermal comfort. Nyembwe et al. [22] highlighted the limited research on indoor climatic conditions in tropical hospitals. In related work, Ibrahim et al. [4] reviewed IEQ intervention strategies, whereas Ibrahim et al. [8] and Isaac et al. [9] investigated energy consumption in residential buildings and household carbon emissions, respectively. Despite these contributions, an integrated assessment of active, passive, hybrid, and control-based RES across multiple IEQ domains, energy consumption, carbon emissions, and economic outcomes remains lacking. In particular, the influence of RES on IEQ, the reliability of existing evidence, and the applicability of findings to tropical climates and low-income settings have not been fully explored [23].

There is still an existing gap in the literature regarding the integration of renewable energy systems (RES) and indoor environmental quality (IEQ) in buildings from cognitive and contextual perspectives. The available reviews have addressed either IEQ or energy performance or have concentrated on specific technologies. Very little insight has been gained into the interactions between various RES in terms of energy and carbon performance and multiple IEQ dimensions. In addition, the available evidence has not been critically assessed to determine the extent to which findings are supported by simulations or empirical measurements. These gaps highlight the need for a systematic review to integrate the sparsely available evidence, assess its quality, and define the boundaries of existing knowledge.

Therefore, this systematic review addresses these gaps through methodological quality appraisal and evidence synthesis in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement. It establishes an input–process–output framework to examine the relationships between RES and IEQ, feedback mechanisms, reported benefits and trade-offs, and gaps in the existing evidence. Accordingly, the review addresses five research questions (RQs):

RQ1: What RES technologies have been investigated using different research methods across various regions, climates and building types?

RQ2: How does the integration of RES affect thermal comfort, indoor air quality (IAQ), visual comfort and acoustic conditions?

RQ3: What is the relationship between energy, carbon, and economic outcomes and IEQ co-benefits and trade-offs?

RQ4: What trade-offs arise between feedback mechanisms, and what design and control strategies can avoid these trade-offs?

RQ5: What geographical, climatic, and methodological limitations constrain the evidence, especially in tropical climates, low-income contexts, and long-term monitoring?

By answering the aforementioned research questions, this study seeks to distinguish established co-benefits from conditional and conflicting benefits and provide evidence-based guidance to architects, building services engineers, renewable energy designers, facilities managers, policymakers and researchers in making informed decisions on building design, RES integration, energy management, decarbonisation strategies and IEQ performance, while safeguarding occupant wellbeing.

2. Conceptual Framework

Two ideas underpin the framework. The input–process–output view treats a building as a system in which mechanisms transform inputs into outputs. Causal-loop reasoning further recognises that outputs can feed back into inputs. A balancing loop offsets a change, such as increased ventilation improving air quality while removing heat, whereas a reinforcing loop amplifies a change, such as higher costs reducing uptake and slowing the cost-learning process that could otherwise reduce costs. Therefore, a linear intervention–outcome model is insufficient for RES because a single intervention can alter several conditions simultaneously, while the resulting outcomes can subsequently modify the conditions that triggered them.

The framework (Figure 1) treats a RES-integrated building as a system in which mechanisms transform inputs into outputs, with outputs also feeding back into inputs. Inputs comprise the RES configuration across seven classes: G1, PV; G2, wind-driven and solar-chimney ventilation; G3, coupled passive systems, such as solar chimneys or windcatchers combined with earth–air heat exchangers (EAHEs); G4, solar thermal; G5, geothermal, heat pump and net-zero energy building (NZEB) systems; G6, hybrid PV-thermal (PV/T), thermoelectric (TE) and air-treatment systems; and G7, smart control with PV. These inputs also include design and operating parameters, as well as contextual factors such as climate, building type, region and season.

Four mechanisms act on these inputs: solar and envelope modulation, airflow and ventilation exchange, thermal conditioning and energy conversion, and control and optimisation logic. The resulting outputs comprise IEQ performance across thermal comfort, indoor air quality, visual comfort and acoustic comfort, alongside energy and carbon performance, and economic and life-cycle performance.

Feedback comprises three balancing loops, namely ventilation–hygrothermal, solar control–visual–thermal–lighting and seasonal thermal asymmetry, and one reinforcing loop, namely economic–life-cycle. It also includes decoupling pathways that weaken the relationship between an IEQ gain and its associated penalty, as well as an evidence loop in which monitoring validates design models. These loops are conceptual hypotheses that organise the evidence rather than empirically validated models.

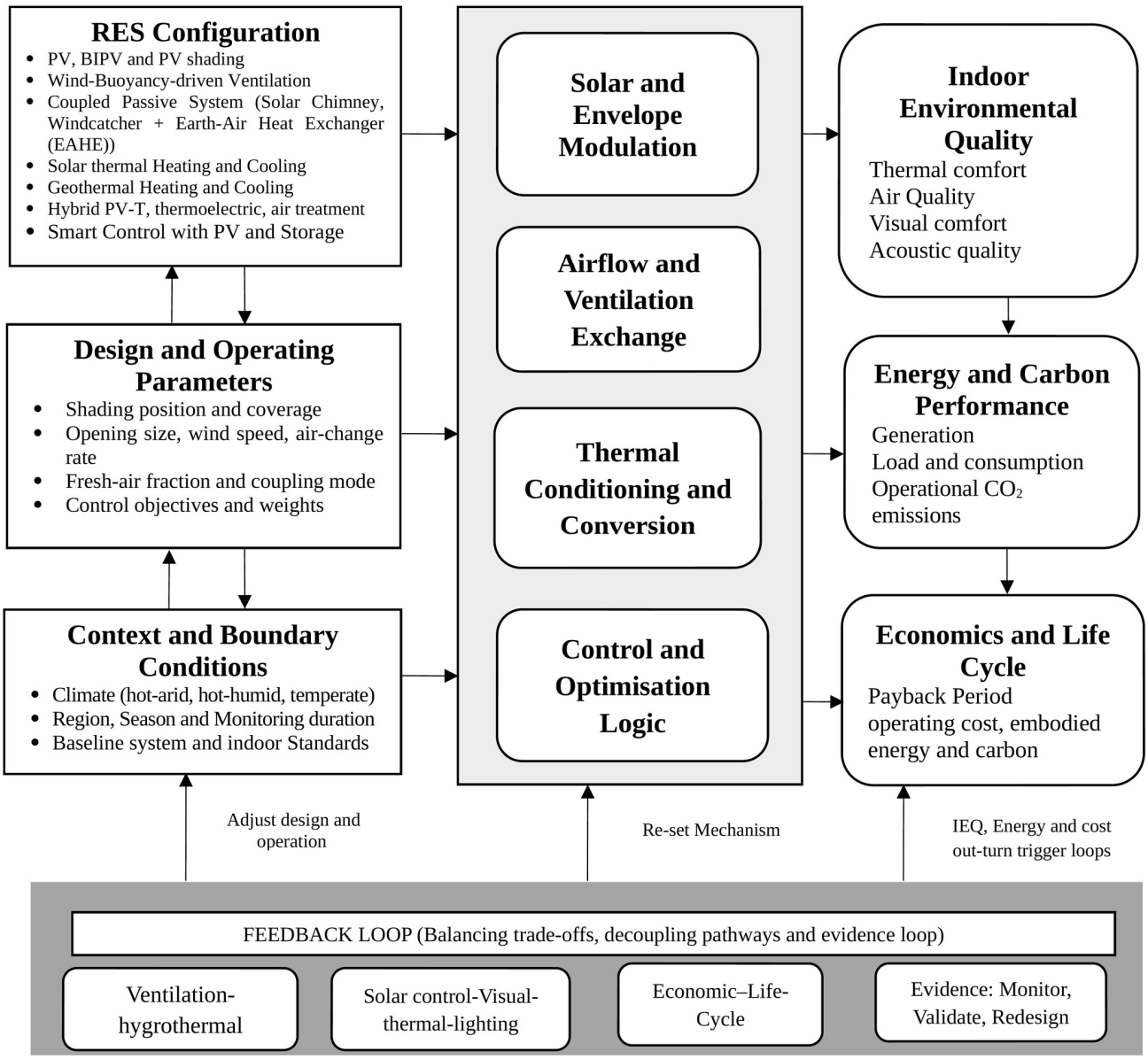

Figure 1. Conceptual framework: inputs, process mechanisms, outputs and feedback loops.

3. Methodology

3.1. Research Design and Reporting

This review followed PRISMA 2020 [24], informed by Nyembwe et al. [22], to identify, appraise and synthesise evidence on RES and IEQ in buildings. Evidence mapping and narrative synthesis were used instead of meta-analysis to show where evidence exists, how strong it is, and whether IEQ and energy outcomes are examined together. Meta-analysis was not considered appropriate because the included studies differed substantially in research design, indicators, and baseline conditions. The protocol was not preregistered. Reporting followed the Synthesis Without Meta-analysis (SWiM) guideline [25], with studies grouped by RES class and research method and presented as counts and percentages.

3.2. Information Sources and Search Strategy

Scopus and Web of Science (WoS) databases were searched on 9 September 2026, yielding 1200 and 890 records, respectively, with a combined total of 2090 records. The search strategy combined three concept groups, namely IEQ, RES, and buildings, using the Boolean operator AND, while terms within

each group were connected using OR. This ensured that each retrieved record addressed all three concepts. The same search string was applied to both databases.

Search string (identical in both databases):

("indoor environmental quality" OR "thermal comfort" OR "indoor air quality" OR "visual comfort" OR daylight OR "acoustic comfort") AND ("renewable energy" OR BIPV OR "PV shading" OR "solar chimney" OR windcatcher OR "wind tower" OR "earth-air heat exchanger" OR "solar thermal" OR geothermal OR "heat pump" OR "PV/T") AND building.

3.3. Eligibility Criteria

Table 1 presents the eligibility criteria. Eligible studies comprised peer-reviewed, English-language journal articles published between 2016 and 2026 that examined building- or room-scale RES and reported at least one quantified IEQ indicator derived from experimental, field, simulation, or hybrid research. This requirement enabled the comparison of IEQ outcomes with corresponding energy outcomes across the included studies.

Table 1. Eligibility criteria, the framework construct each protects, and the records excluded at each criterion.

