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*Review*

# A Critical Review of Trends in Performance Evaluation of Hybrid Solar Dryers: Focus on Energy Efficiency

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**Abstract:** Solar drying of biomass has gained prominence as a pretreatment step for biofuel production. The literature presents a wide diversity of definitions and terminologies for evaluating solar dryer performance, particularly in systems with supplementary energy inputs, limiting consistent comparisons between studies. This review provides a critical analysis of the main energy-based performance indicators, with emphasis on hybrid systems. Collector and drying chamber efficiencies are examined based on thermal and energy concepts, considering different dryer configurations. Standardized formulations are proposed to better represent the underlying processes and clarify the distinctions between PV and PVT-assisted systems. The analysis shows that collector performance in active systems is more consistently represented when based on absorbed solar energy and electrical power consumed by the fan. Accurate assessment of drying performance requires accounting for the heat of moisture desorption, sensible heating of the product, useful solar energy for air heating, fan power and supplementary energy inputs. Instantaneous efficiencies are more informative than cumulative ones, as they enable identification of less efficient drying periods and provide insights for optimizing operating conditions and reducing energy consumption. Continuous monitoring of key process variables including solar radiation intensity, air and product temperatures, and product mass is therefore required. Overall, this review establishes a consistent framework for the assessment of solar dryers, enhancing comparability and supporting more reliable analyses across studies. Future research should focus on the effects of intermittent and variable airflow rates on system performance.

**Keywords:** Solar Energy; Infrared Radiation; Hybrid Drying; Biomass; Performance Parameters

## 1. Introduction

It is currently estimated that approximately 80% of global energy demand is still met by fossil fuels [1]. Efforts to reduce this heavy dependence and mitigate the associated climate impacts have driven significant growth in research and development of sustainable energy sources [2]. Among the most promising alternatives for contributing to a more robust and environmentally sustainable energy matrix are biofuels. These are produced from raw materials such as biomass generated during the harvesting and processing of agricultural crops [3]. This biomass can undergo thermochemical conversion processes—such as combustion for direct energy generation, or torrefaction, pyrolysis, liquefaction, and gasification—to produce biochar, bio-oil, and biogas [4]. Another approach involves subjecting the biomass to fermentation processes for the production of second-generation bioethanol [5].

The use of several types of residual biomass is limited by their high moisture content. Drying is therefore a key pretreatment step to reduce moisture content from 50–75% to 10–15% (w.b.). This improves the yield of thermochemical conversion processes and the quality of the biofuels produced. It also ensures the physical, chemical, and microbiological stability of the biomass during extended storage periods [6].

Pneumatic, rotary drum, and fluidized bed dryers are widely employed for biomass drying [7]. However, these conventional systems generally require high energy input, resulting in elevated operating costs and, in some cases, relatively low drying efficiency [8]. Consequently, increasing attention has been directed toward alternative drying technologies. Among them, solar drying systems, which utilize solar radiation as the primary heat source, have emerged as a sustainable and energy-efficient solution.

Solar energy is an abundant and renewable resource that is widely available. Nevertheless, a major challenge associated with this energy source lies in its effective and efficient utilization. These requirements can be achieved through the application of solar radiation in processes that demand low to medium temperature ranges [9]. A representative example of such an application is the use of solar dryers. These systems are classified based on design features, operational mode, solar energy utilization approach, and other criteria. The nomenclature commonly adopted for this classification includes the categories: active, passive, direct, indirect, mixed, and hybrid [10]. In hybrid dryers, a supplementary energy source is incorporated [11]. This auxiliary source can be employed to ensure the continuity of the drying process under conditions of increased cloud cover and/or during nighttime periods [10].

Various approaches have been reported for evaluating the performance of solar dryers, ranging from economic analysis to energy and exergy assessments [12]. These evaluations are typically based on coefficients, efficiencies, and performance indices [13], which vary according to the system configuration. This lack of standardization may lead to misinterpretations and hinder consistent comparisons across studies. Furthermore, even for a single dryer type, performance can be described using multiple parameters, such as energy efficiency, thermal efficiency, volumetric evaporation rate, specific energy consumption, surface heat losses, and unit steam consumption.

The majority of the energy required for biomass drying is supplied as heat, typically from heaters or combustion. However, in modern systems, additional energy inputs may be significant. Kudra [14] highlights several drying methods that require supplementary energy. For example, microwave drying requires electricity to generate electromagnetic waves and power motors that rotate the sample tray. Similarly, dryers with active hydrodynamics, such as fluidized bed, spouted bed, and pneumatic dryers, require energy to sustain airflow generated by fans. This airflow is essential for maintaining proper operating conditions and removing evaporated moisture.

The contribution of fans can be substantial, reaching up to 50% of the total energy consumption in fluidized bed dryers [15]. Neglecting this contribution may lead to misleading performance assessments. This issue becomes critical in hybrid solar dryers, where solar energy is combined with auxiliary sources, such as infrared lamps, electrical heaters, or photovoltaic-powered fans. In such systems, a comprehensive accounting of all energy inputs is required.

The standardization of performance parameters remains a challenge, as new types of dryers and design modifications continue to emerge, requiring adaptations to the equations employed in current studies.

Therefore, this work provides a comprehensive and critical review of energy-based performance parameters for solar dryers, with focus on indirect and hybrid modes, aiming to support more consistent and accurate evaluations.

## 2. Hybrid, Active and Indirect Solar Dryers

Active and indirect solar dryers essentially consist of a solar collector for air heating, a fan to provide forced airflow, and a drying chamber for biomass samples. The collector is typically inclined at an angle that maximizes solar radiation absorption throughout the year, taking into account the latitude of the location [16]. An example of such a system is shown in **Figure 1**, based on the design used by Andrade [17].

In this drying system, solar radiation (1) strikes the collector and passes through the transparent glass cover (2), reaching the absorber plate (4), which may feature different surface configurations, including flat or corrugated geometries or the incorporation of baffles. Corrugations and baffles increase the effective heat transfer area and promote airflow turbulence, thereby enhancing convective heat transfer to the working fluid within the solar dryer [18–20].

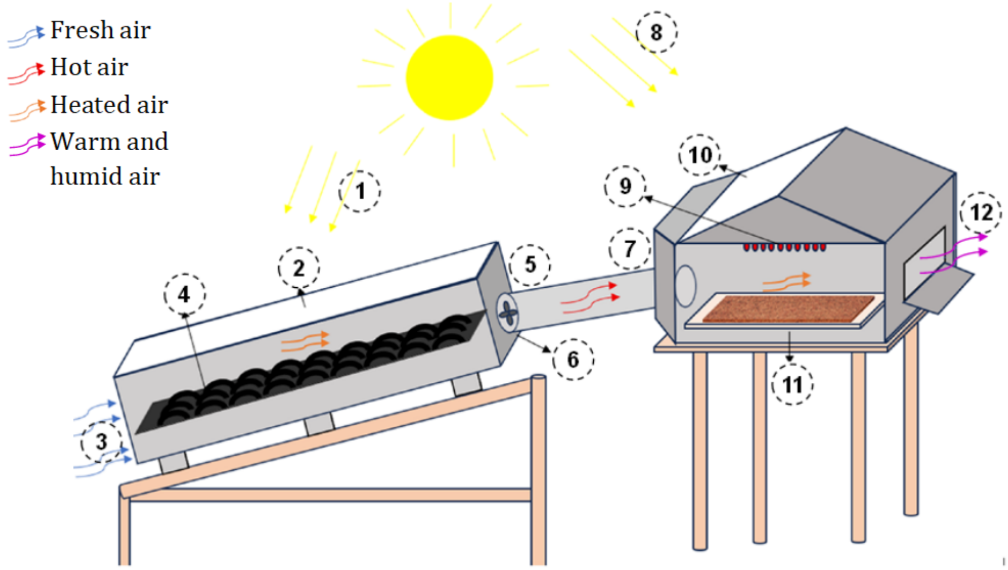


**Figure 1.** Schematic view of indirect solar dryer. ① Solar radiation incident on the collector, ② Transparent glass cover, ③ Fresh air inlet, ④ Absorber plate, ⑤ Hot air outlet from collector, ⑥ Fan, ⑦ Hot air inlet in chamber, ⑧ Solar radiation incident on the chamber, ⑨ Infrared lamp, ⑩ Transparent glass cover of chamber, ⑪ Biomass tray, ⑫ Warm and humid air exhaust.

