

Techno-economic and environmental indicators in greenhouse dryers: toward standardized metrics and carbon accounting

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Abstract. Greenhouse dryers are increasingly recognized as low-carbon post-harvest technologies that combine solar energy utilization with controlled microclimates to enhance agricultural resilience. This systematic literature review explores techno-economic and environmental indicators in greenhouse dryer, with an emphasis on indicator standardization, carbon accounting, system configuration, and product quality. The review applied structured searches across multiple scientific databases and applied inclusion criteria focusing on studies reporting energy, exergy, cost, and environmental metrics. Quality appraisal drew on ISO standards for life cycle assessment and established methodological checklists. Findings reveal substantial heterogeneity in indicator definitions and functional units, with Specific Moisture Extraction Rate, thermal and exergy efficiencies, and economic measures such as payback period frequently reported yet inconsistently applied. Carbon accounting practices are largely confined to operational emissions, with embodied impacts and end-of-life scenarios rarely assessed, limiting the accuracy of sustainability claims. Comparative analysis shows that passive systems provide low-cost options with modest efficiencies, active systems achieve higher throughput at increased operational risk, and hybrid systems with thermal energy storage consistently deliver superior techno-economic outcomes. Importantly, product quality, encompassing color, nutrient retention, and sensory attributes, directly influences market competitiveness, enabling premium pricing and reducing losses. This study highlights the need for harmonized indicator frameworks, comprehensive carbon accounting, and integrative models that connect performance, cost, emissions, and quality. By advancing such approaches, greenhouse dryers can be more effectively scaled to support sustainable agriculture, reduce post-harvest losses, and contribute to climate mitigation.

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1 Introduction

Greenhouse dryers (GHDs) represent a promising low-carbon post-harvest technology that integrates solar energy capture with a controlled microclimate to address critical challenges in agricultural value chains. By combining the structural principles of greenhouses with solar drying processes, these systems enhance resilience against climatic variability while improving product quality and reducing post-harvest losses. Their adoption is increasingly viewed as a pathway toward sustainable agricultural practices, aligning with global commitments to decarbonize food systems, minimize waste, and promote renewable energy utilization. GHDs contribute directly to several Sustainable Development Goals (SDGs), including Zero Hunger (SDG 2), Affordable and Clean Energy (SDG 7), Responsible Consumption and Production (SDG 12), and Climate Action (SDG 13). The growing interest in GHDs reflects their potential to simultaneously enhance food security, reduce dependence on fossil fuels, and mitigate climate change impacts.

The significance of GHDs lies in their capacity to reduce spoilage by offering a protective environment that shields produce from adverse weather, dust, and contamination, common in open-sun drying practices. In parallel, their reliance on solar energy reduces greenhouse gas emissions associated with conventional fossil-fuel-based drying systems. Recent studies highlight the considerable efficiency gains of GHDs, with Specific Moisture Extraction Rate (SMER) values ranging widely from 0.2–0.6 kg/kWh in conventional systems to values approaching 8 kg/kWh in advanced configurations. These findings underscore the transformative potential of modern solar drying technologies when compared to traditional systems.

Life cycle economic analyses further emphasize the importance of GHD adoption. Metrics such as Life Cycle Cost (LCC) and Net Present Value (NPV) are increasingly used to evaluate economic feasibility, with studies reporting favorable payback periods ranging between 1.5 and 4 years for many GHD configurations [1-3]. Such indicators provide investors and policymakers with reliable evidence of long-term viability. Payback analysis, in particular, is frequently applied to determine the timeframe required to offset initial capital investments, highlighting the cost-effectiveness of these systems [4].

Beyond techno-economic considerations, environmental indicators are crucial for evaluating the sustainability of GHDs. Embodied energy, which accounts for the energy consumed during the manufacturing and construction of the system, offers insights into the total resource demand of greenhouse dryers [5,6]. The carbon footprint, often expressed in terms of CO₂ equivalent emissions per kilogram of dried product, provides a quantifiable measure of climate impacts. Empirical studies demonstrate that solar greenhouse dryers substantially reduce emissions relative to conventional systems, while also offering potential opportunities for carbon credit generation under renewable energy frameworks [7,8,4]. These outcomes illustrate the broader environmental value of transitioning to renewable-based drying solutions.

The advantages of greenhouse dryers over traditional methods extend beyond efficiency and emissions reductions. By providing stable drying conditions, GHDs improve product quality, as measured by parameters such as nutrient retention, color preservation, and texture integrity [8]. Enhanced quality outcomes support premium market opportunities and reinforce the economic attractiveness of GHD adoption. Moreover, their operational reliability across diverse climatic zones ensures year-round utility, addressing limitations of open-sun drying, which remains highly vulnerable to weather fluctuations [1]. Integration

with thermal energy storage (TES) systems, including packed beds and phase change materials (PCMs), further enhances performance by extending drying operations into nighttime hours and stabilizing microclimate conditions [9,4].

The relevance of GHDs to the SDGs is particularly notable. With respect to SDG 2 (Zero Hunger), GHDs contribute to reducing food loss by ensuring efficient and hygienic drying of agricultural products, thereby enhancing availability and accessibility of safe, high-quality food [10-12]. In relation to SDG 7 (Affordable and Clean Energy), their reliance on solar resources reduces dependency on fossil fuels, advancing the shift toward renewable energy in agriculture [13,14]. For SDG 12 (Responsible Consumption and Production), GHDs exemplify principles of circular economy by optimizing energy inputs and minimizing waste generation [15,16]. Finally, under SDG 13 (Climate Action), their demonstrated capacity to reduce carbon emissions directly contributes to global climate mitigation efforts [17].

Despite these advances, several challenges and gaps persist in the literature. Studies often report inconsistent definitions and applications of techno-economic and environmental indicators, limiting comparability across systems and regions. Functional units vary, with some studies reporting outcomes per unit of dried product, while others measure moisture removal, complicating cross-study analyses [18,16]. Similarly, boundaries for life cycle assessment differ widely, with many analyses excluding embodied emissions or end-of-life considerations, resulting in incomplete environmental profiles [15,8]. The lack of standardization in reporting hampers the synthesis of findings and obscures a clear understanding of the sustainability performance of GHDs.

Knowledge gaps also remain in understanding long-term economic impacts and scalability of GHD deployment. While small-scale studies demonstrate promising results, less is known about the feasibility of scaling systems for industrial or cooperative use, particularly in regions with limited infrastructure and capital resources [16,19]. Similarly, there is limited research on the social and market implications of GHD adoption, particularly regarding smallholder farmers who represent the majority of agricultural producers in developing economies. Addressing these gaps is critical for promoting equitable and sustainable transitions to renewable drying technologies.

The objectives of this systematic review are therefore threefold. First, it aims to map and standardize the techno-economic and environmental indicators used in GHD studies. Second, it seeks to integrate carbon accounting practices into performance evaluations to provide a holistic understanding of sustainability. Third, it endeavors to synthesize evidence linking design choices to costs, emissions, and product quality outcomes. By addressing these objectives, the review contributes to bridging existing gaps and offering a framework for consistent reporting and assessment.