Domain	Inclusion Criterion	Exclusion Criterion
Duplication	Unique record	Duplicate across or within databases
Document type, language, period	Peer-reviewed journal article; English; 2016–2026	Conference paper, book chapter, editorial; non-English; before 2016
Setting and scale	Building or room scale, including test rooms and rigs	Urban, district, vehicle, agricultural, data-centre or outdoor-comfort studies
Intervention	RES (active or passive renewable-driven) is the studied intervention	No building-scale RES component; RES only as context, or component or material level
Outcome	At least one quantified IEQ indicator (thermal, air, visual, acoustic)	Energy-only or system-efficiency outcomes; no IEQ indicator at full text
Study design	Primary experimental, field, simulation or hybrid study with described boundary conditions	Review, commentary, protocol; model or experiment insufficiently described; conceptual or no primary data or model
Independence	One report per dataset or system; most complete or most recent retained	Redundant report of an included study
Indexing	Journal indexed in Scopus or Web of Science Core Collection	Indexing not confirmed
Availability	Full text retrievable	Full text not retrieved

3.4. Screening and Selection

The search yielded 2090 records, comprising 1200 from Scopus and 890 from Web of Science. After removing 502 duplicates and 214 records based on document type, language, and publication date, 1374 records remained for title and abstract screening. Of these, 1062 were excluded because they did not concern building-scale RES (n = 436), did not report IEQ outcomes (n = 389), had an ineligible research design (n = 142), or fell outside the review scope (n = 95). The remaining 312 reports were assessed for retrieval, of which 303 were retrieved, and nine could not be obtained. Following full-text assessment, 253 reports were excluded for the reasons presented in Table 1 and Figure 2, leaving 50 studies for inclusion in the review. Three reviewers independently screened the records, extracted the data, and appraised methodological quality. Disagreements were resolved through discussion with the supervising authors.

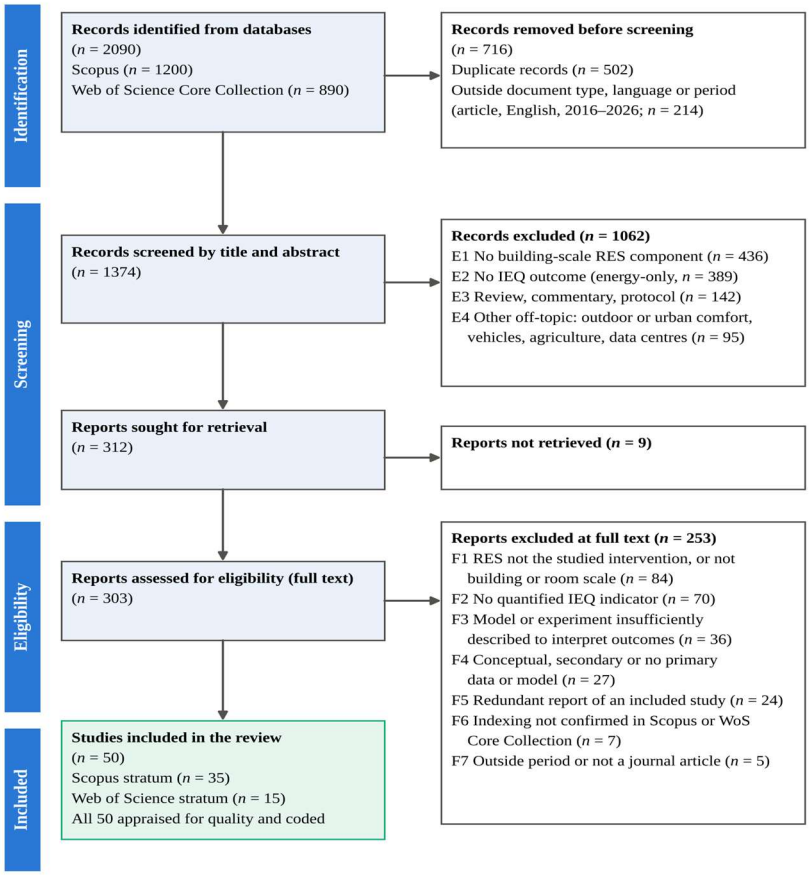

Figure 2. PRISMA 2020 flow diagram of identification, screening, eligibility, and inclusion.

3.5. Data Extraction, Quality Appraisal and Synthesis

Data were compiled in a review matrix (Table 2) comprising the following fields: RES class, country, climate, building type, research method (measured, hybrid or simulated), IEQ domains, key outcomes, IEQ–energy relationship, and energy, carbon and economic indicators. Key outcomes were recorded using the indicators reported by the authors, such as the predicted mean vote (PMV), predicted percentage of dissatisfied (PPD) and adaptive PMV (APMV) for thermal comfort; carbon dioxide (CO_2) concentration and relative humidity (RH) for air quality and moisture; and computational fluid dynamics (CFD) results for airflow and ventilation.

Methodological quality appraisal (QA) was performed using eight items, with one point assigned to each: reporting of location, climate and building type (three items); empirical approach; assessment of two or more IEQ domains; reporting of an energy, carbon or cost outcome; explicit examination of the IEQ–energy relationship; and reporting of a numerical outcome metric. Scores of 0–3, 4–5 and 6–8 were classified as low, moderate and high quality, respectively. No study was excluded based on its quality score. Each IEQ–energy relationship was classified according to the authors' reported findings as a co-benefit, where both IEQ and an energy, carbon, or cost indicator improved; a trade-off, where a gain in one outcome was accompanied by a loss in the other, in another IEQ domain or in another season; or not reported (NR).

Unless otherwise stated, percentages were calculated using the 50 included studies as the denominator. A sensitivity analysis excluding the four low-quality studies was conducted to examine whether the identified relationships depended on their inclusion. Percentages by research method and RES class, as well as the comparisons presented in Section 4, were descriptive and calculated from the data in Table 2. No statistical significance tests were applied.

Table 2. Review matrix of the included studies (n = 50), ordered by RES class and year.

No.	References	Country/Region	Climate	Building	RES Class	Method	IEQ Domains	Key Outcome Reported in the Record	IEQ–Energy Relation	Stratum	QA
1	Elghamry et al. [26]	Egypt	Hot-arid	NS	G1	Simulated	Thermal, Visual	Simulated envelope-integrated panels: generation, energy, comfort, lighting, and CO_2.	Lighting trade-off	WoS	5
2	Pandiaraj et al. [27]	India (Tamil Nadu)	Hot-humid	Test room	G1	Hybrid	Thermal, Air	Building-applied PV (BAPV) measured and simulated in working rooms: temperature, RH, and CO_2.	Humidity trade-off	Scopus	6
3	Bhuvad and Udayraj [14]	India (multiple climate zones)	Multiple	NS	G1	Hybrid	Thermal	Rooftop PV shading cut cooling loads but raised winter heating loads.	Trade-off	WoS	5
4	Abdalazeem et al. [13]	Egypt	Hot steppe-arid (Köppen–Geiger BSh)	Test room	G1	Measured	Thermal	PV and green-roof tests: lower cooling energy and CO_2 emissions.	Co-benefit	WoS	6
5	Chen and Tang [28]	China (Jinan)	Warm-temperate, semi-humid	Office	G1	Simulated	Visual	Façade optimisation of daylight, view quality, solar radiation and PV generation.	Trade-off	Scopus	5
6	Fu et al. [29]	China (multiple climate zones)	Multiple	NS	G1	Hybrid	Thermal	Validated BIPV façade model: generation, heat gain, and heat dissipation by climate zone.	NR	Scopus	4
7	C. Wang et al. [16]	Hong Kong, China	NR	Office	G1	Hybrid	Thermal, Visual	PV/T shading device improved comfort time, daylight, and glare autonomy.	Co-benefit	WoS	5
8	Hao et al. [30]	China (three regions)	Multiple	Educational	G1	Simulated	Thermal, Visual	PV shading with vertical farming improved daylight in Shenzhen; summer comfort varied in Shanghai.	Trade-off	Scopus	5
9	Miraba et al. [31]	Iran (Tehran)	Hot-arid	Office	G1	Simulated	Visual	Adaptive BIPV shading cut energy use, raised net generation, and reduced glare.	Co-benefit	WoS	5
10	M. Wang et al. [32]	Hong Kong, China	Hot-humid	Residential	G1	Simulated	Visual	Machine-learning PV shading control cut energy use and glare; payback ≥ 8 years.	Trade-off	WoS	6
11	Roshan Kharrat et al. [33]	Italy	Multiple	NS	G1	Simulated	Thermal, Visual	Six dynamic PV shading designs raised output and improved glare control.	Co-benefit	Scopus	5
12	Zhao and Gou [34]	Wuhan, China	NR	Office	G1	Simulated	Visual	Semi-transparent BIPV windows generated 5508.86 kWh/year and improved glare autonomy.	Co-benefit	Scopus	5
13	Chen et al. [35]	China	NR	Educational	G1	Simulated	Thermal, Visual	BIPV optimisation cut CO_2 and kept comfort; payback 9.36 years.	Co-benefit	WoS	6
14	Abu Qadourah et al. [36]	Amman, Jordan	Mediterranean	Multi-family residential	G1	Simulated	Thermal	Semi-transparent PV overhangs: high operating savings, longer life-cycle payback.	Trade-off	Scopus	5