The plate is commonly made of aluminum or another material with high absorptivity and emissivity. It is typically coated with black paint to maximize solar radiation absorption. The plate may be positioned at the base of the collector, where the air flows over it, or at the center of the collector box, where air is heated by contact with both its upper and lower surfaces. The heated air is then directed into the drying chamber, where it transfers heat and removes moisture from the biomass (11) by convection [21].

In forced convection systems, air transport is typically provided by a fan (6) or a blower. Smaller devices operate at lower flow rates, resulting in higher temperature increases in the collector, while also enabling more compact design and reduced costs [22].

Depending on the design, supplementary heating systems may be included, such as electrical resistance heaters or infrared sources (9). These configurations are classified as hybrid dryers. Their purpose is to accelerate the drying process and enable operation during nighttime or cloudy days [11].

Mixed drying systems are also employed, in which the biomass (11) receives heat both by convection from heated air and by direct solar radiation (8) through a transparent cover (10).

The performance of solar dryers is commonly evaluated using parameters derived from energy analysis, such as thermal efficiency, energy efficiency, and specific energy consumption. The theoretical background and key aspects of these and other performance indicators are discussed in the following sections.

## 3. Solar Dryer Performance Based on Energy Analysis

### 3.1. Collector Efficiency

Inside the solar thermal collector, fluid flow and heat transfer occur. The latter is described by a thermal energy balance that accounts for heat gains and losses [23], as illustrated in **Figure 2**.

The total rate of energy incident on the glass cover is denoted as $q_{Tc}$ (**Figure 2**). It is determined from the collector surface area ($A_c$) and the instantaneous solar radiation ($I$).

$$q_{Tc} = A_c I \tag{1}$$

A portion of the incident solar radiation is reflected back into the atmosphere, while another is transmitted through the glass cover. Part of the energy is lost to the surroundings, and the remainder is absorbed by the absorber plate and transferred to the air by convection [16]. For example, a 3 mm thick transparent glass typically transmits

86% of the incident radiation, reflects 8%, and absorbs 2%. Therefore, the rate of heat effectively absorbed by the plate ($q_a$) depends on transmittance ($\tau$) and absorptance ($\alpha$) of the cover. However, some studies neglect this distinction and consider only the total incident radiation ($q_{Tc}$).

$$q_a = \tau \alpha I A_c \tag{2}$$

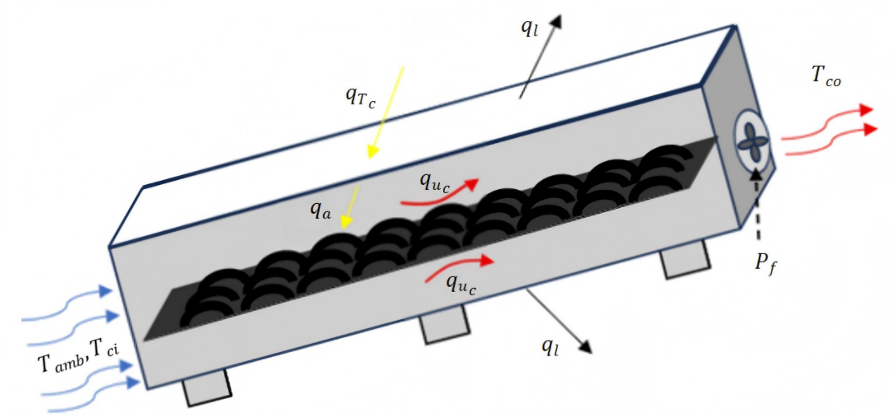


**Figure 2.** Detailed schematic of the solar collector.

The collector captures solar radiation and converts it into heat. Heat losses occur through radiation, conduction, and convection between the collector and the surroundings [24]. According to Imre [25], the heat loss rate ($q_l$) from the absorber plate depends on the overall heat transfer coefficient ($U_l$) and the temperature difference between the plate ($T_a$) and the ambient air ($T_{amb}$):

$$q_l = A_c U_l (T_a - T_{amb}) \tag{3}$$

The useful heat rate in the collector ($q_{uc}$) represents the energy available to heat the air flowing over the plate surfaces (**Figure 2**). It is obtained from the energy balance as the difference between the absorbed solar radiation and the thermal losses:

$$q_{uc} = q_a - q_l \tag{4}$$

Since $T_a$ varies along the collector, it is often approximated by the inlet air temperature ($T_{ci}$). However, this simplification neglects the air temperature rise along the collector, leading to an underestimation of thermal losses. A correction factor $F_R$ is therefore introduced to provide a more accurate estimate of the useful heat gain [25].

The actual useful heat gain ($q_{uc}$) is then given by the product of the collector heat removal factor and the maximum useful energy gain.

$$q_{uc} = F_R A_c [\tau \alpha I - U_l \, (T_{ci} - T_{amb})] \tag{5}$$

Duffie and Beckman [22] also state that in some approaches a definition based on average values is used:

$$q_{uc} = F_{R_{mean}} A_c [t \alpha I - U_l \left(T_{a_{mean}} - T_{amb}\right)] \tag{6}$$

A common method for determining the actual useful heat is to measure the inlet ($T_{ci}$) and outlet ($T_{co}$) air temperatures and the airflow rate ($\dot{m}_a$) during collector operation. From the air side, $q_{uc}$ can be expressed in terms of enthalpy or temperature differences:

$$q_{uc} = \dot{m}_a (h_{co} - h_{ci}) = \dot{m}_a c_{p,a} (T_{co} - T_{ci}) \tag{7}$$

Efficiency is a central concept in engineering, but it is often misunderstood. Thermal efficiency indicates how effectively the system converts the available solar energy into useful work or heat, whereas energy efficiency refers to the overall utilization of energy, including thermal, electrical, mechanical, and chemical forms.

The thermal efficiency of the collector ($\eta_{T,c}$) is defined as [22,25]:

$$\eta_{T,c} = \frac{q_{uc}}{q_{Tc}} \tag{8}$$

By substituting Equations (1) and (5) or (7) into Equation (8), $\eta_{T,c}$ can be expressed in different forms depending on the focus of the analysis:

$$\eta_{T,c} = F_R\left[t\alpha - \frac{U_l\,(T_{ci} - T_{amb})}{I}\right] \tag{9}$$

$$\eta_{T,c} = \frac{\dot{m}_a c_{p,a}(T_{co} - T_{ci})}{\mathrm{A_c I}} \tag{10}$$

When the focus is on collector characterization—i.e., parameters describing how the collector absorbs and loses energy, Equation (9) is typically used due to its higher level of detail. However, from the perspective of the air, which acts as the heating medium for drying, Equation (10) is more appropriate. In this case, thermal efficiency represents the fraction of solar energy converted into convective thermal energy for air heating [11]. Low efficiency values may indicate thermal losses or design limitations.

The efficiency obtained from Equations (9) or (10) is referred to as instantaneous thermal efficiency, as it can be evaluated at any given time. When a representative value for the process is required, it is typically averaged over the drying period. Both instantaneous and average efficiencies are widely employed to analyze and optimize the performance of solar collectors.

**Table 1** summarizes studies that employed Equation (10) and the corresponding nomenclature adopted by each author. Although the performance parameter represents thermal efficiency, some studies incorrectly refer to it as energy efficiency. Others use the term collector efficiency without specifying whether it refers to thermal or energy efficiency.