The scope of the review spans peer-reviewed research conducted between 2000 and 2025, covering diverse climatic zones including tropical, arid, and temperate regions. It includes studies of passive, active, hybrid, and seasonally repurposed greenhouse systems, with specific attention to thermal energy storage strategies, control mechanisms, and value-chain implications. Key terms relevant to this review include Specific Moisture Extraction Rate (SMER), thermal and exergy efficiency, Levelized Cost of Heat (LCOH), cost per kilogram of dried product, Net Present Value (NPV), Internal Rate of Return (IRR), payback period, embodied energy, life cycle assessment (LCA), and carbon accounting under GHG Protocol scopes.

Based on this scope, the review is guided by four central research questions: (1) Which techno-economic and environmental indicators are reported for GHDs, and how are they defined? (2) How does carbon accounting, encompassing both operational and embodied emissions, influence comparative performance evaluations of GHD designs? (3) What design and operational factors exert the greatest influence on costs and CO_{2e} per kilogram of dried

product? and (4) How can indicators be harmonized to ensure comparability and reliability across studies?

This article is organized as follows: Section 2 outlines the methodology applied in identifying, screening, and analyzing relevant literature. Section 3 presents the theoretical foundations underpinning the review, covering techno-economic frameworks, environmental accounting principles, and integrative sustainability models. Section 4 synthesizes findings across four thematic areas: indicator standardization, carbon accounting practices, techno-economic performance by system configuration, and the link between indicators and product quality. Section 5 discusses critical insights, highlighting unresolved challenges and implications for research and practice. Section 6 concludes with a summary of contributions and recommendations for future research directions.

By pursuing these objectives and research questions, this systematic review positions itself to provide a comprehensive, standardized, and policy-relevant assessment of greenhouse dryers. Through harmonization of indicators and integration of carbon accounting, it aims to strengthen the scientific and practical foundations necessary for scaling GHD technologies in sustainable agricultural systems worldwide.

2 Research methods

The methodological framework of this systematic literature review (SLR) follows established international standards for evidence synthesis in engineering and renewable energy research. It adheres to the principles of transparency, reproducibility, and rigor, drawing on PRISMA guidelines [20] to ensure comprehensive reporting. The section is structured into four sub-sections: search strategy, inclusion and exclusion criteria, screening and selection process, and quality assessment tools

2.1 Search strategy

To identify relevant studies, a multi-database approach was applied, encompassing Web of Science, Scopus, ScienceDirect, SpringerLink, IEEE Xplore, and DOAJ, ensuring coverage of peer-reviewed journals across energy, agricultural engineering, and sustainability domains [8]. In addition, Google Scholar was consulted for broader access to theses, dissertations, and conference proceedings. Grey literature was incorporated where relevant, including reports from FAO and UNEP, standards from ISO and GHG Protocol, and doctoral theses via ProQuest.

The search strategy was designed using Boolean operators to maximize recall while maintaining specificity. The principal Boolean template was:

The temporal scope covered literature published between 2000 and 2025, capturing both early foundational studies and the latest innovations [18,16]. Only English-language articles were included, although abstracts in other languages were documented when they provided data-rich insights.

2.2 Inclusion and exclusion criteria

The inclusion and exclusion criteria were developed to ensure rigor and focus in the review process, following best practices in renewable energy SLRs [1,13].

Inclusion criteria:

- a. Peer-reviewed articles, conference proceedings, and relevant grey literature (e.g., FAO/UNEP reports).

- b. Empirical or modeled studies on greenhouse dryers reporting at least one techno-economic or environmental indicator (e.g., SMER, payback, carbon footprint).
- c. Comparative analyses of configurations (passive, active, hybrid, seasonal repurposing).
- d. Studies incorporating life cycle assessment (ISO 14040/44) or carbon accounting.
- e. Research linking drying performance with product quality metrics (e.g., ΔE , nutrient retention).

Exclusion criteria:

- a. Studies on non-greenhouse solar dryers (cabinet/tunnel) unless used as comparators.
- b. Opinion pieces, commentaries, or conceptual notes without empirical data.
- c. Articles lacking methodological transparency.
- d. Duplicate studies.

These criteria reflect the need to capture robust evidence on techno-economic feasibility and environmental sustainability while filtering out non-relevant or low-quality sources [14].

2.3 Screening and selection process

A two-stage screening process was conducted. First, titles and abstracts were screened independently by two reviewers to exclude irrelevant articles. Second, full-text screening was performed on retained studies to confirm eligibility. Discrepancies were resolved through consensus or by consulting a third reviewer.

A structured data extraction form was developed to standardize information collection across studies. Extracted variables included: system typology (passive, active, hybrid), climatic conditions, crop type, reported indicators (definitions, units), system boundaries, cost and emission inputs, and treatment of uncertainty [21]. This ensured consistency in data compilation and facilitated comparative analysis.

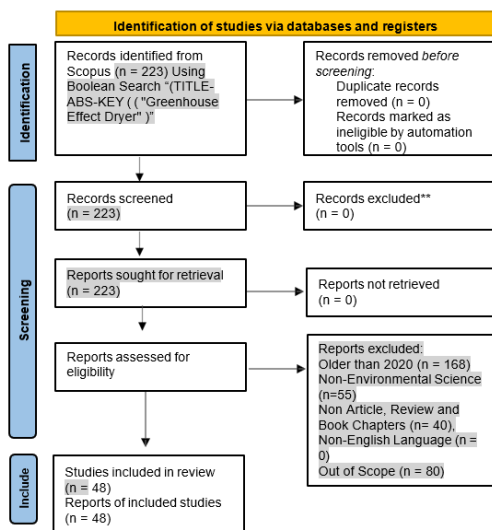


Figure 1. PRISMA flow diagram showing identification, screening, eligibility, and inclusion of studies

The diagram illustrates the initial number of records retrieved, duplicates removed, exclusions at each stage, and the final set of studies included in the review.

2.4 Quality Assessment Tools

To ensure reliability, multiple quality assessment tools were employed:

- a. Methodological rigor: The Joanna Briggs Institute (JBI) and Critical Appraisal Skills Programme (CASP) checklists were adapted to appraise the robustness of experimental and modeling studies [3].
- b. Modeling quality: A rubric was applied to assess geometry fidelity, boundary conditions, radiation models, turbulence closure, and validation practices in CFD-based studies [22].
- c. Environmental rigor: ISO 14040/44 standards guided the appraisal of life cycle assessments, with specific attention to clarity on functional units, allocation rules, and impact assessment methods such as ReCiPe or TRACI [15].
- d. Economic rigor: Studies were evaluated for transparency in cost boundaries (CAPEX, OPEX, maintenance), assumptions on discount rates, and treatment of sensitivity analysis [4].

The Cochrane Risk of Bias tool was additionally consulted to examine bias in experimental designs, while cross-checks were performed with ISO and GHG Protocol standards to ensure comprehensiveness in environmental reporting [6].

3 Results and discussion

3.1 Theoretical framework

This section provides the theoretical underpinnings and conceptual foundations necessary to assess techno-economic and environmental indicators in greenhouse dryers (GHDs). It is divided into three main sub-sections: (i) performance and thermo-economic foundations, (ii) environmental and carbon accounting foundations, and (iii) integrative sustainability and decision models. Each sub-section synthesizes key theories, established models, and scholarly debates to establish a comprehensive framework for subsequent analysis.