15	Liu et al. [37]	China (Shenzhen)	Hot-humid	Office	G1	Simulated	Visual	Surrogate optimisation of PV generation, energy, daylight and glare probability.	NR	WoS	4
16	Ghidini et al. [17]	Germany, Egypt, United Arab Emirates (UAE)	Multiple	Office	G1	Simulated	Visual	Thin-film PV shading cuts solar gain; glare priority raised lighting and winter heating.	Trade-off	Scopus	5
17	Lv et al. [38]	China (multiple climate zones)	Multiple	Office	G1	Simulated	Visual	Multi-objective optimisation of semi-transparent PV walls: energy, daylight, economics.	NR	Scopus	4
18	Abdallah [39]	Assiut, Egypt	Hot-arid	Residential	G2	Measured	Thermal, Air	Solar chimney with cooling tower lowered temperature and RH and improved CO_2.	NR	Scopus	5
19	Abdallah [40]	Assiut, Egypt	Hot-arid	Residential	G2	Measured	Thermal, Air	Solar chimney with cooling wind tower: outlet air 27.3 °C, acceptable PMV, low daytime CO_2.	NR	Scopus	5
20	Nejat et al. [15]	Qatar	NR	NS	G2	Hybrid	Thermal, Air	Windcatcher cooling: adaptive comfort in part of the space; 9.6 kW cooling capacity.	NR	Scopus	5
21	Saif et al. [10]	Kuwait	Hot-arid	Educational	G2	Simulated	Thermal, Air	Evaporative windcatcher increased comfortable and CO_2-compliant hours; RH rose.	Trade-off	Scopus	5
22	Chohan et al. [41]	UAE	Hot-arid	Public / heritage	G2	Hybrid	Thermal, Air	Windcatcher kept indoor temperatures below 35 °C in peak summer with pollutant reduction.	Co-benefit	Scopus	6
23	Liu et al. [12]	Nottingham, United Kingdom	Mild-cold	Educational	G2	Hybrid	Thermal, Air	Measurements and CFD: high wind speed caused overventilation, heat loss, and higher heating demand.	Trade-off	WoS	7
24	Nejat et al. [42]	Western Europe (15 capitals)	Mediterranean, Temperate	Educational	G2	Simulated	Thermal, Air	CFD: windcatchers met adaptive comfort and outdoor-air requirements in most cities.	NR	WoS	4
25	Lekhal et al. [43]	Oran, Algeria	Mediterranean	Residential	G3	Hybrid	Thermal	A direct solar floor with EAHE provided comfort for up to 84% of hours in a validated model.	NR	Scopus	4
26	Serageldin et al. [44]	Egypt	Hot-arid	Residential	G3	Hybrid	Thermal, Air	Solar chimney–EAHE cooled zones under passive or hybrid operation, saving energy.	Co-benefit	Scopus	7
27	Sakhri et al. [45]	Béchar, Algeria	Hot-arid	Test room	G3	Measured	Thermal	Full-scale test room with windcatcher, solar chimney and EAHE: temperature and humidity.	NR	Scopus	4
28	Pouranian et al. [46]	Iran	Hot-arid	Indoor pool	G3	Hybrid	Thermal, Air	Solar chimney–EAHE raised air changes and improved air quality and humidity removal.	NR	WoS	5
29	Li et al. [11]	Chongqing, China	NR	Test rig	G3	Measured	Thermal, Air	Solar chimney–EAHE cut outlet air temperature by up to 12.5 °C; 24-h ventilation.	NR	Scopus	4
30	Sakhri et al. [47]	Algeria	Hot-dry	Residential	G3	Measured	Thermal	EAHE and solar chimney experiments: thermal comfort and energy-saving potential.	Co-benefit	Scopus	6

31	Long et al. [48]	Chongqing, China	Multiple/NR	NS	G3	Simulated	Thermal, Air	Coupled solar chimney–EAHE cooled in summer, warmed in winter; 260–280 m^3/h.	NR	Scopus	3
32	Sakhri et al. [49]	Béchar, Algeria	Hot-arid	Test room	G3	Measured	Thermal	Wind tower with EAHE met ~50% of comfort requirements in a test chamber.	NR	Scopus	4
33	Alkaragoly et al. [50]	Algeria	Hot & moderate	Residential	G3	Simulated	Thermal	Solar chimney, PV and underground space: thermal comfort and energy reduction.	Co-benefit	Scopus	5
34	Zhang et al. [51]	China	Multiple	NS	G3	Simulated	Thermal, Air	CFD of coupled solar chimney–EAHE: spatial performance, ventilation and cooling.	NR	Scopus	3
35	Kazeoui et al. [52]	Algeria	Hot-arid	Residential	G4	Simulated	Thermal	Direct solar floor: heating-load savings and PMV/PPD in two dwelling types.	Co-benefit	Scopus	5
36	Agathokleous et al. [53]	Germany, Italy, Spain	Multiple	Office	G4	Hybrid	Thermal	Façade solar air collectors: comfort, energy and economics in three climates.	NR	WoS	5
37	Mehdaoui et al. [54]	Tunisia	Mediterranean	Residential	G4	Measured	Thermal	Solar floor and wall heating raised temperatures and cut RH in North Africa.	NR	Scopus	4
38	Noferesti et al. [55]	Chabahar, Iran	Hot-arid	Office	G4	Simulated	Thermal, Air	Year-long simulation of solar absorption cooling improved temperature and cut power use.	Co-benefit	WoS	6
39	Zhai et al. [56]	Tibet, China	Cold	Residential	G4	Measured	Thermal	Passive solar house with active heating improved PMV/PPD, cut CO_2; short payback.	Co-benefit	Scopus	6
40	Tanasa et al. [57]	Romania	Temperate	Residential	G5	Measured	Thermal	NZEB with heat pump and PV cut primary energy; comfort categories I–II >93% of year; August overheating.	Trade-off	Scopus	6
41	Mastellone et al. [58]	Athens, Greece	Mediterranean	Educational	G5	Hybrid	Thermal, Air, Visual	Retrofit cut primary energy and CO_2 and improved thermal, air, and visual comfort.	Co-benefit	Scopus	7
42	Darwiche et al. [59]	Lebanon	Mediterranean	NS	G5	Simulated	Thermal, Air	Geothermal all-air HVAC saved 67% energy at 100% fresh air and cut CO_2.	Co-benefit	Scopus	6
43	Llanos-Jiménez et al. [60]	Southern Spain	Mediterranean	Educational	G5	Hybrid	Thermal, Air	Validated model compared PV-powered ventilation and evaporative cooling: energy, comfort, IAQ.	NR	Scopus	6
44	Shen and Yang [61]	Hong Kong, China	Hot-humid	Example room	G6	Simulated	Air	Solar-driven CO_2 capture held CO_2 < 800 ppm and cut cooling energy by 38.18%.	Co-benefit	WoS	6
45	S. Wang et al. [62]	Study location NR	NR	Residential	G6	Simulated	Thermal, Air	PV–thermoelectric–ventilation–desiccant system cuts energy and CO_2 with humidity and IAQ control.	Co-benefit	Scopus	4
46	Feng et al. [63]	Study location NR	NR	NS	G6	Simulated	Thermal	PV–thermoelectric system with EAHE met HVAC demand from RES and cut CO_2.	Co-benefit	Scopus	2

47	Zhao et al. [64]	Xi'an, China	NR	Residential	G6	Simulated	Thermal	PV/T–EAHE optimisation cut net energy, raised PV efficiency, and improved APMV.	Co-benefit	Scopus	4
48	Tarragona et al. [65]	Terrassa, Spain	NR	NS	G7	Simulated	Air	Model predictive control managed IAQ and cost within CO_2 limits (winter simulation).	Co-benefit	Scopus	3
49	Ma and Liu [66]	Study location NR	NR	Office	G7	Hybrid	Thermal, Air, Visual	Deep reinforcement learning with Internet of Things (IoT) cut energy use and improved a composite IEQ index.	Co-benefit	WoS	5
50	Esfehankalateh et al. [67]	Ramsar, Iran	Hot-humid	Office	G7	Simulated	Thermal, Visual	Two-stage optimisation of façade adaptation and RES: thermal and visual comfort in a net-zero office.	NR	Scopus	4

Note: RES classes G1–G7 as defined in Section 2. NS = not stated; NR = not reported; WoS = Web of Science stratum; QA = quality score (0–8). Relation labels are as extracted; "Lighting trade-off" and "Humidity trade-off" are classed as trade-offs in the analysis.

4. Results and Discussion

4.1. Characteristics and Quality of the Included Studies

The 50 studies span 2016–2026 (Figure 3), with 28 (56%) published in 2024–2026, including 14 of the 17 PV and shading studies (82%). Twenty-six studies (52%) were simulation-based, 14 (28%) hybrid and 10 (20%) measured, indicating that 24 (48%) had an empirical component.

Quality scores averaged 4.9 out of 8 (median = 5): 15 studies (30%) were rated high quality, 31 (62%) moderate quality, and four (8%) low quality (Figure 4). The main weaknesses were the absence of numerical outcome metrics (44 studies, 88%), the lack of an empirical component (26 studies, 52%), and the assessment of fewer than two IEQ domains (25 studies, 50%).

Removing the four low-quality studies left the 11 trade-offs unchanged, while co-benefits decreased from 21 to 19 and studies reporting no relationship decreased from 18 to 16. Thus, the main patterns did not depend on the weakest studies.

Recent growth is concentrated in simulated PV and shading optimisation. If this trend continues, modelled predictions will probably accumulate faster than field validation.