**Table 1.** Overview of recent studies employing Equation (10) and the corresponding nomenclature.

| Authors | Used Efficiency Name | Dryer Type |
|---|---|---|
| Goud et al. [26] | Collector efficiency | Active dryer with external PVT |
| Şevik et al. [27] | Collector thermal efficiency | Active hybrid dryer with IR heating |
| Ebadi et al. [28] | Collector energy efficiency | Active hybrid dryer with parabolic collector and electric heater |
| Mugi et al. [29]; Mugi and Chandramohan [30–32] | Collector efficiency | Active dryer with external PVT, similar to Goud et al. [26], with modifications in the cabin |
| Lingayat et al. [16] | Collector efficiency | Passive indirect dryer |
| Kumar et al. [33] | Thermal efficiency | General solar dryers |
| Ghasemi et al. [34] | Collector energy efficiency | Active hybrid (IR) dryer with parabolic collector and electric heater |

Five of the dryers listed in **Table 1** are active systems, similar to that shown in **Figure 1**. In these systems, airflow is driven by a fan, which may require additional electrical power ($P_f$). However, this energy consumption is not accounted for in the equation used. Therefore, a standardized nomenclature for collector thermal efficiency is required.

Goud et al. [26], Mugi et al. [29] and Mugi and Chandramohan [30–32] employed similar systems with minor modifications to the drying chamber, all powered by external photovoltaic (PV) panels. In recent studies, the main difference lies in the definition of the area used to calculate drying efficiency (see Section 3.3.4).

It is important to clarify that drying efficiency refers to the energy directly applied to the product within the chamber. It is therefore distinct from collector efficiency. In the aforementioned studies, the solar irradiation area includes both the collector and PV areas, suggesting an attempt to account for the electrical energy consumed by the fan. This raises the question of whether such contribution should also be included in the definition of collector thermal efficiency, since part of the solar energy is converted into electrical energy to drive the airflow.

In systems without PV panels, when electrical energy is required to sustain airflow, the collector efficiency should be defined as energy efficiency ($\eta_{E,c}$) rather than thermal efficiency. Nevertheless, inconsistencies in the terminology adopted still persist in the literature.

Since these different approaches to collector efficiency follow general concepts, they should not be regarded new performance metrics. Instead, they should be viewed as formulations adapted to specific configurations of active dryers.

César et al. [35] analyzed a mixed active dryer and defined the collector energy efficiency ($\eta_{E,c}$) by incorporating the fan power ($P_f$) into the denominator:

$$\eta_{E,c} = \frac{q_{uc}}{q_{Tc} + P_f} = \frac{\dot{m}_a c_{p,a}(T_{co} - T_{ci})}{IA_c + P_f} \tag{11}$$

This formulation assumes that electrical and solar inputs are used, respectively, to drive and heat the air within the collector. Although two studies [36,37] are cited by César et al. [35], neither adopts this definition.

Chowdhury, Bala and Haque [37] investigated an active tunnel dryer equipped with an external PV system and included the PV contribution in the definition of efficiency:

$$\eta_{T,c} = \frac{q_{uc}}{q_{Tc} + IA_{PV}} = \frac{\dot{m}_a c_{p,a}(T_{co} - T_{ci})}{IA_c + IA_{PV}} \tag{12}$$

In this case, the formulation represents the collector thermal efficiency, as the denominator accounts for the total incident solar energy used for air heating and flow. The term $IA_{PV}$ can be interpreted as the solar energy converted into electrical power for the fan. Some works [4,11] instead include this contribution in the numerator, treating it as useful energy.

Arslan [38] investigated a photovoltaic–thermal (PVT) collector, in which part of the incident solar radiation is converted into electricity and the remainder is used for thermal air heating. The generated electricity powers both the infrared lamp and the fan, enabling efficient utilization of solar energy for drying.

The performance of PVT collectors is generally evaluated in terms of thermal and electrical efficiencies, as well as their combined effect, defined as the overall efficiency ($\eta_{total,\ PVT}$), as presented in Equations (13)–(15).

$$\eta_{total,\ PVT} = \eta_{T,\ PVT} + \eta_{elec,\ PVT} \tag{13}$$

$$\eta_{T,\ PVT} = \frac{q_{uc,PVT}}{q_{Tc,PVT}} = \frac{\dot{m}_a c_{p,a}(T_{PVT,o} - T_{PVT,i})}{IA_{PVT}} \tag{14}$$

$$\eta_{elec,\ PVT} = \frac{P_{elec}}{q_{Tc,PVT}} = \frac{V_{\max} i_{\max}}{IA_{PVT}} \tag{15}$$

The key difference between PVT and external PV approaches lies in the use of the collector area. In the PVT configuration, the PV module covers the collector, and the same surface area is used simultaneously for electricity generation and air heating, as described by Equations (14) and (15).

In contrast, in external PV systems, the collector area ($A_c$) is used exclusively for thermal energy generation, while the PV area ($A_{PV}$) is dedicated to electricity production. Accordingly, in Equation (12), the total energy input is given by $IA_c + IA_{PV}$.

Drawing a parallel with Equation (11), the term $P_f$ represents additional electrical consumption not supplied by a PV system, justifying the use of energy efficiency for performance evaluation.

These observations indicate that fan power should be explicitly included in collector efficiency analyses.

Similarly, Nnamchi et al. [11] included fan power in the denominator, while defining useful heat based on Equation (6), replacing $T_{amb}$ with $T_{co}$:

$$\eta_{E,c} = \frac{q_{uc}}{q_{Tc} + P_f} = \frac{F_R A_c[t\alpha I - U_l\left(T_{a_{mean}} - T_{co}\right)]}{IA_c + P_f} \tag{16}$$

Kedar et al. [9] distinguish two types of collector efficiency: thermal efficiency, as defined by Equation (10), and effective efficiency ($\eta_{eff,c}$). The latter represents the net useful heat gain by incorporating energy losses associated with energy transmission and conversion:

$$\eta_{eff,c} = \frac{q_{uc} - (P_{mec}/C_{mec})}{q_{Tc}} \tag{17}$$

where $C_{mec}$ is a conversion factor (≈ 0.18) used to relate thermal energy to the mechanical power required by the fan ($P_{mec}$) [39]. $P_{mec}$ depends on the fluid pressure drop.

Hassan et al. [40] proposed a simplified formulation by subtracting the fan power ($P_f$) directly in the numerator, effectively replacing the term ($P_{mec}/C_{mec}$):

$$\eta_{eff,c} = \frac{q_{uc} - P_f}{q_{Tc}} = \frac{\dot{m}_a c_{p,a}(T_{co} - T_{ci}) - P_f}{IA_c} \tag{18}$$

In Equation (18), the numerator is reduced due to the subtraction of the fan power ($P_f$) from the useful heat rate ($q_{uc}$). As a result, effective efficiency provides an alternative measure of collector performance compared to Equations (10)–(12). It represents the fraction of incident solar energy ($q_{Tc}$) converted into thermal energy, excluding airflow-related energy consumption.

Dutta, Dutta and Kalita [41] replaced the total incident irradiance ($q_{Tc}$) in the denominator with the absorbed heat ($q_a$):

$$\eta_{T,c} = \frac{q_{uc}}{q_a} = \frac{\dot{m}_a c_{p,a}(T_{co} - T_{ci})}{t\alpha IA_c} \tag{19}$$

This approach yields higher thermal efficiency values, as it excludes energy losses during transmission through the glass cover. Therefore, using $q_a$ in the denominator provides a more representative measure than $q_{Tc}$.

**Table 2** presents a summary of selected studies cited in this review, allowing comparison of the nomenclature and efficiency formulations adopted.

**Table 2.** Overview of collector efficiency equations and nomenclature used for different solar dryers.

| Authors | Used Efficiency Name | Equation | Dryer Type |
|---|---|---|---|
| Chowdhury et al. [37] | Collector efficiency | (12) | Active tunnel dryer with external PV |
| César et al. [35] | Instantaneous thermal efficiency | (11) | Active mixed dryer |
| Dutta et al. [41] | Collector energy efficiency | (19) | Active mixed dryer |
| Arslan [38]; Arslan and Aktaş [42] | PVT thermal and electrical energy efficiency | (13)–(15) | Active hybrid PVT dryer with IR |
| Nnamchi et al. [11] | Instantaneous thermal efficiency | (16) | General solar dryers |
| Kedar et al. [9] | Thermal and effective collector efficiency | (10) and (17) | General solar dryers |
| Hassan et al. [40] | Effective collector efficiency | (18) | Indirect active dryer |

Equations (17) and (18) define the effective efficiency of the collector, which depends on the fluid flow conditions. By incorporating mechanical and electrical energy contributions, this parameter is more appropriately termed effective energy efficiency of the collector.