3.1.1 Performance and thermo-economic foundations

First-law efficiency, often referred to as thermal or energy efficiency, represents the ratio of useful energy output to the total energy input. In GHD studies, this metric evaluates how effectively supplied energy contributes to moisture removal from agricultural products. For example, [23] reported that a passive greenhouse dryer achieved an energy efficiency of 23.49%, demonstrating that a significant portion of supplied energy was converted into useful drying work. This metric is central to operational evaluations of dryer performance and highlights opportunities for improving energy utilization.

Second-law efficiency, or exergy efficiency, goes beyond energy quantity to consider energy quality. Defined as the ratio of exergy output to exergy input, this metric assesses how effectively energy is transformed into useful work within the drying process. Passive GHD configurations often exhibit relatively low exergy efficiencies, around 4.5% in some cases [23]. Although these values appear modest, they reveal critical losses in energy quality that inform design improvements in airflow, heat transfer, and control strategies.

Together, first-law and second-law efficiencies provide a dual lens for analyzing GHD performance. While the first law captures the magnitude of energy use, the second law reveals

hidden inefficiencies in conversion quality, making both indispensable for a comprehensive evaluation.

3.1.2 Drying kinetics and specific moisture extraction rate (SMER)

Drying kinetics models describe the rate and extent of moisture removal from agricultural commodities under varying conditions. A critical indicator, Specific Moisture Extraction Rate (SMER), quantifies the mass of water evaporated per unit of energy consumed (kg/kWh). Documented that conventional solar drying systems typically operate at 0.2–0.6 kg/kWh, whereas advanced systems can achieve values up to 7.94 kg/kWh, illustrating substantial efficiency gains. In greenhouse dryers, SMER serves not only as a technical metric but also as a comparative benchmark across system designs, storage strategies, and climatic conditions.

3.1.3 Economic Indicators: LCOH, cost per kg dried, and payback period

Economic feasibility of GHDs is frequently assessed through multiple indicators. The Levelized Cost of Heat (LCOH) aggregates capital expenditures (CAPEX), operational expenditures (OPEX), and lifetime energy outputs to produce a standardized cost metric (\$/kWh_{th}). [24] demonstrated its application in solar-assisted drying systems, revealing cost variability linked to system design and scale. Complementarily, cost per kilogram of dried product captures operational realities by dividing total lifecycle costs by the total mass of dried product [4,1].

Payback period analysis estimates the number of years required for cumulative savings to offset initial capital costs. Reported values range between 1.6 and 3.6 years depending on climatic conditions and system efficiencies [25,26]. These economic indicators are increasingly applied in concert with energy and exergy metrics, producing what scholars refer to as a 4E + Q framework, integrating Energy, Exergy, Economics, Environment, and Quality [27].

3.1.4 Learning curves and scale effects

Economic viability is also shaped by scale and learning effects. As production and deployment of GHDs expand, unit costs typically decrease due to economies of scale and learning-by-doing. These effects influence investment decisions, particularly in rural and smallholder contexts where affordability is a key barrier. Theoretical models of technology diffusion in renewable energy systems support the argument that wider adoption of GHDs can significantly reduce per-unit costs, thereby enhancing accessibility and competitiveness in agricultural markets.

3.1.5 Life cycle assessment (LCA) framework

Environmental sustainability assessments of GHDs rely heavily on Life Cycle Assessment (LCA) frameworks established by ISO 14040 and 14044 standards. LCA comprises four phases: (i) goal and scope definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation. Lenzo et al. (2018) emphasized the importance of defining system boundaries cradle-to-grave, cradle-to-gate, or gate-to-gate to ensure consistent reporting. Inventory analyses capture inputs (e.g., solar energy, construction materials, auxiliary fuels) and outputs (e.g., CO₂ emissions, wastewater), while impact

assessments quantify environmental burdens using metrics such as Global Warming Potential [28].

In greenhouse dryers, LCA enables comparisons between renewable-based and fossil-fuel-based drying technologies, highlighting opportunities for carbon mitigation and resource conservation. For example, [29] demonstrated that LCA-driven analyses can inform policy by quantifying emission reductions attributable to solar drying interventions.

3.1.6 Embodied vs. operational energy

Distinguishing between embodied and operational energy is critical for a holistic evaluation of GHDs. Embodied energy refers to the total energy consumed in manufacturing, transporting, and constructing the dryer, while operational energy refers to energy consumed during use. [5,6] highlighted that embodied energy can represent a substantial portion of total lifecycle energy, especially in material-intensive systems incorporating phase change materials (PCMs) or photovoltaic/thermal (PV/T) hybrids. Studies excluding embodied energy often underestimate the true environmental footprint of GHDs.

3.1.7 Carbon accounting methodologies

Carbon accounting methodologies provide tools for quantifying greenhouse gas emissions in small-scale renewable systems. Boundary setting is a primary concern: cradle-to-grave approaches encompass the entire lifecycle, cradle-to-gate focuses on production, and gate-to-gate examines operational phases [30-32]. Selection of emission factors also significantly influences results. Standardized factors from the IPCC Guidelines ensure comparability, while localized factors improve accuracy in specific contexts [33,34]. Integrating carbon accounting with LCA provides robust insights into both direct and indirect emissions [35,36].

Integrating Energy and Emissions

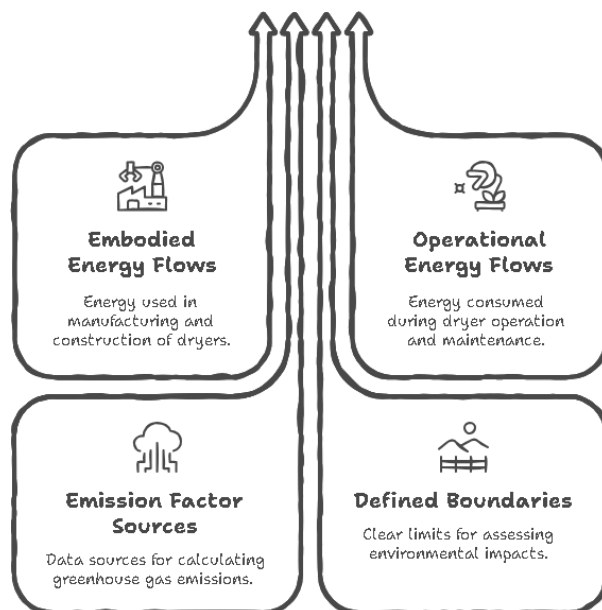


Figure 2. Conceptual framework for environmental and carbon accounting in greenhouse dryers, showing integration of embodied and operational energy flows, boundary definitions, and emission factor sources

3.1.8 *Regional grid intensity and emission factors*

Regional variations in electricity grid intensity strongly influence carbon footprints of GHDs, especially hybrid systems utilizing auxiliary electric heaters or PV/T modules. For instance, dryers connected to coal-intensive grids yield higher emissions compared to those in regions with cleaner energy mixes. Incorporating grid-specific emission factors ensures that carbon accounting reflects local contexts and supports the scalability of GHD adoption across diverse geographies.

3.1.9 *The triple bottom line (TBL) framework*

The Triple Bottom Line (TBL) framework emphasizes that sustainability assessments must integrate economic, environmental, and social dimensions. In the context of GHDs, this requires consideration not only of efficiency and cost but also of impacts on food security, labor conditions, and community resilience. TBL encourages stakeholders to view GHD adoption as both a technological and socio-economic transition, aligning renewable energy deployment with broader sustainable development goals.