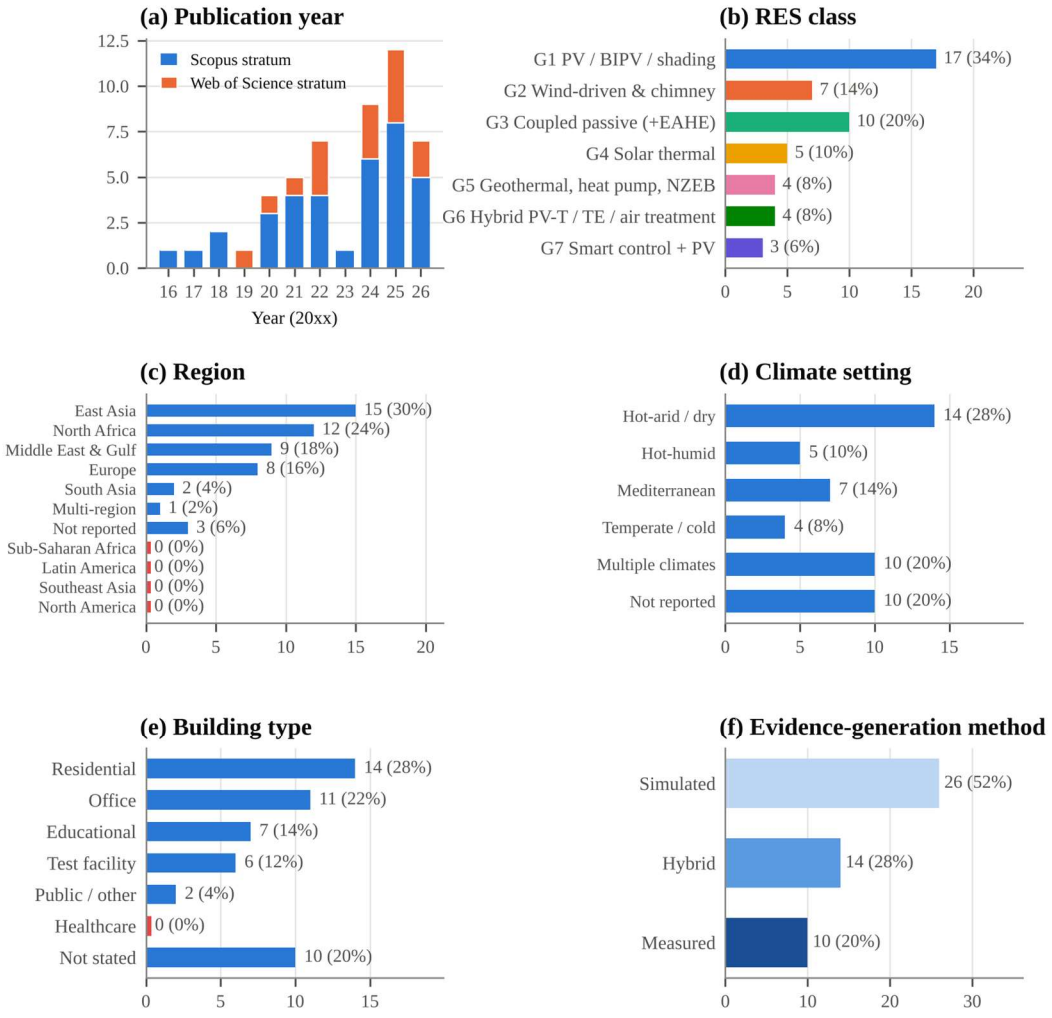

Figure 3. Evidence profile: (**a**) year and stratum; (**b**) RES class; (**c**) region; (**d**) climate; (**e**) building; (**f**) method.

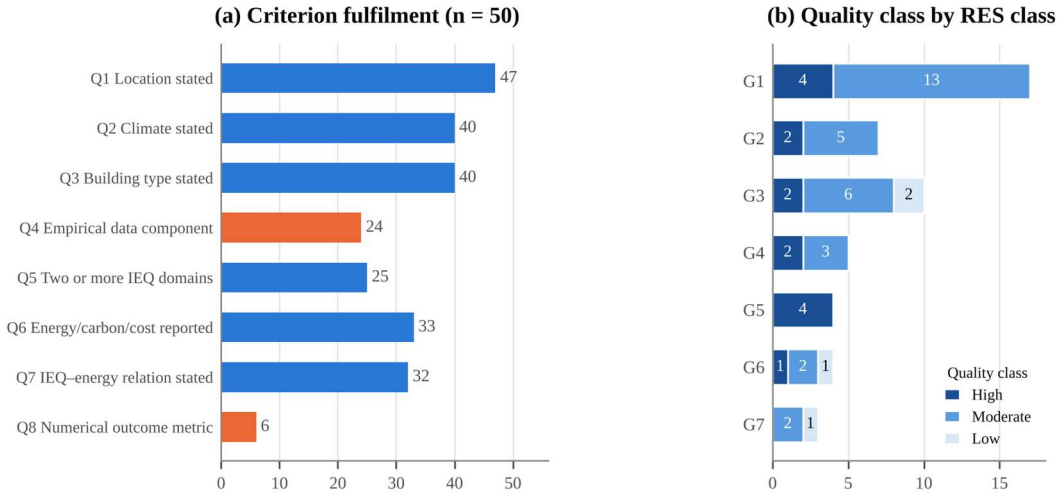

Figure 4. Quality appraisal: (**a**) studies meeting each checklist item; (**b**) quality class by RES class. In (**a**), blue bars indicate checklist items met by at least half of the included studies and orange bars indicate items met by fewer than half (Q4 and Q8). In (**b**), dark, medium and light blue denote high (6–8), moderate (4–5) and low (0–3) quality scores, respectively.

4.2. Input Constructs: RES Configuration, Design and Operating Parameters, and Context

4.2.1. RES Configuration

The majority of studies focus on two groups: envelope-integrated PV (17 studies) and passive or coupled passive ventilation (17 studies: seven in G2 and ten in G3), which together account for 68% of the included studies (Figure 3b). Other technologies, such as geothermal heating, ventilation and air-conditioning (HVAC) [59] and heat pumps [57], are each covered by a single study. This indicates that technology development is concentrated on technologies that are more visible or easier to model, while heat pumps, as a key decarbonisation measure, have limited IEQ examples. The available evidence documents the IEQ implications of PV and passive ventilation systems but provides a limited basis for comparison with geothermal HVAC and geothermal heat pumps. Thus, the IEQ effectiveness of some key RES options remains insufficiently established.

4.2.2. Design and Operating Parameters

Only a few studies investigate changes in operating conditions that lead to co-benefits or trade-offs, such as the influence of wind speed on co-benefits [12], the fresh-air fraction in renewable preconditioning [59], passive or hybrid operation [44], and glare priority in dynamic shading [17]. If these parameters are not systematically varied, the evidence remains insufficient to indicate when benefits occur or when they are reversed. This limits the ability to determine the operating conditions under which RES can enhance IEQ without adversely affecting energy performance. It also restricts building professionals' flexibility in selecting appropriate system settings for different buildings and climates.

4.2.3. Context and Boundary Conditions

Evidence has limited transferability between regions. East Asia (15 studies), North Africa (12), the Middle East and Gulf (nine), and Europe (eight) account for 88% of the studies. Two studies come from South Asia, one is multiregional, and three do not specify their locations. No studies originate from Sub-Saharan Africa, Latin America, Southeast Asia, North America, or Oceania. Hot-arid or dry conditions (14 studies) and hot-humid conditions (five studies) are also underrepresented in the climate coverage.

Additionally, empirical support differs by climate. Nine of the 14 hot-arid or dry studies (64%) used measured or hybrid methods, while only one of the five hot-humid studies used a hybrid method and the

remaining four were simulation-only. The findings demonstrate that evaporative windcatchers and building-applied photovoltaics (BAPV) can have humidity-related penalties when used to improve thermal comfort or PV generation [10,27]. Two of the five hot-humid studies (40%) report a trade-off: one reports a humidity penalty [27] and the other a long payback period [32], compared with 22% of all studies. However, five studies are insufficient to draw a definitive conclusion. This suggests a probable blind spot in humid climates, where moisture loads are highest.

The results suggest that the available evidence is concentrated in geographically and climatically distinct areas, limiting its applicability to other regions of the world. In particular, there are no studies from Sub-Saharan Africa to determine the performance of RES under the region's building and climatic conditions. The limited number of existing datasets for hot-humid climates also complicates the validation of simulated performance under actual indoor humidity conditions.

4.3. Process Mechanisms and IEQ Outputs

Figure 5 presents the 77 study-domain pairs linking RES classes to IEQ domains and their reported relationships with energy. PV studies primarily focus on visual and thermal effects, while passive systems focus on thermal comfort and air quality (Table 3). Of these, 41 studies (82%) consider aspects of thermal comfort, 21 studies (42%) consider aspects of air quality, and 15 studies (30%) consider aspects of visual comfort (Figure 6). Only 25 studies (50%) assess two or more IEQ domains, and only two studies assess all three IEQ domains [58,66]. An improvement in one domain does not necessarily reflect an overall IEQ gain.

The results indicate that the evidence linking RES to thermal comfort is stronger than the evidence linking RES to air quality and visual comfort. The available evidence does not allow for determining whether an improvement in one IEQ dimension can be achieved without negatively affecting the other dimensions. As a result, the overall IEQ performance of RES remains insufficiently substantiated by the reviewed studies.

Table 3. Appraisal of IEQ evidence by RES class.

RES Class (*n*)	Domains T/A/V	Method M/H/S	Relation	QA	Principal Limitation
G1 PV, BIPV, shading (17)	10/1/12	1/4/12	6/8/3	5.1	12 of 17 simulated; 8 document trade-offs; air quality in one study
G2 Wind-driven, chimney (7)	7/7/0	2/3/2	1/2/4	5.3	Humidity rise and winter heat loss; airflow used as air-quality proxy
G3 Coupled passive (10)	10/5/0	4/3/3	3/0/7	4.5	Energy reported in 3 of 10; test-room scale; duct hygiene unexamined
G4 Solar thermal (5)	5/1/0	2/1/2	3/0/2	5.2	Thermal domain only in practice; heterogeneous baselines
G5 Geothermal, heat pump, NZEB (4)	4/3/1	1/2/1	2/1/1	6.3	Four studies; August overheating in the measured NZEB
G6 Hybrid PV-T, TE, air treatment (4)	3/2/0	0/0/4	4/0/0	4.0	All simulated; two without stated location
G7 Smart control + PV (3)	2/2/2	0/1/2	2/0/1	4.0	No measured evidence; author-defined objectives

Note: Domains T/A/V = thermal/air/visual studies; method M/H/S = measured/hybrid/simulated; relation = co-benefit/trade-off/not stated; QA = mean quality score (0–8). Domain counts overlap.