Both Equations (11) and (16) define collector energy efficiency, although they are referred to as thermal efficiency in the literature. The performance of solar collectors in active dryers should be standardized using energy or effective efficiency metrics, which account for the fan electrical consumption.

However, for solar dryers assisted by PV or PVT systems, thermal efficiency should be adopted as the reference parameter, as part of the solar energy is converted into electrical energy to drive airflow.

With regard to the solar energy input, it is recommended that all dryer types include transmittance and absorptance parameters, replacing $q_{Tc}$ with $q_a$. Therefore, Equation (19) is more representative of the collector efficiency than the conventional formulation given by Equation (10).

**Table 3** summarizes the recommended collector efficiency expressions and their corresponding nomenclature for each dryer type.

**Table 3.** Recommended expressions and nomenclature for collector efficiency according to dryer type.

| Type of Indirect Dryer | Suggested Expressions | Equation | Suggested Name |
|---|---|---|---|
| Passive | $\eta = \frac{\dot{m}_a c_{p,a}(T_{co}-T_{ci})}{t\alpha IA_c}$ | (19) | Collector thermal efficiency (passive dryers) |
| Mixed | $\eta = \frac{\dot{m}_a c_{p,a}(T_{co}-T_{ci})}{t\alpha IA_c + IA_d\alpha_d\tau_d}$ | (20) | Collector thermal efficiency (mixed dryers) |
| Active | $\eta = \frac{\dot{m}_a c_{p,a}(T_{co}-T_{ci})}{t\alpha IA_c + P_f}$ | (21) | Collector energy efficiency (active dryers) |
| Active with external PV in collector | $\eta = \frac{\dot{m}_a c_{p,a}(T_{co}-T_{ci})}{t\alpha IA_c + IA_{PV}}$ | (22) | Collector thermal efficiency (active dryers with PV) |
| Active with PVT collector | $\eta = \frac{\dot{m}_a c_{p,a}(T_{co}-T_{ci}) + V_{max} i_{max}}{IA_{PVT}}$ | (23) | Collector Energy efficiency (active dryers with PVT) |

Alternatively, the numerator may be based on the useful heat formulations given in Equations (5) or (6). For a more reliable efficiency evaluation, the denominator should follow the proposed expressions, replacing $q_{Tc}$ with $q_a$.

## 3.2. Drying Chamber Efficiency

Following the analysis of collector performance, this section examines how drying chamber performance has been evaluated in the literature.

Kudra [15] emphasizes that efficiency depends on material properties, process parameters, and dryer configuration. For instance, a single rotary dryer cannot be directly compared with a three-stage system, which benefits from heat recovery. The author also highlights inconsistencies in terminology, as drying performance can be described using various indices, such as energy efficiency, thermal efficiency, and specific energy consumption.

The standardization of these parameters remains a challenge due to the continuous development of new dryer designs.

**Figure 3** shows the drying chamber in detail. A glass cover allows the direct incidence of solar radiation at a rate $q_{Td}$, characterizing a mixed-mode solar dryer. The system is also hybrid, as it includes infrared (IR) radiation ($q_{IR}$) as a supplementary energy source to heat the product at a rate $q_{IR}$. The air heated in the solar collector enters the drying chamber with enthalpy $h_{di}$, temperature $T_{di}$, and humidity ratio $Y_{di}$, typically, matching the collector outlet conditions when the connecting duct is well insulated.

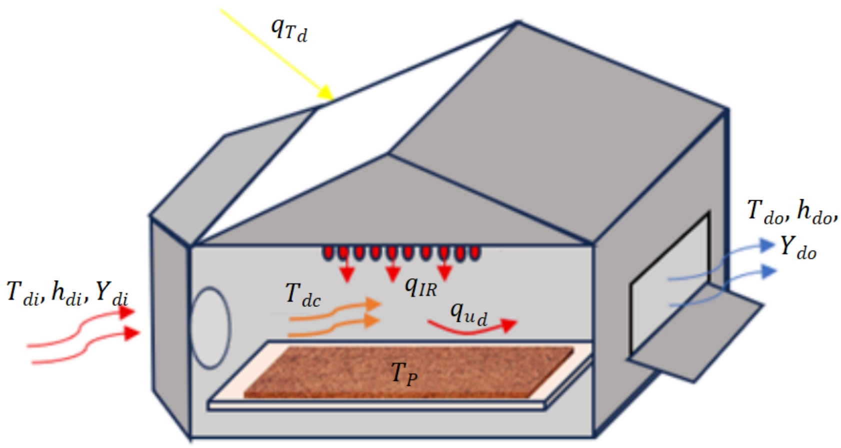


**Figure 3.** Detailed schematic of the drying chamber.

Within the chamber, the air transfers heat ($q_{ud}$) to the product, leaving with lower enthalpy ($h_{do}$) and temperature ($T_{do}$), and higher humidity ($Y_{do}$) due to moisture removal from the material. The average chamber air temperature is denoted by $T_{dc}$, while the product temperature is $T_P$.

The following sections address different drying performance indices, from fundamental definitions to recent developments.

### 3.2.1. Thermal and Energy Efficiencies

The energy performance of solar dryers must be assessed in a way that reflects the specific characteristics of each configuration, including direct, indirect, mixed-mode, hybrid, passive, active, and heat pump systems. Energy and thermal efficiencies are the most commonly used indices.

The energy efficiency of drying ($\eta_{E,d}$) is defined as the ratio between the energy required for moisture evaporation ($e_{ev}$) and the total energy supplied to the dryer ($e_t$) [14,15,43–45].

$$\eta_{E,d} = \frac{e_{ev}}{e_t} \tag{24}$$

Most of the energy in solar drying originates from solar radiation. However, depending on the dryer configuration, it is essential to account for the specific characteristics of the energy inputs. Particular attention should be given to supplementary energy sources, which are commonly present in hybrid and active solar dryers.

The energy required for moisture evaporation ($e_{ev}$) is generally calculated as the product of the evaporated water mass and the latent heat of vaporization of free water [14]. This mass can be determined either from the change in moisture content of the material or from the humidity variation of the drying air.

Nevertheless, the energy requirement for drying is not limited to free water evaporation, since most porous solids dry predominantly during the falling-rate period. This stage is governed by internal mass transfer resistances and involves mechanisms such as capillary flow, vaporization–condensation, gravity-driven flow, temperature gradient-driven flow, vapor diffusion, and pressure diffusion. Consequently, additional energy is required not only to heat the wet material initially and subsequently the dried layers, but also to remove bound water.

Thus, the energy demand for drying depends on the product's moisture content. In this context, it is recommended to replace, in Equation (24), the latent heat of vaporization of free water with the heat of desorption of moisture [14,44].

Heat balance data of convective dryers indicate that 20–60% of the supplied heat is used for moisture evaporation, 5–25% for heating the material, 15–40% is lost with exhaust air, 3–10% is lost through the dryer walls, and 5–20% corresponds to other losses [46].

Neglecting supplementary energy inputs, the thermal efficiency of solar drying ($\eta_{T,d}$) can be formulated based on air enthalpies and humidity ratios [47]:

$$\eta_{T,d} = \frac{\Delta H(Y_{do} - Y_{amb})}{(h_{di} - h_{amb})} \tag{25}$$

where $\Delta H$ is the latent heat of vaporization of water (kJ/kg); $h$ and $Y$ are the air enthalpy and absolute humidity, respectively. The subscripts "*di*," "*do*," and "*amb*" refer to dryer inlet, outlet, and ambient conditions, respectively.

In this way, $\eta_{T,d}$ represents the fraction of thermal energy from the air heated in the solar collector that is effectively used for moisture evaporation.

Under adiabatic conditions and assuming constant specific heats, it can be expressed as [15]:

$$\eta_{T,d} = \frac{T_{di} - T_{do}}{T_{di} - T_{amb}} \tag{26}$$

This formulation relates the cooling of the drying air in the chamber to its heating in the collector. It provides a simplified method for determining thermal efficiency based solely on the air temperatures.