3.1.10 *Multi-criteria decision analysis (MCDA)*

Decision-making in renewable drying systems often involves trade-offs across multiple indicators. Multi-Criteria Decision Analysis (MCDA) tools such as Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) provide structured methods for prioritizing alternatives. AHP enables hierarchical decomposition of complex decisions into pairwise comparisons of criteria, accommodating both qualitative and quantitative inputs [37]. TOPSIS ranks options by proximity to ideal and nadir solutions, offering practical rankings of dryer designs [38,39].

Hybrid approaches combining AHP, TOPSIS, and fuzzy logic have been applied to renewable energy evaluations, enhancing robustness under uncertainty [37]. These tools are particularly valuable in GHD contexts where stakeholders must balance efficiency, cost, emissions, and product quality.

3.1.11 *Integration of techno-economic, environmental, and quality indicators*

For decision models to be effective, they must integrate techno-economic, environmental, and product-quality indicators. Economic indicators such as LCOH, cost per kilogram dried, and payback provide financial viability assessments [40]. Environmental indicators, including carbon footprint and energy consumption, capture sustainability dimensions [41]. Product-quality indicators, such as nutrient retention and sensory attributes, ensure that market and consumer requirements are met [42].

Incorporating these indicators into MCDA frameworks ensures a balanced evaluation that reflects the multifaceted goals of sustainable agriculture. Mathematical models leveraging AHP-derived weights and TOPSIS rankings enable systematic integration, supporting evidence-based decision-making for GHD deployment [43,44].

3.1.12 Uncertainty propagation and monte carlo simulations

Uncertainty remains a significant challenge in sustainability assessments of GHDs, arising from variability in climatic data, market prices, emission factors, and system lifespans. Monte Carlo simulations address this challenge by propagating uncertainties through probabilistic modeling, offering distributions of possible outcomes rather than deterministic values. When applied alongside MCDA, uncertainty analysis provides stakeholders with robust insights into risk, reliability, and sensitivity of alternative GHD designs.

3.2 Review of themes/findings

3.2.1 Indicator standardization & definitions

Indicator standardization is a cornerstone for the comparability and robustness of techno-economic and environmental assessments in greenhouse dryers (GHDs). Despite the rapid expansion of literature in this field, the definitions, formulas, functional units, and system boundaries applied across studies remain inconsistent. These discrepancies hinder cross-comparison and meta-analysis, ultimately weakening the evidence base required for policy and investment decisions. This sub-section synthesizes the state of knowledge on indicator standardization and definitions, drawing directly on reported measures such as Specific Moisture Extraction Rate (SMER), thermal efficiency, exergy efficiency, Levelized Cost of Heat (LCOH), cost per kilogram dried, payback period, Net Present Value (NPV), Internal Rate of Return (IRR), carbon intensity, embodied energy, and energy payback time (EPBT).

The findings are presented in Table 1, which summarizes the indicators, formulas, units, functional units, system boundaries, required data inputs, reported ranges, and critical assumptions. The subsequent discussion unpacks these dimensions in relation to both the theoretical foundations presented in Section 3 and the broader literature..

Table 1. Standardization of Indicators and Definitions in Greenhouse Dryer Studies (Theme 1)

Indicator	Definition / Formula	Unit	Functional Unit	System Boundary	Key Data Inputs	Reported Range	Notes / Assumptions
SMER	$SMER = \frac{m_{evap}}{E_{in}}$	kg water /kWh	1 kg water removed	Operational	Energy input (kWh), water mass removed (kg)	0.5–3.0 [23,13]	Reported without uncertainty; varies with design and climate
Thermal Efficiency	$\eta_{th} = \frac{\dot{m} \cdot a \cdot c_p \cdot \Delta T + Q_{evap}}{Q_{solar}}$	%	One drying batch	Operational	Airflow rate, ΔT , insulation, collector area	20–60% [45,13]	Some studies exclude latent heat; definitions differ

Exergy Efficiency	$\eta_{ex} = \frac{\sum Ex_{out}}{\sum Ex_{in}}$	%	One drying batch	Operational	Inlet/outlet temperature & RH, radiation, air properties	4.5–80% [46,47,7]	Captures energy quality; rarely standardized
LCOH	$(CAPEX \cdot CRF + OPEX) / Q_{heat}$	\$/kWh _{th}	1 kWh _{th} delivered	Cradle-to-gate (cost), operational (output)	CAPEX, OPEX, lifetime, discount rate	Variable [24]	Sensitive to discount rate and capacity factor
Cost per kg dried	Total lifecycle cost / m _{dried}	\$/kg dried	1 kg dried product	Gate-to-gate	Energy, labor, maintenance, shrinkage	System-dependent [4,1]	May include or exclude quality premiums
Payback Period	CAPEX / Annual savings	years	System	Cradle-to-gate (CAPEX), operational (savings)	Energy price, annual production	1.5–4 years [13,48]	Highly sensitive to seasonal utilization
NPV	$\sum CF_t / (1+r)^t - CAPEX$	\$	System	Cradle-to-gate (CAPEX), operational (CF)	Cash flows, discount rate, project lifetime	Positive or negative depending on assumptions [47,49]	Sensitive to energy price assumptions
IRR	$\sum CF_t / (1+IRR)^t - CAPEX = 0$	%	System	Cradle-to-gate / Operational	Cash flows, CAPEX	10–25% typical [23,45]	Requires explicit WACC for comparability
Carbon Intensity	$(CO_{2e_op} + CO_{2e_emb}) / m_{dried}$	kg CO _{2e} /kg dried	1 kg dried product	Cradle-to-grave (ideal)	Energy use, materials, emission factors	0.2–1.5 typical [7,8]	Operational vs embodied often not separated
Embodied Energy	$\sum (m_i \times EI_i)$	MJ	System	Cradle-to-gate	Material mass, embodied energy intensity database	500–2000 MJ/system [5,6]	Source database must be stated

EPBT	Embodied energy / Net annual energy output	years	System	Cradle-to-gate / Operational	Embodied energy, annual useful energy output	1.6–3.6 years [26]	Requires net (not gross) energy output
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3.2.2 SMER, thermal and exergy efficiencies

SMER remains the most widely cited indicator for energy performance in GHDs. Its formula is consistent across studies (mass of water evaporated divided by energy input), yet reported ranges vary substantially from 0.5 to 3.0 kg/kWh [23]. This variability reflects differences in climatic conditions, design geometries, and operational loads. The theoretical basis discussed in Section 3.1.2 emphasizes SMER’s role as a direct linkage between drying kinetics and energy efficiency. However, the absence of standardized reporting on uncertainties undermines its comparability.

Thermal efficiency shows similar heterogeneity, reported between 20% and 60% [45,13]. Some studies exclude latent heat in their calculations, artificially inflating reported values. By contrast, exergy efficiency, although conceptually more rigorous, remains inconsistently applied. Studies report exergy efficiencies ranging from 4.5% in passive modes [23] to over 80% in advanced hybrid systems [46,47]. This wide spread demonstrates both the potential and the methodological inconsistencies of exergy-based analysis. Harmonizing assumptions regarding reference states and boundary conditions is necessary for comparability.