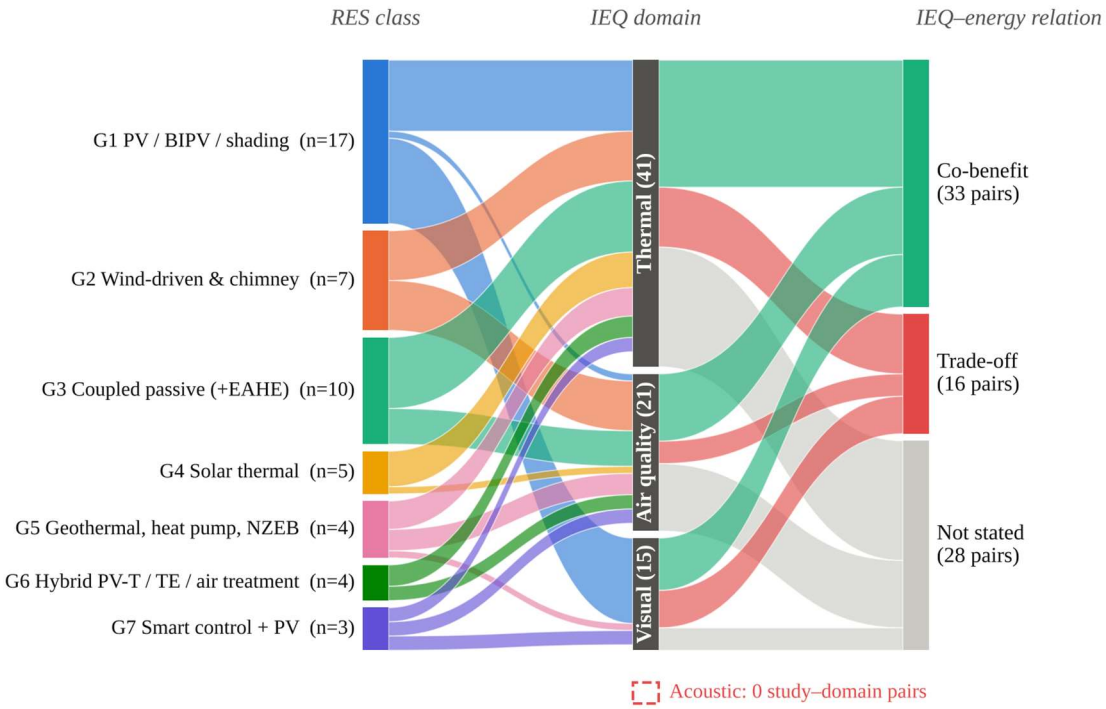

Figure 5. Flows of study–domain pairs (n = 77): RES class, IEQ domain, reported relation. Flow colours identify the RES class of origin; the relation nodes are green (co-benefit), red (trade-off) and grey (not stated). The red dashed box beneath the IEQ domain column is retained to show that no study–domain pair addressed acoustic comfort.

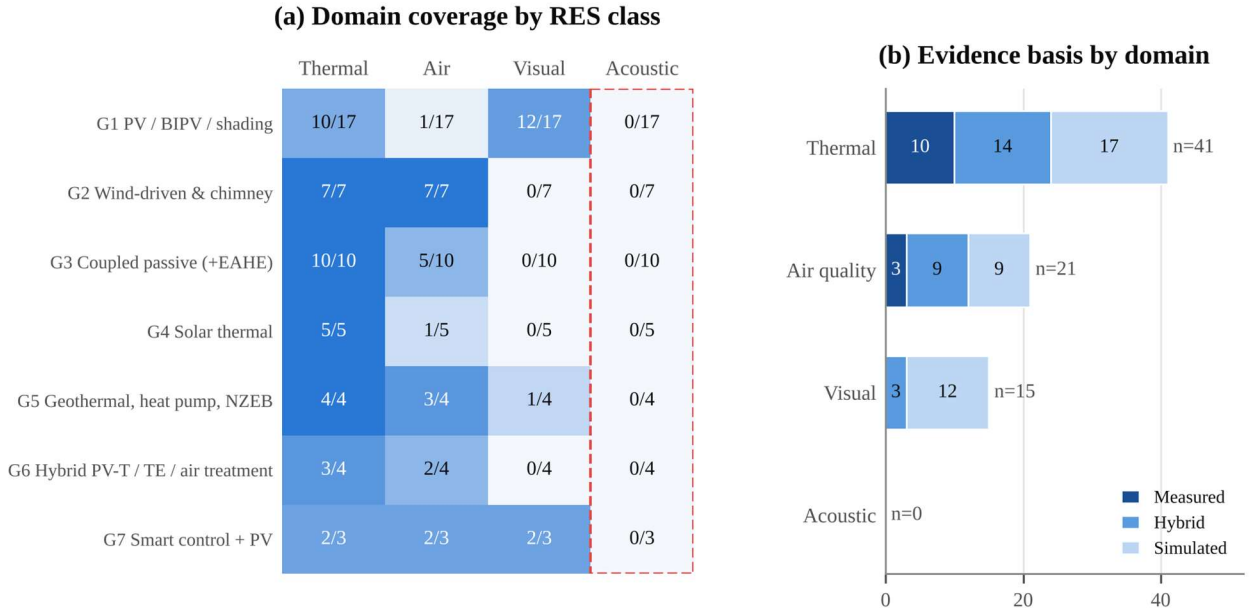

Figure 6. IEQ domain coverage: (**a**) studies per domain by RES class; (**b**) evidence basis of each domain. In (**a**), cell shading is proportional to the share of studies in each RES class that assessed a domain (darker blue = higher share), and the red dashed box highlights the acoustic domain, which none of the 50 studies assessed. In (**b**), dark, medium and light blue denote measured, hybrid and simulated studies, respectively.

4.3.1. Envelope Modulation by Solar Radiation (G1, G4)

PV shading has been shown to reduce cooling loads and increase heating loads in India [14]. Adaptive/dynamic PV shading was found to provide better daylight metrics related to daylighting and glare [16,31,33,34]. The studies in the G1 group, however, show that eight of the 17 studies reported a conflict

or an economic penalty, indicating that improved cooling performance does not necessarily result in overall energy benefits. Only one study on air quality [55] was identified among the five solar-thermal (G4) studies, while the remaining four studies focused on thermal comfort [52–54]. This focus on thermal comfort limits the evidence on the wider IEQ benefits of solar-thermal systems.

4.3.2. Airflow and Ventilation Exchange (G2, G3)

These classes have the strongest empirical support, with 12 of the 17 studies using measured or hybrid methods. During peak summer periods, windcatchers maintained indoor temperatures below 35 °C [41] and ensured adaptive comfort and outdoor-air requirements in most of the 15 European capital cities [42]. Even on the hottest summer days, the outlet air temperature of the solar chimney system coupled with the EAHE was reduced by up to 12.5 °C [11], while the combined direct solar floor and EAHE system was found to provide comfort for up to 84% of the hours in a validated model [43]. These results demonstrate the performance of passive cooling and ventilation systems. However, limitations are evident in the air quality evidence: nine of the 21 air-quality studies reported CO_2, while the others referred to ventilation, air changes or pollutant reduction without specifying the pollutants. The ventilation advantages of passive systems [40,42,46] therefore refer to ventilation adequacy rather than reduced exposure. Thus, adequate ventilation is not necessarily equivalent to reduced exposure to indoor air pollution (IAP).

4.3.3. Thermal Conditioning, Conversion and Control (G3–G7)

Darwiche et al. [59] demonstrated 67% annual energy savings from geothermal preconditioning, while Mastellone et al. [58] achieved improvements in energy use, CO_2 emissions, and thermal, air, and visual comfort through an integrated retrofit. All four G6 studies reported co-benefits, including CO_2 concentrations below 800 ppm and a 38.18% reduction in cooling energy [61]. These results illustrate the potential of integrated systems to provide multiple IEQ and energy benefits. However, the reported co-benefits from the G7 studies are restricted to the outcomes included in the authors' objective functions, as these studies do not measure IEQ but rather treat it as an optimisation target [65–67]. Therefore, the optimal results cannot be used to directly assess actual indoor environmental conditions.

4.3.4. Visual and Auditory Outcomes

Among the 15 visual-comfort studies, 12 were simulated, three were hybrid, and none was measured. This dependence on simulation also reduces the ability to verify the reported visual-comfort results in real building settings. None of the 50 studies reports acoustic outcomes, although openings, windcatchers and roof/façade equipment have the potential to affect sound. Without an acoustic assessment, the potential noise implications of these systems therefore remain unknown.

The findings indicate that each technology is evaluated primarily in relation to the IEQ domain or domains with which it has the most direct relationship, namely PV in relation to visual and thermal comfort, and ventilation in relation to thermal comfort and air quality. Therefore, a better outcome in one domain does not necessarily indicate a better outcome in other IEQ domains. For instance, PV shading systems that improve daylight are seldom evaluated for indoor air quality, while windcatchers that improve thermal comfort are not evaluated for noise. In addition, the co-benefits reported for G6 and G7 might reflect the outcomes that the authors chose to report rather than necessarily indicating the absence of trade-offs in other IEQ domains. The available evidence is therefore still inadequate to confirm the overall IEQ performance of integrated RES across different environmental domains.

4.4. Energy, Carbon and Economic Outputs

The reporting of energy, carbon and economic outcomes varies across the 50 studies. While 17 studies (34%) report none of these outcomes, eight (16%) report carbon emissions, seven (14%) report economic or life-cycle outcomes, and 30 (60%) report energy outcomes (Figure 7). Only six studies provide numerical energy, capacity, and/or payback values: 5508.86 kWh/year of generation [34]; 9.6 kW cooling capacity [15]; annual energy savings of 67% at 100% fresh air [59]; cooling energy savings of 38.18% [61]; and payback periods of at least eight years [32] and 9.36 years [35]. No numerical carbon information is reported. The carbon evidence relates to operational CO_2 emissions, with only one study reporting a life-cycle indicator [36]. However, despite the high frequency of energy reporting, the limited quantitative evidence and lack of quantified carbon outcomes restrict comparisons of the actual energy and decarbonisation effects of RES.

Co-benefits are reported in 21 studies (42%), trade-offs in 11 (22%), and no relationship in 18 (36%). In addition, none of the 22 studies in G3, G4, G6, and G7 report a trade-off. Instead, trade-offs are reported only in G1 (eight of 17), G2 (two of seven) and G5 (one of four). The absence of reported trade-offs in these four groups does not necessarily indicate an absence of conflicting performance, as fewer IEQ domains may have been assessed.