Thermal efficiency approaches zero when $T_{do} = T_{di}$. The maximum value is attained when the air reaches its maximum moisture-carrying capacity and exits the chamber at the adiabatic saturation temperature ($T_{AS}$) or wet-bulb temperature ($T_{wb}$) [43]. Under this condition ($T_{do} = T_{wb}$), drying occurs in the constant-rate period, with latent heat entirely used for surface moisture evaporation.

When $T_{do} > T_{wb}$, moisture compensation ceases and dry regions appear. Part of the energy is then converted into sensible heat, raising the solid temperature. As a result, convective heat transfer decreases, the outlet air temperature increases, and thermal efficiency drops. This behavior characterizes the falling-rate drying period [48].

A maximum thermal efficiency ($\eta_{T,d,max}$) can therefore be defined as:

$$\eta_{T,d,max} = \frac{T_{di} - T_{wb}}{T_{di} - T_{amb}} \tag{27}$$

Thermal efficiency is meaningful only when compared with this maximum value. In solar drying, maximizing efficiency requires high inlet temperatures and near-saturated outlet air conditions. However, operating constraints must be considered, as excessive humidity can reduce the drying potential, while excessive temperatures may degrade product quality [14,49].

"Energy efficiency" ($\eta_{E,d}$) and "thermal efficiency" ($\eta_{T,d}$) are often used interchangeably in solar drying studies. However, for hybrid dryers with supplementary energy sources, energy efficiency is the more appropriate term. The same applies to convective dryers, where the electrical energy required for forced airflow is included in the total energy input.

Energy and thermal efficiencies quantify the fraction of energy used for water evaporation but do not account for losses with the exhaust air. An alternative metric is the drying efficiency ($\eta_D$), which incorporates the exhaust air enthalpy to account for these losses [15]:

$$\eta_D = \frac{energy\ used\ for\ evaporation\ at\ time\ t}{(input\ energy - output\ energy\ with\ outlet\ air)\ at\ time\ t} \tag{28}$$

Values of $\eta_D$ are generally higher than those for $\eta_{T,d}$ and $\eta_{E,d}$, as drying efficiency indicates how effectively the sensible heat supplied by the collector is used for evaporation.

According to some authors, the $\eta_D$ index is more suitable than $\eta_{T,d}$ and $\eta_{E,d}$ for evaluating drying performance, possibly due to the higher values it yields. However, $\eta_D$ contradicts the concept of thermal efficiency, since the total energy available in the drying air originates from solar heating, i.e., from the air conditions at the chamber inlet. In practice, depending on the solid–air contact conditions and the air residence time within the chamber, not all the available energy is effectively utilized.

By neglecting energy losses, $\eta_D$ tends to overestimate the drying performance. This may partly explain why this parameter is not widely applied in the evaluation of solar dryers. Even so, it may serve as a complementary metric to support the analysis.

Misuse of this index is common in the drying literature. When drying efficiency is incorrectly labeled as energy efficiency, the results are inherently overestimated, since thermal losses and additional energy inputs are not considered.

Therefore, a clear distinction among performance indices is essential for accurate analysis. This highlights the importance of a proper understanding of the underlying concepts and definitions to ensure the appropriate use of each index.

#### 3.2.2. Cumulative and Instantaneous Efficiencies

Energy, thermal and drying efficiencies can be expressed as either instantaneous or cumulative values.

Instantaneous efficiency enables the evaluation of energy performance at any drying time, revealing how it varies as the material dries. By plotting efficiency as a function of time or moisture content, less efficient periods can be identified, providing insights for adjusting operating conditions and reducing energy consumption.

The integration of instantaneous efficiency over time yields cumulative efficiency, which represents an average value over a given moisture range. By averaging fluctuations, cumulative efficiency provides an overall measure of system performance. However, it may mask efficiency losses at specific stages.

Cumulative efficiency is a global parameter, useful for comparing different dryers, but less informative for analyzing a specific process, as it is based on inlet and outlet conditions [50].

This approach is valid primarily under constant operating conditions, typically observed during the constant-rate period. However, in porous solids drying, the falling-rate period predominates, making efficiency highly dependent on the product moisture content. In this stage, energy is required not only for free-water evaporation but also for bound moisture removal. As a result, even under constant inlet conditions, the outlet air temperature and humidity vary [51].

Therefore, instantaneous indices are more suitable than cumulative ones for evaluating drying performance [14, 52]. However, accurate determination requires continuous monitoring of process variables. These include air temperature, humidity, velocity, solar radiation, infrared heat flux, and solid temperature. Sensors integrated with data acquisition and processing systems should be used.

#### 3.2.3. Alternative Dryer Performance Parameters

Specific energy consumption (*SEC*) is another parameter used to assess solar dryer performance, defined as the total energy supplied to the dryer per unit mass of evaporated water:

$$SEC = \frac{total\ energy\ consumption}{mass\ of\ water\ removed} \tag{29}$$

Another performance metric often employed in solar dryers is the coefficient of performance (*COP*). In its original form, *COP* is a heat pump efficiency index [43], defined as:

$$COP = \frac{useful\ heat\ output}{power\ input} \tag{30}$$

According to Strumiłło et al. [43], the specific moisture extraction rate (*SMER*) is a more suitable performance indicator. It is the reciprocal of *SEC* and represents the mass of water evaporated per unit of energy consumed (kg/kWh):

$$SMER = \frac{mass\ of\ water\ removed}{total\ energy\ consumption} \tag{31}$$

The theoretical maximum SMER for conventional thermal drying is 1.55 kg/kWh, corresponding to the latent heat of water evaporation at 100 °C. In practice, heat pump dryers can achieve values of around 3 kg/kWh, which are significantly higher than those of conventional systems, typically ranging from 0.5 to 1 kg/kWh.

Drying effectiveness (*DE*), proposed by Vijayan et al. [44], represents the ratio of outlet to inlet air relative humidity during the drying process:

$$DE = \frac{relative\ humidity\ of\ air\ at\ outlet}{relative\ humidity\ of\ air\ at\ inlet} \tag{32}$$

From this perspective, drying can be viewed as an air humidification process. Thus, a higher outlet relative humidity indicates a greater ability of the air to absorb moisture from the material, resulting in a higher *DE*.

Recent reviews [12,16] have introduced another parameter, known as pick-up efficiency. It measures the ability of heated air to absorb moisture relative to a saturated outlet condition:

$$\eta_{pick-up} = \frac{Y_{do} - Y_{di}}{Y_{sat} - Y_{di}} \tag{33}$$

### 3.2.4. Different Approaches to Solar Dryers Efficiency Reported in the Literature

A clear understanding of the different efficiency concepts enables a consistent analysis of the approaches reported in the literature on solar dryers.

Since the nomenclature used by different authors is not always consistent with the definitions of drying efficiency ($\eta_D$) and energy efficiency ($\eta_E$) adopted in this work, a generic symbol ($\eta$) is used, accompanied by the appropriate designation. Recommendations for nomenclature standardization are also provided.

- **Indirect solar dryers**

**Table 4** lists the main efficiency parameters commonly used in indirect solar drying. The following sections address more specific cases. It is important to note that, although some authors omit drying time ($t_d$) from the denominator, dimensional consistency requires its inclusion to ensure that all terms are expressed in the same extensive energy unit (kJ).

**Table 4.** Summary of the most frequent parameters in literature by type of indirect dryer.

| Type | Efficiency | |
|---|---|---|
| Passive | $\eta = \frac{m_w \Delta H}{t_d I A_c}$ | (34) |
| Mixed | $\eta = \frac{m_w \Delta H}{t_d (I A_c + I A_d)}$ | (35) |
| Active | $\eta = \frac{m_w \Delta H}{t_d (I A_c + P_f)}$ | (36) |
| Active with external PV in collector | $\eta = \frac{m_w \Delta H}{t_d (I A_c + I A_{PV})}$ | (37) |
| Hybrid mixed and passive | $\eta = \frac{m_w \Delta H}{(I A_d + I A_c + P_{IR})\ t_d}$ | (38) |

In indirect solar dryers, the total energy input is commonly defined as the solar energy supplied to the collector ($q_{Tc}$). Efficiency thus represents the fraction of incident solar energy used for water evaporation, neglecting heat losses to the surroundings.