3.2.3 Functional unit inconsistencies

The definition of functional units represents another major source of inconsistency. Some studies employ kilograms of dried product as the functional unit [43], while others use kilograms of water removed [45,13]. As [46] highlight, such discrepancies distort cross-comparisons because the chosen unit frames system performance differently. From a theoretical standpoint (Section 3.2.1), functional unit definition is foundational in LCA and techno-economic studies. Adopting dual reporting both per kilogram of dried product and per kilogram of water removed may offer a pragmatic pathway toward comparability.

3.2.4 Economic indicators and assumptions

Economic indicators such as LCOH, cost per kg dried, payback period, NPV, and IRR are essential for evaluating feasibility. However, their calculation often depends on assumptions that vary widely across studies. For instance, payback periods for GHDs have been reported between 1.5 and 4 years [13,48], yet these estimates hinge heavily on local energy prices, seasonal utilization rates, and maintenance assumptions. Similarly, NPV outcomes fluctuate depending on the discount rate and lifespan applied, as demonstrated in [47,49]. IRR values, typically reported between 10% and 25% [23,45], require explicit comparison with the weighted average cost of capital (WACC) to be meaningful. Without such standardization, results risk being context-specific and non-transferable.

The integration of these economic indicators with performance metrics, as discussed in Section 3.1.3, underscores the need for the 4E + Q framework [27]. By explicitly combining

energy, exergy, economic, environmental, and quality dimensions, future research can move beyond fragmented analyses toward a holistic approach.

3.2.5 *Carbon intensity, embodied energy, and EPBT*

Environmental indicators complement techno-economic assessments but face similar challenges of definition and scope. Carbon intensity, expressed as kg CO_{2e} per kg of dried product, is often reported without distinguishing between operational and embodied emissions [7,8]. This omission underestimates the full lifecycle footprint, as highlighted in Section 3.2.2 on embodied energy. Reported embodied energy values for GHD systems range between 500 and 2000 MJ [5,6], with EPBT typically falling between 1.6 and 3.6 years [26]. Yet, the absence of standardized databases and inconsistent system boundaries hinder comparability across studies.

Adopting ISO-compliant LCA methods (ISO 14040/44) with clear cradle-to-grave boundaries would enhance the robustness of these indicators, aligning practice with theoretical frameworks (Section 3.2.1). Explicit reporting of emission factor sources (e.g., IPCC vs regional databases) would further strengthen the credibility of carbon intensity values.

3.2.6 *Toward harmonization of reporting standards*

To address the inconsistencies observed, scholars propose harmonized reporting protocols. These include: (i) establishing standardized functional units [46], (ii) developing consensus-based guidelines for indicator definitions [50], (iii) integrating multi-criteria decision analysis (AHP, TOPSIS) to balance trade-offs across indicators [38,39], and (iv) creating collaborative platforms for data sharing [48]. Such proposals align with the hypothesis articulated in Section 1, namely, that standardized indicator frameworks will improve comparability and synthesis across studies.

3.2.7 *Implications and linkages to hypothesis*

The synthesis of findings under Theme 1 supports the central hypothesis of this review: that the lack of standardized indicators is a critical barrier to evidence accumulation and practical deployment of GHDs. The heterogeneity in SMER, efficiency, functional units, and economic metrics demonstrates the fragmentation identified in the research problem (Section 1). By aligning indicator definitions with the theoretical frameworks of energy and exergy analysis, LCA boundaries, and MCDA approaches, this review underscores the feasibility and necessity of standardization. Table 1 provides a reference point for harmonized definitions, which can inform both academic research and policy frameworks. Harmonization not only enhances comparability but also ensures that techno-economic and environmental evidence can be effectively integrated into investment decisions, sustainability reporting, and agricultural innovation strategies.

3.2.8 *Carbon accounting & LCA practices in GHDs*

Carbon accounting and Life Cycle Assessment (LCA) practices are fundamental for evaluating the environmental performance of greenhouse dryers (GHDs). Unlike purely techno-economic indicators, which emphasize efficiency and financial feasibility, carbon accounting provides a systematic framework to quantify greenhouse gas (GHG) emissions

across the entire life cycle of a system. This includes both operational emissions during use and embodied emissions associated with materials, construction, and end-of-life stages. The integration of carbon accounting into GHD research responds directly to the research gaps identified in Section 1 and is supported by the theoretical frameworks elaborated in Section 3.2, particularly ISO 14040/44 standards and GHG Protocol scopes. Despite its importance, current literature demonstrates inconsistencies in boundary definitions, choice of impact assessment methods, and treatment of uncertainties. Table 2 summarizes how selected studies address functional units, system boundaries, impact assessment methods, emission factors, Global Warming Potential (GWP) for operational and embodied phases, end-of-life considerations, and sensitivity analyses.

Table 2. Carbon Accounting & LCA Practices in Greenhouse Dryer Studies (Theme 2)

Study / Reference	Functional Unit	System Boundary	Impact Method	Emission Factor Source	GWP Operational (kg CO ₂ e/kg)	GWP Embodied (kg CO ₂ e/kg)	EoL / Recycling Treatment	Uncertainty / Sensitivity Analysis
[51]	kg dried product	Operational + embodied (partial)	NR	NR	NR	NR	Economic carbon credit valuation	Reported qualitatively
[52]	kg dried product	Operational + embodied (partial)	NR	NR	NR	NR	Not reported	Not reported
[53]	kg dried product	Operational + embodied (partial)	NR	NR	NR	NR	Not reported	Not reported
[11]	NR	NR	NR	NR	NR	NR	NR	NR
[22]	kg dried product	Operational + embodied (partial)	NR	NR	NR	NR	Not reported	Not reported
[54]	kg dried product	Operational + embodied (partial)	NR	NR	NR	NR	Not reported	Not reported
[55]	NR	NR	NR	NR	NR	NR	NR	NR
[55]	NR	NR	NR	NR	NR	NR	NR	NR
[54]	kg dried product	Operational + embodied (partial)	NR	NR	NR	NR	Not reported	Not reported
[56]	NR	NR	NR	NR	NR	NR	NR	NR

[57]	NR	NR	TRACI	Ecoinvent	Quantified	Quantified	Included	Sensitivity included
[58]	kg dried product	Operational + embodied	NR	NR	NR	NR	Not reported	Not reported
[59]	kg dried product	Operational + embodied	NR	NR	NR	NR	Not reported	Not reported

3.2.9 Operational vs. embodied emissions

The distinction between operational and embodied emissions is central to accurate carbon accounting. Operational emissions capture GHGs generated during use, often linked to auxiliary heaters, fans, or PV/T modules [5,6]. For instance, electricity consumption during extended drying periods contributes significantly to operational footprints. Embodied emissions, by contrast, include the carbon costs of materials, construction, and transport. Studies such as [12,19] emphasize the importance of capturing both dimensions, yet Table 2 shows that most GHD-focused studies report only partial or qualitative data. This imbalance risks underestimating total lifecycle impacts, especially for systems integrating material-intensive TES or PCM modules.

3.2.10 Impact assessment methods

Impact assessment methods vary across studies, with ReCiPe, TRACI, and Environmental Footprint (EF) being the most common in related solar-thermal research. ReCiPe allows assessment at midpoint (e.g., GWP, eutrophication) and endpoint (e.g., damage to human health) levels [19]. TRACI, widely applied in North America, aligns with regulatory frameworks and has been used in LCA of biomass digestate processing [57]. EF, promoted by the European Commission, facilitates alignment with EU sustainability metrics. However, as shown in Table 2, most GHD studies either omit explicit mention of methods or rely on unspecified assumptions. This omission undermines transparency and limits comparability. Harmonization through ISO 14040/44-compliant methods is therefore essential, as highlighted in Section 3.2.1.