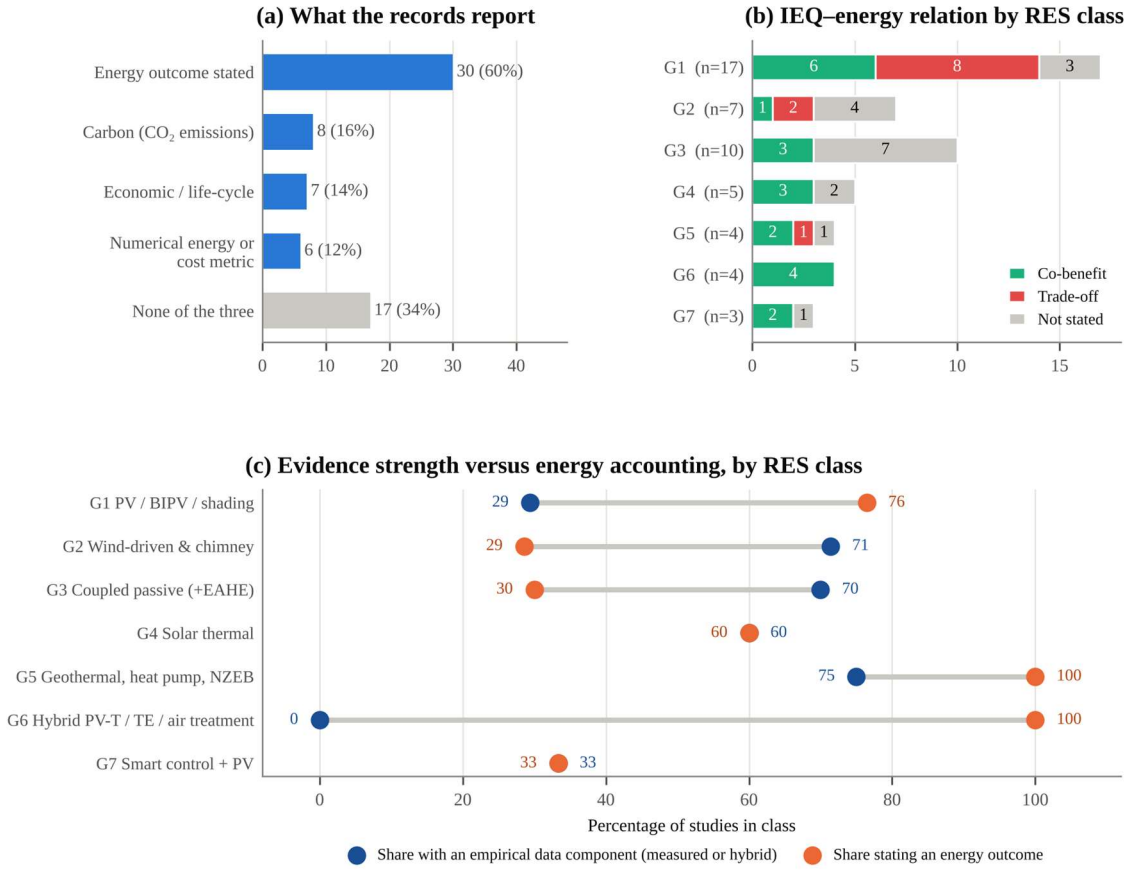

Figure 7. Energy, carbon and economic reporting: (**a**) outcomes reported; (**b**) relation by class; (**c**) empirical component versus energy outcome. In (**a**), blue bars denote studies reporting each outcome type and the grey bar denotes studies reporting none of the three. In (**b**), green, red and grey denote co-benefit, trade-off and not stated, respectively. In (**c**), blue circles show the share of studies in each class with an empirical component (measured or hybrid), orange circles show the share stating an energy outcome, and the grey line marks the gap between them.

There is an inverse relationship between empirical evidence and energy accounting (Figure 7c). Seventy-one per cent of the passive-ventilation studies (G2–G3) include an empirical component, while

only 29% of PV and shading studies do. Conversely, 76% of PV and shading studies report energy outcomes. No studies combine IEQ measurements with sub-metered energy data. This separation reduces the ability to determine whether energy savings correlate with measured improvements in IEQ. These findings indicate two concurrent research communities: simulation-based energy optimisation of PV and shading, and measurement-based comfort studies of passive systems. Consequently, no study has measured both IEQ and energy gains within the same project, and the 21 reported co-benefits are primarily based on models or author-defined objectives.

The distribution across research methods (Table 2) further supports this observation. Of the 14 hybrid studies, six (43%) do not report an IEQ–energy relationship, compared with six (60%) of the measured studies and six (23%) of the simulated studies. Co-benefits were reported in 3 of 10 measured studies (30%), 5 of 14 hybrid studies (36%), and 13 of 26 simulated studies (50%). Additionally, co-benefits were more common in the two lowest-scoring classes (G6 and G7; 6 of 7 studies, 86%; mean QA = 4.0) than in the remaining classes (15 of 43 studies, 35%). Studies reporting no relationship had lower quality scores (mean QA = 4.3) than those reporting co-benefits (5.2) or trade-offs (5.5). However, part of this difference reflects the inclusion of an item in the quality checklist that awards a point for explicitly stating the relationship.

These results may be influenced by modelling assumptions and the optimisation objectives selected, particularly given that co-benefits are more frequently reported in simulated studies and in the lower-scoring technology groups. Co-benefits are therefore more likely to be identified when models are optimised for specific author-defined objectives rather than evaluated against actual performance outcomes. The 42% co-benefit frequency should therefore not be interpreted as a realistic estimate of demonstrated performance, as the available evidence remains insufficient to support the claim that RES-based decarbonisation does not negatively affect IEQ in practice.

4.5. Feedback Loops and Trade-Offs

The 11 trade-offs fall into four loops (Figure 8), comprising three balancing loops, namely ventilation–hygrothermal ($n = 3$), solar control-visual-thermal-lighting ($n = 4$) and seasonal thermal asymmetry ($n = 2$), and one reinforcing loop, namely economic-life-cycle ($n = 2$). Figure 9 shows their causal structure, while Table 4 presents the supporting evidence. Trade-offs were identified in seven of 26 simulated studies (27%), three of 14 hybrid studies (21%), and one of ten measured studies (10%). The higher frequency of reported trade-offs in simulated studies suggests that modelling may reveal interactions that are not readily captured by empirical assessments. However, the shorter observation periods of some measured studies may also limit the detection of such interactions.

Table 4. Feedback loops: evidence, sign-reversing conditions and testable propositions.

Loop (Type)	Sign-Reversing Conditions	Testable Proposition	Source
A Ventilation–hygrothermal (balancing)	Outdoor temperature and humidity; wind speed	An outdoor-keyed damper or evaporative-duty rule removes the reversal cheaply	[10,12,27]
B Solar control–visual–thermal–lighting (balancing)	Heating- or cooling-dominated climate; objective weights	Co-benefit persists only under joint heating, cooling and lighting optimisation	[17,26,28,30]
C Seasonal thermal asymmetry (balancing)	Seasonality; thermal mass; shading deployment	Seasonal comfort hours reported with annual energy expose the loop	[14,57]
D Economic–life-cycle (reinforcing)	Payback horizon; energy price; valuation of IEQ	Valuing IEQ shortens effective payback	[32,35,36]
E Evidence (reinforcing, largely open)	Year-long data with sub-metered energy	Validated models resolve loops A–D with narrower error	10 measured, 14 hybrid, 26 simulated studies
F Decoupling pathways	Technology readiness; climate; control accuracy	Preconditioned fresh air lets ventilation rise without net energy penalty	[59,61,65,66]

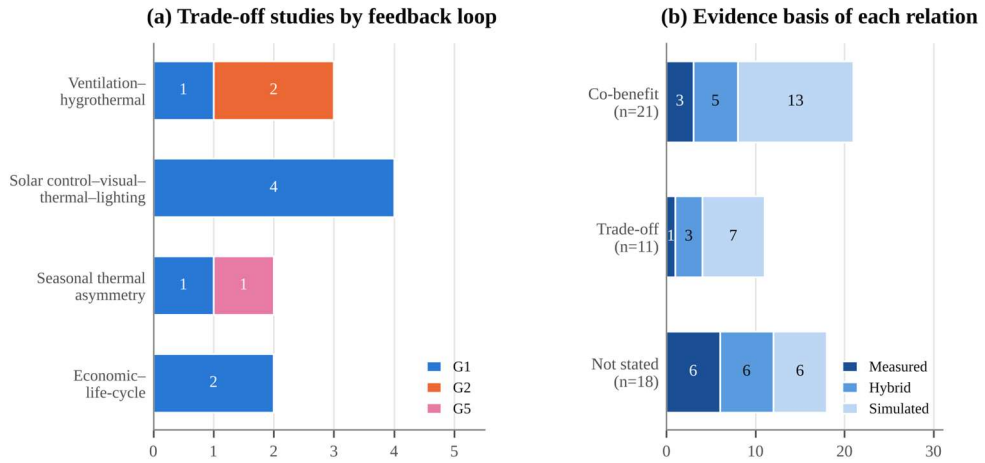

Figure 8. Feedback evidence: (**a**) trade-off studies by loop and RES class; (**b**) evidence basis of each relation.