Under natural convection (passive mode), thermal and drying efficiencies become equivalent in the absence of losses and can be calculated using Equation (34) [16].

For mixed active dryers, Dutta et al. [41] introduced, in Equation (35), an additional term representing the solar energy incident on the chamber glass ($q_{Td}$). This formulation was referred to as the thermal efficiency of the dryer.

Equation (36), employed in some studies on active dryers, includes in its denominator the electrical energy consumed by the fan ($P_f$) to drive airflow into the chamber [11]. The calculated parameter is sometimes referred to as thermal efficiency of the dryer. However, energy efficiency would be a more appropriate designation.

When an external photovoltaic (PV) panel is used to power active dryers, some authors [30–32]—except Goud et al. [26] and Mugi et al. [29]—include a term ($IA_{PV}$) to account for the solar energy incident on the panel, as in Equation (37). This term is equivalent to the electrical energy input represented by $P_f$ in Equation (36).

Because this energy originates from solar radiation, the parameter is often referred to as thermal efficiency. These cases were discussed earlier in the section on collectors.

For passive (natural convection), mixed, and infrared-assisted dryers, the efficiency described in Equation (38) is similar to that of the mixed dryers, with the addition of an infrared power term ($P_{IR}$). The total energy input is thus given by the combined contribution of solar energy and the auxiliary infrared (IR) radiation [53]. Accordingly, the performance parameter should be classified as the energy efficiency of the dryer.

From this point onward, several variations with non-standardized nomenclature and definitions are presented. These variations depend on the dryer type, assumptions, and reference sources.

Mugi and Chandramohan [30–32] also used *SMER* and *SEC* as performance metrics:

$$SMER = \frac{m_w}{t_d(IA_c + IA_{PV})} \tag{39}$$

$$SEC = \frac{t_d(IA_c + IA_{PV})}{m_w} \tag{40}$$

In this context, energy consumption is considered as the sum of solar energy used for air heating and electricity generation. However, as will be shown later, most studies account only for electrical energy consumption, leading to an incomplete assessment.

Mugi and Chandramohan [32] defined the energy utilization ratio (EUR) as:

$$EUR = \frac{m_w \Delta H}{t_d\, q_{uc}} = \frac{m_w \Delta H}{t_d[\dot{m}_a c_{p,a}\,(T_{co} - T_{ci})]} \tag{41}$$

Using the total solar energy input ($q_{Tc}$), as in the equations listed in **Table 4**, may lead to unrealistic estimates, since part of this energy is not effectively transferred to the air due to thermal losses. A more representative approach is to consider the useful energy transferred to the air ($q_{uc}$), as in Equation (41). This results in a denominator analogous to that of Equation (25), as the enthalpy variation is directly related to the air temperature difference. Therefore, EUR is essentially equivalent to the thermal efficiency of the drying process.

Goud et al. [26] and Lingayat et al. [16] studied active solar dryers and defined efficiency as:

$$\eta = \frac{m_w \Delta H + m_w c_{p,w}(T_{do} - T_{air})}{t_d\, q_{uc}} = \frac{m_w \Delta H + m_w c_{p,w}(T_{do} - T_{air})}{t_d[\dot{m}_a c_{p,a}\,(T_{co} - T_{ci})]} \tag{42}$$

Where $c_{p,w}$ is the specific heat of water at constant pressure, $T_{do}$ is the outlet air temperature from the drying chamber, and $T_{air}$ is the ambient air temperature.

The numerator includes an additional term resembling the sensible heat of water. This is expressed in terms of air temperature difference, and an unclear definition of $T_{air}$. In practice, part of the supplied energy is also used to heat the product.

Overall, the formulation reflects how much of the useful thermal energy carried by the air is utilized during drying and is therefore consistent with thermal efficiency.

Despite the system operating in active mode, fan energy consumption is neglected, and energy efficiency is therefore not used for performance evaluation.

- **Mixed Active Solar Dryers**

Cesar et al. [35] proposed several efficiency definitions for a mixed active solar dryer. A distinct name was assigned to each expression, as shown in **Table 5**.

**Table 5.** Efficiency types and corresponding values reported by César et al. [35].

| Used Name | Value (%) | Equation | |
|---|---|---|---|
| Dryer efficiency | Mean: 7.5<br>Range: 0.6–20.3 | $\eta = \frac{m_w \Delta H}{t_d[P_f + IA_c + IA_d]}$ | (43) |
| Drying efficiency | Mean: 11.6<br>Range: 0.9–31.5 | $\eta = \frac{m_p c_{p,p}\left(T_{p,t+dt} - T_{p,t}\right) + m_w \Delta H}{[IA_c E_{,c} + IA_d \tau_d + P_f]t_d}$ | (44) |
| Experimental thermal efficiency | Mean: 7.0 | $\eta = \frac{\dot{m}_a c_{p,a}(T_{do} - T_{di})}{\left[IA_d + \dot{m}_a c_{p,a}(T_{co} - T_{ci})\right]t_d}$ | (45) |
| Energy utilization ratio (EUR) | Mean: 13.6<br>Range: 0.9–32.3 | $EUR = \frac{m_w \Delta H}{[IA_d + \dot{m}_a c_{p,a}(T_{co} - T_{ci})]t_d}$ | (46) |
| Theoretical thermal efficiency | Mean: 26.8 | $\eta = \frac{T_{dc} - T_{do}}{T_{dc} - T_{amb}}$ | (47) |

The dryer efficiency described in Equation (43) was adapted from Equations (35) and (36).

Drying efficiency is defined in Equation (44), where $m_p$ and $c_{p,p}$ are the product mass and specific heat capacity, respectively. The terms $T_{p,t}$ and $T_{p,t+dt}$ represent the product temperatures at consecutive time steps. This formulation accounts for the energy required to heat the material by incorporating the product's sensible heat term in addition to the latent heat of water. Furthermore, solar energy losses through the collector and drying chamber are considered by including the collector efficiency ($\eta_c$, Equation (11)) and the chamber transmittance ($\tau_d = 0.86$). These considerations make the approach more representative and result in a relatively high mean efficiency (11.6%).

The experimental thermal efficiency is defined in Equation (45), where $T_{di}$ and $T_{do}$ are the inlet and outlet air temperatures of the drying chamber, respectively. The drying air is considered as the control volume. In this formulation, the total supplied energy includes both the solar energy directly incident on the chamber and the energy transferred by the air heated in the collector. The numerator represents the energy absorbed by the air within the chamber, which is subsequently transferred to the product as sensible and latent heat.

César et al. [35] also defined an energy utilization ratio (EUR) in Equation (46). This parameter represents the ratio of the energy required to convert the moisture in the product into vapor. It indicates the effectiveness of the input energy in driving the drying process.

The theoretical thermal efficiency, given in Equation (47), was defined based on Equation (26). $T_{dc}$ and $T_{do}$ correspond to the maximum and outlet air temperatures of the drying chamber, respectively. This metric expresses the ratio between the actual and maximum possible air temperature drops in the chamber.

Similar to Equations (41) and (42), Equations (45) and (46) employ useful heat in the denominator, which is preferable to total heat. Among the approaches presented in **Table 5**, Equation (44) appears to be the most representative.

The following section addresses hybrid solar dryers supplemented with infrared (IR) energy, aiming to provide an overview of how their performance parameters are formulated.

- **Active and Hybrid (Infrared-Assisted) Solar Dryers**

Şevik et al. [27] proposed the following performance parameters for active dryers with IR assistance:

$$\eta = \frac{m_w \Delta H}{\left(P_f + P_{IR}\right) t_d} \tag{48}$$

$$\eta = \frac{m_p c_{p,p}\left(T_{p,\,t+dt} - T_{p,\,t}\right) + m_w \Delta H}{\left(P_f + P_{IR}\right) t_d} \tag{49}$$

Equations (48) and (49) yield the same type of energy efficiency metric. These formulations resemble those presented previously. However, they differ in how the total energy input is defined. In this case, the supplied energy includes only the electrical consumption of the fan ($P_f$), which drives airflow from the collector to the drying chamber, and the infrared source ($P_{IR}$), which provides additional heat for drying.