3.2.11 End-of-life (EoL) scenarios

End-of-life scenarios strongly influence carbon accounting outcomes. Options include reuse, recycling, or disposal. [6,35] show that recycling of metals and plastics reduces embodied GHGs, while emphasize the benefits of incorporating reuse into dryer design. Conversely, disposal through landfill or incineration increases emissions. Table 2 illustrates that most GHD studies fail to document EoL assumptions, reflecting a major gap in sustainability reporting. Integrating explicit EoL modeling into GHD LCAs would align with best practices in renewable energy assessment and improve credibility.

3.2.12 Emission factors and regional grid intensity

Emission factor selection is another critical determinant of accuracy. While IPCC default values provide global comparability, localized emission factors better capture regional electricity mixes [33,34]. For example, hybrid GHDs connected to coal-dominant grids exhibit higher operational GWP than those using renewable-rich grids. Yet, as seen in Table 2, most GHD studies fail to specify emission factor sources, obscuring context-specific insights. Linking carbon accounting to regional grid intensities enhances relevance for policymakers evaluating scaling potential.

3.2.13 Uncertainty and sensitivity analyses

Uncertainty and sensitivity analyses remain underdeveloped in GHD carbon accounting. Sources of uncertainty include variability in climatic data, emission factors, and system performance. Studies applying Monte Carlo simulations [27] demonstrate how probabilistic approaches enhance robustness by identifying parameters most influential on GWP outcomes. Table 2 shows that only a handful of studies incorporate such analyses, with [57] providing an example of sensitivity assessment in related digestate systems. Expanding uncertainty treatment in GHD LCAs is crucial to align with Section 3.3.4's emphasis on uncertainty propagation.

3.2.14 Implications and linkages to hypothesis

The synthesis of evidence confirms the hypothesis advanced in Section 1: without standardized boundaries, impact methods, and explicit reporting of emission factors, carbon accounting in GHD studies remains fragmented. The omission of embodied emissions, EoL scenarios, and uncertainty analysis constrains comparability and risks underestimating true environmental impacts. Table 2 highlights these deficiencies, underscoring the urgent need for harmonized practices. By aligning GHD carbon accounting with ISO 14040/44, GHG Protocol scopes, and robust uncertainty treatment, the field can transition from fragmented assessments toward a standardized evidence base. Such harmonization will not only improve research comparability but also enhance the policy relevance of GHD studies, enabling their integration into carbon markets and climate mitigation strategies.

3.2.15 Techno-economic performance by configuration & storage

The techno-economic performance of greenhouse dryers (GHDs) varies considerably depending on system configuration, thermal energy storage (TES) integration, climatic conditions, and control strategies. This section reviews empirical and modeling-based studies on passive, active, hybrid, and repurposed systems, with a focus on how TES options including pebble beds, phase change materials (PCMs), and hybrid storage systems affect performance outcomes. The analysis links back to the theoretical frameworks outlined in Section 3, particularly the 4E + Q approach (energy, exergy, economics, environment, and quality). The findings are summarized in Table 3, which maps performance indicators such as Specific Moisture Extraction Rate (SMER), thermal and exergy efficiencies, drying time, cost per kilogram dried, and financial viability metrics including Net Present Value (NPV), Internal Rate of Return (IRR), and payback period.

Table 3. Techno-Economic Performance of Greenhouse Dryers by Configuration and Storage (Theme 3)

System Type	Location / Climate	Product / Target Moisture	TES Type	Control Strategy	SME R (kg/kWh)	Thermal / Exergy Efficiency (%)	Cost per kg Dried	NPV / IRR / Payback	Key Sensitive Parameters	Reference ID
Passive GHD	Tropical (NR)	General crops	None	Natural convection	~0.20 (Desai et al., 2021)	20–41.5% [16]	Low	Payback 3–4 yrs	Energy price seasonality	#1
Active GHD	Semi-arid (NR)	Vegetables	None	Forced convection	>0.20	28–40% [19]	Medium	Payback 2–3 yrs	Electricity tariff, airflow	#2
Hybrid GHD	Temperate	Multiple crops	PCM	Mixed (active + TES)	0.27–0.31 (Shimpy et al., 2022)	>30% [19,1]	Medium	Payback 1.6–2.5 yrs	PCM cost, discount rate	#3
Repurposed GH	Variable	Herbs, fruits	Various	Retrofit	Variable	Variable	Medium	Case-specific	Retrofit cost	#4
Pebble Bed GHD	Arid	Vegetables	Pebble bed	Natural convection	Improved	+17.5% efficiency [26]	Low	Shortened by ~50%	Pebble availability	#5
PCM-based GHD	Temperate	Vegetables	PCM	Controlled	Improved	Extended operation hours [26]	Medium	Payback 2–3 yrs	PCM cost	#6
Hybrid TES GHD	Temperate / Variable	Multiple crops	Hybrid (PCM + sensible)	Controlled with auxiliary	High	>35%	Medium–High	Positive NPV (Rulaz et al., 2023)	Energy price, PCM lifespan	#7
CFD-Optimized GHD	Variable	General crops	PCM / Pebble	Optimized airflow	Enhanced SME R	Higher exergy [22]	Predicted lower costs	Model IRR <20%	Model parameters	#8

3.2.16 Passive, active, hybrid, and repurposed systems

Passive GHDs, relying solely on natural convection, demonstrate modest SMER (~0.20 kg/kWh) and thermal efficiencies of 20–41.5% [16]. While capital and operating costs remain

low, drying times are long, and payback periods often extend to 3–4 years. Active GHDs enhance airflow using fans, yielding thermal efficiencies between 28% and 40% and reducing drying time. However, the reliance on electricity introduces sensitivity to tariff fluctuations. Hybrid systems, which integrate TES such as PCMs, achieve SMER values of 0.27–0.31 kg/kWh with efficiencies exceeding 30% [1]. These systems reduce drying times significantly and shorten payback to as low as 1.6 years [26]. Repurposed greenhouses, converted from agricultural use, show highly variable performance depending on retrofitting quality [8]. While potentially cost-effective, outcomes remain case-specific.

3.2.17 Thermal energy storage (TES) Impacts

TES integration is pivotal in enhancing techno-economic performance. Pebble beds, a low-cost option, increase thermal efficiency by ~17.5% and reduce drying times by half compared to open sun drying [26]. PCM-based TES extends drying operations beyond sunset, stabilizing microclimates and reducing reliance on auxiliary power [26]. Although PCM costs are higher, shortened payback periods (2–3 years) often offset initial investments. Hybrid TES systems combining PCMs with sensible storage or auxiliary heaters deliver the highest efficiencies (>35%) and demonstrate positive NPVs under realistic discount rates [24].

3.2.18 Climatic influences

Climatic conditions significantly shape techno-economic outcomes. Tropical climates favor passive and active GHDs due to abundant solar irradiance and stable ambient conditions. In arid zones, low humidity accelerates drying but extreme heat may necessitate cooling, raising costs [7,24]. Temperate climates often demand hybrid TES solutions to counter variability in insolation, with [26] showing TES reduces payback periods despite higher capital costs. Thus, climate-contextualized evaluations are critical for policy and investment decisions.