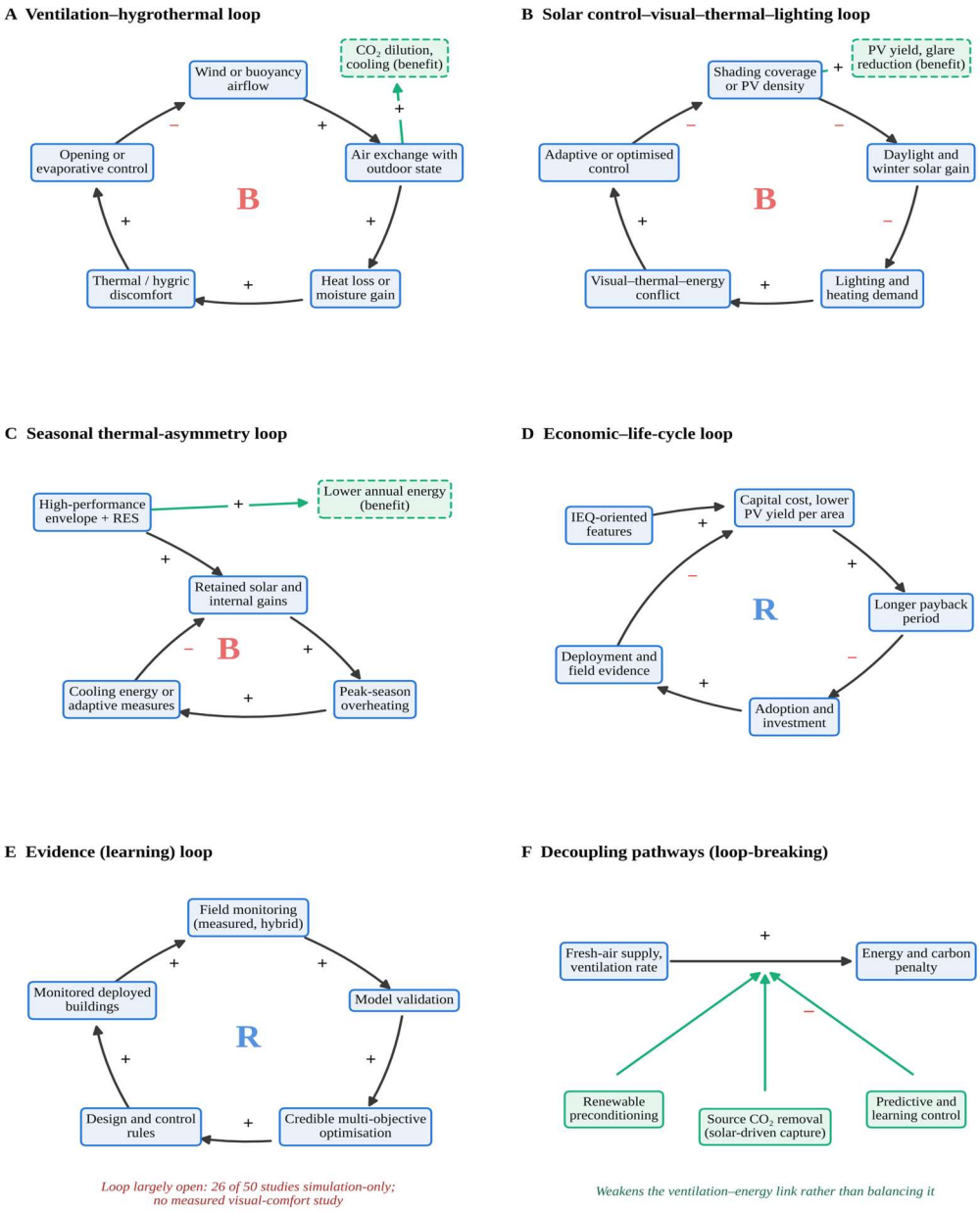

Figure 9. Causal-loop diagrams of the feedback structures identified in the review: (**A**) ventilation–hygrothermal loop; (**B**) solar control–visual–thermal–lighting loop; (**C**) seasonal thermal-asymmetry loop; (**D**) economic–life-cycle loop; (**E**) evidence

(learning) loop; (**F**) decoupling pathways (loop-breaking). The letters B (red) and R (blue) at the centre of each loop denote balancing and reinforcing loops, respectively. Black arrows denote causal links within a loop; a plus sign (+) indicates that the linked variables change in the same direction and a minus sign (−) indicates that they change in opposite directions. Green arrows and dashed green boxes denote benefits generated outside the loop in (**A**)–(**C**) and, in (**F**), decoupling interventions that weaken the ventilation–energy link.

4.5.1. Ventilation–Hygrothermal Loop (Balancing)

Air exchange reduces heat and CO_2 concentrations but can also result in heat loss or increased moisture levels, depending on outdoor conditions. In Kuwait, the use of evaporative windcatchers increased the number of hours during which indoor temperatures remained within the acceptable thermal comfort range and the number of hours meeting CO_2 requirements, while RH also increased [10]. In Nottingham, high wind speeds caused overventilation, heat loss, and increased heating demand [12]. In a hot-humid climate, BAPV also demonstrated a humidity-related trade-off [27]. These results show that increased ventilation does not necessarily lead to improved indoor environmental conditions, as its effects depend on outdoor temperature, humidity, and airflow.

4.5.2. Solar Control-Visual-Thermal-Lighting Loop (Balancing)

This is the most prevalent loop, accounting for four of the 11 trade-offs. In studies of PV shading, increased lighting and winter heating demand were reported with glare-first PV shading [17], while PV shading with vertical farming improved daylight conditions in Shenzhen but reduced summer thermal comfort in Shanghai [30]. Envelope-integrated PV shading was also found to affect lighting conditions [26], while façade optimisation involved trade-offs between daylight, PV generation and views [28]. The studies reporting solutions to these conflicts primarily used optimisation approaches [31,33,34,37,38]. The recurrence of this trade-off suggests that improved solar control and PV generation may involve greater compromises with other façade functions. Optimisation analysis is also used to address these conflicts, which limits the assessment of system performance under actual operating conditions.

4.5.3. Seasonal Thermal Asymmetry Loop (Balancing)

Energy savings during the high season can come at the expense of the low season. PV shading reduced cooling loads and increased heating loads in Indian climate zones [14]. A Romanian NZEB was found to maintain comfort categories I and II for 93% of the year, with August being the only month that exceeded the comfort categories [57]. These results indicate that the performance of a given season is not always representative of annual thermal performance, which highlights the importance of assessing the performance of a RES intervention at the seasonal level.

4.5.4. Economic–Life-Cycle Loop (Reinforcing)

Dynamic shading, semi-transparent PV, and predictive control increase the cost and payback period of IEQ-related interventions, which may reduce uptake, field evidence, and the cost learning needed to reduce costs. Machine-learning shading control [32] and optimised BIPV [35] had payback periods of at least eight years and 9.36 years, respectively. The operational savings of semi-transparent PV overhangs were high, despite their long life-cycle payback period [36], while a short payback period was reported for active solar heaters in Tibet [56]. The different payback periods indicate that the economic potential of RES interventions depends on the context. In addition, the number of studies reporting life-cycle outcomes is relatively small, limiting conclusions about their long-term economic feasibility.

4.5.5. Decoupling Pathways and the Evidence Loop

The three mechanisms that can disconnect the link between an IEQ-improving action and its associated penalties are (1) renewable preconditioning of fresh air [59], (2) removal of CO_2 at the source [61], and (3) predictive or learning control [65,66]. These mechanisms can only be hypothesised, as models alone cannot validate them. Their performance under no-trade-off conditions will therefore need to be tested experimentally under the operating conditions of real buildings.

The four loops share a common structure in which tuning to a single outcome, season, or climate has a counterbalancing effect elsewhere. The evaluation of a particular condition, such as summer cooling or annual energy performance, can therefore overestimate the benefits. G1 has the highest number of trade-offs (8/17, 47%), potentially because solar gain, daylight and winter heating are all affected by PV shading in G1. The solar control loop is the best supported ($n = 4$), while the seasonal and economic loops are each based on two studies and should be considered hypotheses to be tested. The proportion of empirical studies decreased as the frequency of reported trade-offs decreased across all three research methods: simulated, hybrid, and measured (27%, 21%, and 10%, respectively). There are two possible explanations: measured conditions may involve fewer conflicts, or short-term monitoring limited to a single season may overlook conflicts that are captured through parametric simulation. The second explanation cannot be ruled out. If this is the case, year-long measured studies should report more trade-offs, a proposition that can be tested but is not yet supported by the available evidence (Table 5). The results of the measured studies, therefore, do not necessarily indicate less conflict in empirical systems.

Table 5. Evidence gaps and recommended research agenda.

Gap	Evidence in the Sample	Recommended Design
Hot-humid and tropical settings	5 of 50 (4 simulated, none measured); none in Sub-Saharan Africa, Latin America, Southeast Asia	Multi-season field studies with humidity and mould indicators
Healthcare and low-income buildings	0 healthcare; no low-income setting identified	Field trials in clinics and low-income housing
Pollutant-level air quality	0 of 21 air studies name PM or VOC; 9 name CO_2	Measure $PM_{2.5}$, VOC, and microbial indicators
Acoustic quality	0 of 50	Sound-level and annoyance measures
Measured visual comfort	0 of 15 visual studies	Field measurement with occupant votes for adaptive PV shading
Carbon accounting	8 emission statements; no numerical value; 1 life-cycle record	Whole-life carbon assessment paired with IEQ outcomes
Seasonal and long-term data	Monitoring duration not recorded; 2 explicit seasonal conflicts	Year-long monitoring with sub-metered energy
Control levers	No record on storage or occupant-reported outcomes	Occupant-centric control trials with PV and storage
Validation and reporting	26 simulated; 4 low-quality; 10 climates, 10 buildings not stated	Validate models on measured data; report context and monitoring duration

4.6. Evidence Strength and Gaps

Evidence gaps are concentrated in contexts where there is a particular need for research coverage (Figure 10; Table 5). Only five reviewed studies (10%) address hot-humid climates, four of which are based solely on simulations and none of which are based purely on measurements. No studies are from Sub-Saharan Africa, Latin America, or Southeast Asia. Particulate matter (PM) and volatile organic compounds (VOCs) are not reported, nor are healthcare buildings, acoustics, or measured visual comfort addressed.

This underrepresentation is particularly significant because high cooling loads, occupant vulnerability, and limited mechanical systems intersect in hot-humid regions, healthcare facilities, and low-income residential buildings. While passive and low-cost RES can provide significant opportunities for decarbonisation in these settings, their performance is least supported by evidence under high moisture loads. Likewise, the lack of pollutant and acoustic measurement data means that IEQ assessment remains largely focused on thermal and visual comfort, which may not capture the effects on particle exposure and noise. If unaddressed, the lack of attention to the priorities identified in Table 5 could lead to further research in the same geographical and methodological areas without addressing the existing evidence gaps.