Solar energy is considered only in the calculation of collector efficiency. By adding the sensible heat contribution of the product to the latent heat, Equation (49) yields slightly higher mean values (5–13.16%) than Equation (48) (4.8–12.9%).

This approach treats solar energy as a free source, enabling performance assessment in terms of supplemental energy, which may be relevant for operating cost analysis. Nevertheless, it does not fully represent the drying process, since air heating depends fundamentally on solar energy.

The authors also employed other indices, such as the specific energy consumption (*SEC*) and the coefficient of performance (*COP*):

$$SEC = \frac{\left(P_f + P_{IR}\right) t_d}{m_w} \tag{50}$$

$$COP = \frac{\dot{m}_a c_{p,a} \left(T_{co} - T_{ci}\right)}{\Sigma W} \tag{51}$$

The higher the SEC value, the lower the process efficiency. As in Equations (48) and (49), energy consumption refers exclusively to electrical energy.

The coefficient of performance (*COP*) appears to be more closely related to the collector than to the drying chamber, as it depends on the outlet air thermal energy. However, the definition of $\Sigma W$ as the energy utilization rate does not clarify whether electrical energy is fully included, which may affect the interpretation of the results.

Regarding the coefficient of performance (*COP*), it appears to be more closely related to the collector than to the drying chamber, as it depends on the outlet air thermal energy. The term $\Sigma W$, defined as the energy utilization rate, does not clarify whether electrical energy is fully included, which may affect the interpretation of the results.

- **Active Hybrid Dryers with PVT Collectors**

Arslan [38] used SEC (Equation (50)) and its reciprocal, SMER, to evaluate the process performance in an active, hybrid solar dryer with auxiliary infrared heating and a PVT collector.

$$SMER = \frac{m_w}{\left(P_f + P_{IR}\right) t_d} \tag{52}$$

For a hybrid dryer with a photovoltaic panel integrated into the collector (PVT), Mirzaei et al. [54] defined the system efficiency (maximum of 9%) as the ratio between evaporation energy and the total solar energy incident on the PV panel ($q_{T,PV}$):

$$\eta = \frac{m_w \Delta H}{q_{T,PV}} = \frac{m_w \Delta H}{I A_{PV}} \tag{53}$$

Since this type of panel generates both electrical and thermal energy, the authors also defined a dryer efficiency (maximum of 31%). In addition to the energy supplied by the heated air ($q_{uc}$), this parameter includes the electrical energy generated by the panel ($P_{PV}$), which is used to power the fan and the infrared (IR) lamps:

$$\eta = \frac{m_w \Delta H}{P_{PV} + q_{uc}} = \frac{m_w \Delta H}{i_{PV} \cdot V_{PV} + \dot{m}_a c_{p,a} \left(T_{co} - T_{ci}\right)} \tag{54}$$

where $i_{PV}$ and $V_{PV}$ are the current and voltage of the PV module, respectively.

Compared to Equation (48), which does not account for solar energy input, this approach explicitly incorporates both the electrical and thermal contributions of solar radiation. As a result, it provides a more comprehensive representation of the energy flows in the system, although it may complicate direct comparisons with studies that neglect solar inputs.

Resvani et al. [55] investigated a hybrid, active conveyor-belt dryer equipped with a PVT collector, which provides both thermal energy and a fraction of the electrical energy. In this system, the material is placed on a surface in contact with hot water. Moisture removal occurs through the combined effects of the heated bed, the overhead IR lamp, and the hot air stream.

For the drying chamber energy efficiency, the authors employed the following expression:

$$\eta = \frac{m_w \Delta H}{e_T} \tag{55}$$

The authors state that the denominator corresponds to the total energy supplied by the PVT unit, which likely represents the combined thermal and electrical contributions, similarly to the formulation adopted in Equation (54).

In PVT-based analyses, the denominator in Equation (54) provides a more realistic representation of system efficiency. In contrast, Equation (53) yields significantly higher values, which may lead to an overestimation of performance.

- **Active and Hybrid Dryer (Electrical and Infrared Heating) with a Parabolic Collector**

For an active hybrid dryer with two supplementary energy sources—an electric heater ($E_e$) and infrared energy ($E_{IR}$)—Ghasemi [34] evaluated an active hybrid dryer with electric ($E_e$) and infrared ($E_{IR}$) heating using both specific energy consumption (*SEC*) and an energy utilization ratio (*EUR*), as defined below:

$$EUR = \frac{m_w \Delta H}{\left(P_f + P_{IR}\right) t_d} \tag{56}$$

This *EUR* differs from that proposed by César et al. [35], Equation (46), and instead aligns with the energy efficiency formulation reported by Şevik et al. [27], Equation (48).

This inconsistency highlights the lack of standardization in the definition and application of EUR across different studies.

- **Active Hybrid Dryers with Heat Pump and Infrared Heating**

Singh et al. [56] studied a hybrid system composed of a solar heater, a heat pump cycle, IR heaters, and forced convection. Energy efficiency (mean value of 47.73%) was expressed as the ratio between the energy required for water evaporation and the total electrical energy input:

$$\eta = \frac{m_w \Delta H}{t_d (P_{compr} + P_{fan} + P_{IR} + P_{pump})} \tag{57}$$

This formulation implicitly assumes that solar energy is freely available, as in Equation (48).

To quantify the air's moisture absorption capacity, the authors used a parameter referred to as drying efficiency (mean value of 61.92%). This parameter represents the fraction of product moisture absorbed by the air relative to a saturated-air reference. It is also known in the literature as pick-up efficiency (Equation (33)).

It can also be expressed as a function of temperature variations, in a manner similar to the theoretical efficiency defined by César et al. [35], Equation (47), where the ambient temperature ($T_{amb}$) is used as the reference:

$$\eta = \frac{(Y_{do} - Y_{di})}{(Y_{sat} - Y_{di})} = \frac{(T_{do} - T_{di})}{(T_{do} - T_{sat})} \tag{58}$$

The performance indices *SMER*, *SEC*, and *COP* were also employed. However, *COP* was applied exclusively to heat pump systems, in accordance with its original definition:

$$SMER = \frac{m_w}{t_d (P_{compr} + P_{fan} + P_{IR} + P_{pump})} \tag{59}$$

$$SEC = \frac{t_d (P_{compr} + P_{fan} + P_{IR} + P_{pump})}{m_w} \tag{60}$$

$$COP = \frac{q_{pump}}{P_{pump}} \tag{61}$$

**Table 6** provides a summary of the studies discussed above, including the types of dryers and the nomenclature adopted by each author. As with collector efficiency, terminology varies significantly. The term drying efficiency, as reported in **Table 6**, refers to the unit operation occurring within the drying chamber. It differs conceptually from the drying efficiency defined earlier in Equation (28), which accounts for energy losses associated with exhaust air above ambient temperature.

**Table 6.** Summary of nomenclature used for performance parameters of different solar dryers.

| Authors | Efficiency Name | Dryer Type |
|---|---|---|
| Lingayat et al. [16] | Drying efficiency | Review |
| Lingayat et al. [16]; Goud et al. [26] | Dryer thermal efficiency | Active dryer with external PV panel |

**Table 6.** *Cont.*

| Authors | Efficiency Name | Dryer Type |
|---|---|---|
| Mugi and Chandramohan, [30–32]; Mugi et al. [29] | Drying efficiency, EUR, SMER, SEC | Active dryer with external PV panel |
| Nnamchi et al. [11] | Dryer thermal efficiency | Review |
| Lingayat et al. [16] | Drying efficiency | Review |
| César et al. [35] | Drying efficiency | Active mixed dryer |
| Dutta et al. [41] | Dryer thermal efficiency | Active mixed dryer |
| Nnamchi et al. [11] | Dryer thermal efficiency | Review |
| César et al. [35] | Dryer efficiency; drying efficiency; theoretical thermal efficiency; energy utilization ratio (EUR) | Active mixed dryers |
| Abedini et al. [53] | Dryer efficiency | Passive, mixed, and hybrid (IR) dryer |
| Şevik et al. [27] | Energy and drying efficiency; SEC and COP | Active hybrid (IR) dryer |
| Arslan [38] | SMER and SEC | Active hybrid (IR) dryer with PVT collector |
| Ghasemi [34] | SEC and EUR | Active hybrid dryer (electric heater and IR) with parabolic collector |
| Resvani et al. [55] | Cabin energy efficiency | Active hybrid (IR) dryer with PVT collector |
| Singh et al. [56] | Cabin energy efficiency; drying efficiency; SMER; SEC and COP | Active hybrid dryer (heat pump and IR) |

Improved standardization of expressions and appropriate naming for performance parameters are required, along with proper adaptation to each dryer type. This is essential to ensure correct usage and enable consistent comparisons across studies.