3.2.19 Role of control strategies

Control strategies, such as ventilation management and load ratio optimization, directly affect SMER and energy use. Passive systems lack precise control, while active and hybrid configurations enable adaptive airflow and temperature management. Retrofitted repurposed systems depend heavily on design interventions, with poorly optimized controls limiting performance gains [8]. The integration of CFD-informed designs [22] shows strong potential for enhancing uniform airflow, reducing stratification, and optimizing energy use.

3.2.20 Contribution of CFD modeling

CFD simulations provide predictive insights into airflow, moisture migration, and thermal dynamics [22]. Studies demonstrate their ability to optimize fan placement, vent geometry, and TES integration, yielding higher SMER and exergy efficiency. CFD reduces the need for costly prototypes, offering virtual optimization pathways that enhance cost-effectiveness. Linking CFD to techno-economic models enables estimation of ROI under varied conditions, providing a valuable decision-support tool [43].

3.2.21 Implications and linkages to hypothesis

The evidence reviewed confirms the hypothesis that system configuration, TES, and climate conditions critically shape techno-economic performance. Passive systems, while low-cost, are limited in efficiency and drying speed. Active and hybrid systems provide superior performance, with TES integration proving essential for achieving favorable SMER, efficiency, and financial viability. Climatic variability underscores the importance of context-specific evaluations, while CFD optimization highlights the pathway toward standardized, cost-effective designs. As summarized in Table 3, the heterogeneity of outcomes reflects the gaps in standardized reporting, reinforcing the need for harmonized indicators discussed in Section 4.1. Ultimately, aligning techno-economic analysis with the frameworks in Section 3 ensures comparability and strengthens the case for scaling GHD adoption globally.

3.2.22 Linking indicators to product quality & value

The relationship between greenhouse dryer (GHD) performance indicators and product quality has emerged as a crucial dimension in evaluating their techno-economic and environmental viability. While earlier research focused primarily on energy efficiency and drying kinetics, recent studies emphasize how these indicators translate into tangible product quality attributes such as color retention, nutrient preservation, texture integrity, and sensory acceptability. These quality outcomes, in turn, shape market value, enabling producers to capture premium prices and reduce losses from spoilage or consumer rejection. As outlined in the theoretical framework (Section 3), integrating quality metrics within the 4E+Q paradigm (Energy, Exergy, Economics, Environment, and Quality) allows for a holistic assessment of GHD systems.

Table 4 synthesizes evidence from selected studies on how specific indicators drying time, energy intensity, and CO₂e emissions are directly linked to product quality metrics and, consequently, economic value. The discussion below unpacks these relationships, highlighting trade-offs between drying speed, energy costs, and product quality.

Table 4. Linking Indicators to Product Quality and Value in GHD Studies (Theme 4)

Product	Quality (ΔE, a w)	Metrics Vitamin,	Trade-offs	Validation Notes	Ref ID
Mixed crops (repurposed GH, summer use)	Color, water activity	Nutrients, moisture activity (NR)	Time vs. quality vs. energy	Sensory/market tests (NR)	#1
Mint	Color	Essential oils	Time vs. quality vs. energy	NR	#2
Pepper	Color, texture	(NR)	Temperature vs. vitamin loss	NR	#6
Coffee	Cup quality (flavor, color)	(NR)	Drying speed vs. cup quality	Sensory validation	#9
General crops	NR	NR	Temperature–time balance	NR	#12
Various crops	NR	NR	Time–energy–quality relationship	NR	#13

3.2.23 Impact of drying parameters on quality metrics

Drying time and temperature are primary determinants of quality outcomes [20,17] demonstrate that excessive drying temperatures accelerate throughput but induce non-enzymatic browning, causing ΔE shifts that lower consumer appeal. Moderate operating temperatures, conversely, retain more natural color and prevent texture hardening, thereby preserving marketability. Similarly [60] show that improper parameter control results in brittle or leathery textures, reducing consumer acceptability. Optimizing these parameters ensures that energy efficiency indicators such as Specific Moisture Extraction Rate (SMER) align with product quality outcomes.

3.2.24 Nutritional retention and economic implications

Studies [61] highlight that nutrient retention, particularly vitamin C and antioxidants, diminishes sharply at elevated temperatures and prolonged drying durations. GHDs designed with integrated thermal energy storage (TES) provide stable conditions that mitigate such losses, reinforcing links between embodied energy, operational efficiency, and product nutritional quality. Economically, high-quality dried products command premium prices, often 20–50% higher, as reported by [62]. This premium directly correlates with techno-economic metrics such as cost per kilogram dried and payback period, as better quality reduces waste and increases profitability.

3.2.25 Trade-offs between speed, energy use, and quality

Empirical evidence indicates a clear tension between rapid drying and quality preservation. Accelerating drying through high temperatures or forced convection reduces drying time and improves throughput, but often at the expense of color and nutrient integrity [17,20]. Conversely, slower drying at lower temperatures preserves quality but requires higher energy input per unit of water removed. Optimization models incorporating multi-criteria decision analysis (MCDA) are increasingly used to balance these competing objectives, allowing stakeholders to maximize SMER while maintaining acceptable quality thresholds.

3.2.26 Market value and consumer preferences

Consumer willingness to pay for premium dried products underscores the importance of linking performance metrics to value creation.[17] emphasize that quality differentiation provides competitive advantage in markets oriented toward organic and specialty products. Sensory testing and consumer surveys validate the link between preserved attributes (color, aroma, nutrient content) and higher market prices. In repurposed greenhouse dryers [51], such validation is particularly important to justify seasonal retrofitting investments.

3.2.27 Validation approaches linking indicators and value

Validation of quality–value linkages relies on sensory analysis, chemical assays, and market surveys. Sensory tests provide organoleptic confirmation of product appeal [17], while nutritional analyses quantify retention of vitamins and bioactive compounds. Comparative studies, such as those on cocoa beans or coffee [63], reinforce that GHDs outperform conventional sun drying in both quality and economic returns. Process modeling,

including response surface methodology (RSM), further validates trade-offs by predicting how shifts in temperature or airflow affect both ΔE and energy use.

3.2.28 *Implications and linkages to hypothesis*

The synthesis presented in Table 4 and supporting studies confirms the hypothesis that integrating product quality into techno-economic and environmental metrics is essential for a holistic evaluation of GHDs. Indicators such as drying time, energy intensity, and CO_{2e} emissions not only define system efficiency but also shape consumer perception and market value. By linking these dimensions, the 4E+Q framework ensures comparability and strengthens the evidence base for scaling GHDs as sustainable post-harvest technologies. Furthermore, harmonizing validation approaches across sensory, market, and chemical domains enhances credibility and policy relevance.

Suggested Figure 4. Radar chart comparing selected GHD configurations on four axes: product quality (ΔE , nutrient retention), cost per kilogram dried, CO_{2e} per kilogram dried, and drying time. This visualization would illustrate trade-offs and highlight configurations capable of simultaneously achieving efficiency, sustainability, and quality-driven value capture.