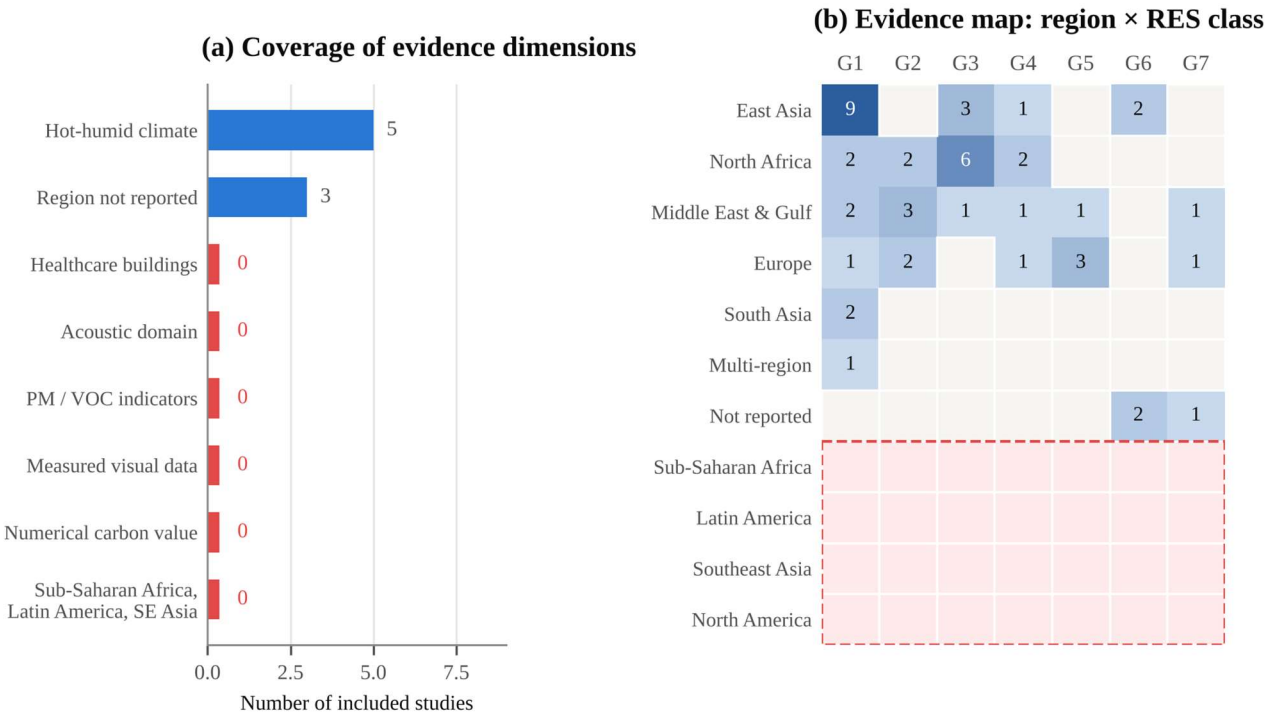

Figure 10. Evidence gaps: (**a**) coverage of evidence dimensions; (**b**) evidence map of region by RES class. In (**a**), blue bars denote dimensions covered by at least one included study and red bars mark dimensions with no included study. In (**b**), cell shading is proportional to the number of studies (darker blue = more studies; grey = none), and the red dashed box highlights regions from which no included study originated.

5. Implications and Limitations

5.1. Guidance for Practice and Policy

The results support an IEQ-informed approach to RES integration. Designers should establish thermal, pollutant-specific, visual and acoustic targets at the outset rather than subordinate them to energy performance. They should also consider context-dependent trade-offs, including winter heat loss and humidity from ventilation systems, glare and heating conflicts from PV shading, and seasonal overheating. Facilities managers should monitor CO_2, RH, and seasonal comfort hours, as operational data are almost absent from the available evidence. Policymakers should require IEQ reporting alongside energy and carbon performance, as energy and carbon performance alone do not ensure acceptable IEQ. Researchers should pair measured IEQ outcomes with metered energy data.

Table 6 summarises this guidance by RES class, together with the level of confidence that can be placed in the recommendations.

Table 6. Evidence-informed guidance by RES class and confidence in the evidence.

RES Class	Supported IEQ Benefit	Documented Risk or Trade-Off	Recommended Action	Confidence
G1 PV, BIPV and shading	Dynamic PV shading improved daylight and glare metrics [16,31]	More lighting and winter heating demand when glare is prioritised [17]; more heating in India [14]	Optimise shading for heating, cooling and lighting together; report seasonal energy	Low: 12 of 17 simulated; no measured visual study
G2 Wind-driven and chimney	Below 35 °C in peak summer [41]; adaptive comfort met in most of 15 capitals [42]	Humidity from evaporative cooling [10]; overventilation in a mild-cold climate [12]	Key dampers or evaporative duty to outdoor temperature, humidity and wind speed; monitor CO_2 and RH	Moderate: mean QA 5.3; airflow used as an air-quality proxy
G3 Coupled passive	Outlet air cooled by up to 12.5 °C [11]; comfort for 84% of hours in a validated model [43]	Energy reported in only three of ten studies; duct hygiene unexamined	Report energy; check filtration and duct hygiene; test in occupied buildings	Moderate–low: mean QA 4.5; test-room scale
G4 Solar thermal	All five studies address thermal comfort [52–54]	Heterogeneous baselines; air quality covered in one study [55]	State baselines; add air-quality and humidity indicators	Moderate: mean QA 5.2; three of five measured or hybrid
G5 Geothermal, heat pump and NZEB	93% of the year within comfort categories I and II in a Romanian NZEB [57]	August overheating in the measured NZEB [57]	Report seasonal comfort hours alongside annual energy	Moderate: mean QA 6.3, but only four studies
G6 Hybrid PV/T, TE and air treatment	All four studies report co-benefits, e.g., CO_2 below 800 ppm with 38.18% lower cooling energy [61]	None reported; all simulated, two with no location	Validate in field trials; state location and climate	Low: all simulated; mean QA 4.0
G7 Smart control with PV	IEQ treated as an optimisation target [65–67]	Benefits limited to the outcomes in the authors' objective functions	Add occupant-reported comfort to objectives; validate in operating buildings	Low: no measured study; mean QA 4.0

In addition to building decarbonisation, RES also play a role in broader decarbonisation pathways. The future environmental effects of global hydrogen production have been explored using prospective life-cycle assessment [68], while the potential contribution of a hydrogen network in Europe has been investigated using energy-system modelling [69]. Neither study addresses IEQ, indicating that building-related decisions regarding hydrogen or other renewable energy carriers may be made without supporting IEQ evidence. If these technologies are installed in buildings, IEQ assessments should also be incorporated into Table 6.

5.2. Limitations

The search covered only two databases, English-language journal articles and publications from the last ten years (2016–2026). Publications after 9 September 2026 and grey literature were excluded, while the language filter is likely to have excluded studies from some geographical areas, including Latin America. The custom eight-item checklist measures reporting rather than risk of bias or model accuracy. One item rewards the inclusion of an IEQ–energy relationship, meaning that studies without an explicitly stated relationship receive lower scores by design. Some categories contained only a few studies, and the use of mixed methods meant that category-level counts and percentages by research method were descriptive only. Therefore, findings on co-benefit frequency and feedback loop typology remain tentative. The protocol was not registered, so changes made after its preparation cannot be ruled out. The three reviewers screened, extracted, and appraised records without a formal consensus procedure for resolving disagreements.

Relationships were classified based on the authors' own findings and are therefore subject to reporting bias. The inferences in Section 4 are descriptive and were not statistically tested.

6. Conclusions and Recommendations

6.1. Conclusions

A review of 50 studies revealed limited evidence on RES and IEQ in buildings, with the available evidence predominantly simulation-based, geographically restricted, and limited in scope. None of the studies assessed acoustics, particulate matter, or VOCs. Co-benefits (42%) were reported more frequently than trade-offs (22%), but co-benefits were most frequently reported in simulated and optimisation studies. In studies measuring energy, IEQ was least frequently reported. It is therefore not possible to conclude that the included studies demonstrate that whole-life carbon neutrality can be achieved without affecting IEQ. The relationships appear to be influenced by four feedback loops that depend on climate, season, system configuration and design priorities, while the effectiveness of mitigation measures remains unvalidated. This evidence is organised for further testing through the framework, loop typology and evidence gap map. The conclusions provide a descriptive mapping rather than a quantitative synthesis, as the protocol was not registered and most studies were simulated.

6.2. Future Research Directions

Further field studies are needed in Sub-Saharan Africa, particularly in hot-humid and tropical climates, low-income housing and healthcare buildings, covering year-long energy consumption. These studies should assess thermal, air-quality (CO_2, PM2.5 and VOCs), visual and acoustic comfort through occupant assessments, alongside energy, whole-life carbon and cost. Educational buildings should be prioritised. Exposure to poor indoor air quality in schools adversely affects health in Europe [7], while the impact of RES on such exposure remains unknown. The location, climate, building type, and monitoring duration should be reported alongside numerical measurements for each domain. Measured data should also be used to validate models and test feedback mitigation strategies.

Controlling is a second priority. Only three studies (G7) combined smart control with PV, only one of which was measured, while all three optimised author-defined objectives. Other control methods, such as model predictive control [65] and deep reinforcement learning [66], can achieve trade-offs between comfort and energy savings. However, under extreme conditions, it is crucial that controllers remain reliable. Physical constraints have been proposed for integration into deep reinforcement learning controllers through a physics-embedded actor-critic proximal policy optimisation approach to maintain frequency stability and avoid blackouts, even under out-of-distribution weather and load events [70] in hydrogen-integrated microgrids. The same concept could be applied to RES-integrated buildings, with physical constraints defined by comfort limits, ventilation requirements, and thermal dynamics, ensuring that IEQ is not compromised when weather and/or occupancy conditions vary from the training data.

Third, building-level IEQ evidence should be connected with system-level assessments of renewable energy supply. Life-cycle assessments of hydrogen [68] and models of hydrogen networks indicate the impacts and costs associated with different hydrogen supply options but do not consider indoor conditions. When integrated with whole-life carbon assessments, including storage and hydrogen-integrated systems, IEQ can be evaluated across different scales, while digital twins [23] can provide monitored data to complete the evidence loop.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

The authors used Grammarly and ChatGPT (OpenAI; GPT-6.2) to improve language, correct errors, and clarify the text. The authors reviewed and edited the content and take full responsibility for the published work.

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Author Contributions

Conceptualization, E.C.I.; Methodology, E.C.I.; Data extraction and curation, E.C.I., P.P.I. and E.S.S.; Writing—original draft preparation, E.C.I.; Writing—review and editing, E.C.I., L.A. and A.M.S.; Supervision, L.A. and A.M.S. All authors have read and agreed to the published version of the manuscript.

Ethics Statement

This study was a systematic review of published literature and did not involve human participants or the collection of data from human subjects. Therefore, ethical review and approval were not required, and informed consent was not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data supporting the findings of this systematic review are contained in the article. Additional data related to this article will be made available upon request from the corresponding author.

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Declaration of Competing Interest

The authors declare no conflicts of interest.

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