3.3 Discussion

The synthesis of findings from Section 4 highlights both the progress achieved and the persistent challenges in evaluating greenhouse dryers (GHDs) through techno-economic, environmental, and quality-linked indicators. By integrating evidence across themes indicator standardization, carbon accounting, techno-economic performance, and quality–value linkages this section critically reflects on consistencies, contradictions, methodological limitations, and broader implications.

3.3.1 *Fragmentation and the need for standardization*

The review underscores that heterogeneity in indicator definitions continues to undermine comparability across GHD studies. Indicators such as Specific Moisture Extraction Rate (SMER), thermal efficiency, and exergy efficiency are widely reported, yet studies adopt divergent formulas and system boundaries. For instance, SMER values range from 0.5 to 3.0 kg/kWh depending on methodological assumptions [23,13], while exergy efficiency is reported from as low as 4.5% to as high as 80% [46,47,7]. Such discrepancies, as captured in Table 1, reflect the lack of harmonization in reference states and functional unit definitions. This fragmentation not only impedes meta-analysis but also obscures policy-relevant insights. The integration of canonical formulas, as proposed in Section 4.1, is therefore essential for building a coherent evidence base.

3.3.2 *Operational vs. embodied emissions: a persistent blind spot*

Carbon accounting in GHDs remains partial and inconsistent. Most studies focus on operational emissions such as energy use for fans or auxiliary heaters while embodied emissions related to construction materials, thermal energy storage (TES), and PV/T modules are often omitted. As shown in Table 2, only a limited number of studies report life cycle results aligned with ISO 14040/44. This neglect risks underestimating the full carbon footprint, particularly for material- intensive hybrid and PCM-based systems. Section 3.2

emphasized the theoretical necessity of cradle-to-grave boundaries, yet practice lags behind. The absence of end-of-life (EoL) considerations, noted by [35], further narrows the reliability of assessments.

3.3.3 *Divergence in techno-economic performance*

Performance comparisons across configurations reveal both strengths and trade-offs. Passive GHDs remain attractive for low-resource contexts due to low CAPEX but demonstrate limited efficiency (SMER ~0.20 kg/kWh) and long payback periods of 3–4 years [16]. Active systems achieve higher efficiencies (28–40%) but are vulnerable to electricity tariffs. Hybrid systems with TES consistently outperform both, with SMER of 0.27–0.31 kg/kWh and payback periods as short as 1.6 years [26]. Pebble beds, a low-cost TES option, deliver efficiency gains of ~17.5% [26], while PCMs provide superior control but at higher upfront costs. As detailed in Table 3, these variations underscore the importance of context-specific design choices. Climatic conditions further amplify divergence, with tropical regions enabling robust passive systems, while temperate climates demand hybrid TES to buffer variability [7,24].

3.3.4 *Linking quality to economic and environmental indicators*

A salient contribution of this review is the recognition that product quality cannot be separated from techno-economic and environmental evaluations. Studies consistently show that high drying temperatures, while reducing time and energy use, degrade color (ΔE), texture, and nutrient retention [20,17,60]. Conversely, quality preservation enables premium pricing of 20–50% above conventional products [62], reducing effective payback periods and boosting NPV. As shown in Table 4, trade-offs between speed, energy, and quality necessitate optimization models that integrate sensory validation, chemical analysis, and market surveys [63]. The incorporation of quality into techno-economic frameworks validates the 4E+Q paradigm outlined in Section 3.3 and strengthens the holistic case for GHDs.

3.3.5 *Methodological limitations and biases*

Several methodological gaps constrain the robustness of current evidence. First, few studies explicitly report uncertainty or sensitivity analyses, despite their importance for carbon accounting [27]. Second, functional unit inconsistencies (kg dried product vs. kg water removed) impede cross-comparison [46]. Third, reliance on localized assumptions about energy prices, discount rates, and maintenance costs biases financial indicators such as NPV and IRR [49,47]. Finally, EoL scenarios are rarely modeled, although reuse and recycling have demonstrable potential to reduce embodied emissions [35]. These omissions reflect a methodological conservatism that must be addressed through harmonization and adoption of ISO-compliant, MCDA-supported frameworks.

3.3.6 *Theoretical and practical implications*

The findings have important implications for both theory and practice. Theoretically, the results validate integrative frameworks such as the 4E+Q, confirming that quality must be embedded within techno-economic and environmental assessments. They also reinforce the relevance of exergy-based evaluations in uncovering hidden inefficiencies overlooked by

first-law analyses. Practically, the evidence suggests that TES particularly PCMs and hybrid configurations offer the most reliable pathway to improve efficiency, reduce emissions, and preserve quality across climates. Moreover, the capacity of GHDs to generate carbon credits [7,8] positions them as not only technological but also financial instruments within emerging carbon markets.

3.3.7 *Future research directions*

Future research should prioritize three key areas. First, harmonization of indicator definitions and system boundaries is essential to enable meta-analyses and comparability across studies. Second, comprehensive LCAs incorporating operational, embodied, and EoL phases are needed to provide accurate carbon accounting. Third, greater emphasis on linking product quality with techno-economic and environmental metrics through standardized sensory and market validation will strengthen the case for GHD adoption. CFD simulations, already applied in design optimization [22], should be further integrated with economic and quality models to enhance predictive capability. Finally, attention must be given to the scalability of GHDs in diverse socio-economic contexts, ensuring benefits extend to smallholder farmers as well as industrial producers.

Overall, the discussion confirms that GHDs offer significant potential as low-carbon, quality-preserving post-harvest technologies, but this potential is constrained by fragmented methodologies and inconsistent reporting. The synthesis of Sections 4.1 to 4.4 demonstrates the interdependence of performance, emissions, economics, and product quality. Addressing methodological gaps through standardization, comprehensive carbon accounting, and robust quality validation will not only enhance academic rigor but also strengthen the policy and market relevance of GHD research.

4 Conclusion

This systematic literature review examined the techno-economic and environmental indicators of greenhouse dryers (GHDs) with a particular focus on standardization, carbon accounting, system configuration, and linkages to product quality. The review found that while indicators such as Specific Moisture Extraction Rate, thermal and exergy efficiency, and economic metrics like payback period and Net Present Value are frequently reported, inconsistent definitions and functional units hinder comparability. Carbon accounting practices remain fragmented, with most studies focusing on operational emissions while neglecting embodied emissions and end-of-life scenarios. Techno-economic performance varies widely across system types: passive systems offer low-cost but limited efficiency, active systems improve throughput but depend on electricity tariffs, and hybrid systems with thermal energy storage deliver superior performance and shorter payback periods. Importantly, product quality emerges as a central determinant of value, with color retention, nutrient preservation, and sensory attributes directly influencing market competitiveness and premium pricing.

The research questions posed in this review are answered as follows: (1) Key indicators are reported but inconsistently defined; (2) Carbon accounting that integrates both operational and embodied emissions reveals a fuller sustainability profile, though rarely applied; (3) Design, storage type, and climatic conditions strongly influence costs and carbon intensity; (4) Harmonization of indicators is essential to enable cross-study synthesis and policy relevance. Overall, the study contributes to advancing the framework by embedding product quality alongside energy, exergy, economics, and environment. Future research

should focus on developing consensus-based reporting guidelines, expanding ISO-compliant life cycle assessments, and integrating computational fluid dynamics with economic and quality models to improve predictive capacity and scalability. By addressing these gaps, GHDs can be positioned as robust, low-carbon technologies supporting sustainable agriculture and climate action..

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