**Table 7** presents a proposed standardization of efficiency expressions and nomenclature for different types of indirect solar dryers. The proposed formulations aim to physically represent the processes occurring in each dryer configuration, while adopting terminology consistent with the general concepts of thermal and energy efficiencies.

**Table 7.** Recommended expressions and nomenclature for the drying performance parameter of different types of indirect dryers.

| Type of Indirect Dryer | Suggested Expression | Equation | Suggested Name |
|---|---|---|---|
| Passive | $\eta = \frac{m_p c_{p,p}(T_{p,\,t+dt} - T_{p,\,t}) + \Delta H_{des}}{t_d\ [\dot{m}_a c_{p,a}(T_{co} - T_{ci})]}$ | (62) | Drying thermal efficiency (passive dryers) |
| Mixed | $\eta = \frac{m_p c_{p,p}(T_{p,\,t+dt} - T_{p,\,t}) + \Delta H_{des}}{t_d\ [\dot{m}_a c_{p,a}(T_{co} - T_{ci}) + I A_d \alpha_d \tau_d]}$ | (63) | Drying thermal efficiency (mixed dryers) |
| Active | $\eta = \frac{m_p c_{p,p}(T_{p,\,t+dt} - T_{p,\,t}) + \Delta H_{des}}{t_d [\dot{m}_a c_{p,a}(T_{co} - T_{ci}) + P_f]}$ | (64) | Drying energy efficiency (active dryers) |
| Active with external PV in collector | $\eta = \frac{m_p c_{p,p}(T_{p,\,t+dt} - T_{p,\,t}) + \Delta H_{des}}{t_d [\dot{m}_a c_{p,a}(T_{co} - T_{ci}) + I A_{PV}]}$ | (65) | Drying thermal efficiency (active dryers with PV) |
| Active with PVT collector | $\eta = \frac{m_p c_{p,p}(T_{p,\,t+dt} - T_{p,\,t}) + \Delta H_{des}}{t_d \left[\dot{m}_a c_{p,a}(T_{co} - T_{ci}) + i_{PV} V_{PV}\right]}$ | (66) | Drying thermal efficiency (active dryers with PVT) |
| Hybrid and active | $\eta = \frac{m_p c_{p,p}(T_{p,\,t+dt} - T_{p,\,t}) + \Delta H_{des}}{t_d [c_{p,a}(T_{co} - T_{ci}) + P_f + P_{IR}]}$ | (67) | Drying energy efficiency (hybrid and active dryers) |

During drying, part of the supplied energy is used to heat the wet material, superheat vapor, and raise the temperature of already dried layers. However, evaporation remains the dominant contribution. In addition to free-water removal, energy is also required to release bound water. Therefore, the heat of desorption ($\Delta H_{des}$) is recommended instead of the latent heat of vaporization of free water. Its limited use in efficiency equations is due to the scarcity of constitutive equations relating heat of desorption to moisture content for different materials.

Accordingly, for any dryer type, the numerator should include both the sensible heat of the product and the heat of desorption ($\Delta H_{des}$). The denominator, in turn, depends on the dryer configuration. It is recommended to consider the useful energy of the air ($q_{uc}$), the direct solar energy incident within the chamber after transmission losses, the power supplied by any auxiliary energy sources, and, when applicable, the contribution of PV or PVT systems.

Following the same rationale adopted for collector efficiency, the performance of hybrid and active dryers should be evaluated in terms of energy efficiency. Neglecting fan or infrared power and analyzing performance solely from a thermal-efficiency perspective may lead to misinterpretations. In such cases, efficiency values tend to be overestimated and may not accurately represent actual operating conditions.

Conversely, in PV- or PVT-assisted systems, where electrical energy is derived from solar radiation, thermal efficiency may be adopted as the reference parameter.

It should be emphasized that the inclusion of fan power, infrared power, and PV- or PVT-derived energy does not alter the fundamental definitions of performance. Rather, it guides the selection of the most conceptually consistent efficiency metric for a given system.

When solar energy is treated as a free resource, it is appropriate to standardize performance indices that account exclusively for electrical energy consumption, such as SEC and SMER. These metrics are well established in the literature and vary depending on the dryer configuration, as shown in Equations (50), (52), (59) and (60). Notably, they are not applicable to passive solar dryers.

The proposed framework provides a consistent basis for future studies, thereby enhancing the comparability and reliability of solar drying system evaluations.

## 4. Conclusions

To enhance terminological clarity, a standardized classification of thermal and energy efficiencies is essential for evaluating both collector and drying performance. Efficiency formulations should be selected based on physically meaningful energy terms to ensure consistent interpretation.

Instantaneous efficiencies provide a more representative assessment of system performance than cumulative measures, as they capture variations throughout the drying process. Their accurate determination depends on continuous monitoring of key process variables using integrated data acquisition systems.

Collector efficiency is strongly dependent on system configuration, including operation mode (active or passive) and the use of PV or PVT modules. Standardization is recommended so that the transmitted solar energy accounts for the glass transmissivity and absorptivity, representing the fraction effectively available for air heating. For active dryers, energy efficiency is the most appropriate performance parameter due to the inclusion of fan power consumption. In contrast, thermal efficiency is more suitable for PV- or PVT-assisted systems, where solar energy is partially converted into electricity and then into mechanical energy for airflow.

Drying performance is governed by operating conditions, material properties, and dryer design. For hybrid, active, and indirect dryers without photovoltaic modules, energy efficiency provides a consistent basis for evaluation. Considering both the sensible heat for product heating and the heat of desorption for free and bound water removal ensures a more realistic representation of the energy required for drying. The definition of total energy input must reflect the specific system configuration and include all relevant energy contributions, such as useful air energy, fan power, and auxiliary energy inputs. For fully PV- or PVT-assisted systems, thermal efficiency is the most conceptually appropriate parameter, since the electrical energy generated by the modules is not included in the total energy input.

Future research should focus on control strategies to enhance solar dryer performance. Implementing intermittent or variable airflow rates may promote multiple constant-rate drying periods, during which efficiency is maximized.

Overall, this review establishes a consistent framework for the evaluation of solar drying systems, contributing to improved comparability and reliability across studies.

## Author Contributions

Conceptualization, M.M.d.P. and K.S.A.; methodology, K.S.A. and G.A.C.; validation, K.S.A. and G.A.C.; formal analysis, M.M.d.P.; investigation, K.S.A. and G.A.C.; resources, G.A.C. and M.F.F.S.; data curation, K.S.A. and G.A.C.; writing—original draft preparation, K.S.A. and G.A.C.; writing—review and editing, M.M.d.P. and M.F.F.S.; supervision, M.M.d.P. All authors have read and agreed to the published version of the manuscript.

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## Conflicts of Interest

The authors declare no conflict of interest

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## Abbreviation

| **Abbreviation** | **Full Name** |
|---|---|
| $A_c$ | Collector surface area (m$^2$) |
| $A_d$ | Cabin area exposed to solar radiation (m$^2$) |
| $A_{PV}$ | PV area (m$^2$) |
| $A_{PVT}$ | PVT area (m$^2$) |
| $c_{p,a}$ | Specific heat of air (kJ/kg K) |
| $c_{p,p}$ | Specific heat of product (kJ/kg K) |
| $c_{p,w}$ | Specific heat of water(kJ/kg K) |
| $C_{mec}$ | Conversion factor (-) |
| $COP$ | Coefficient of performance (-) |
| $DE$ | Drying effectiveness (-) |
| $e_{ev}$ | Energy used for water evaporation (J) |
| $e_t$ | Total energy supplied to the dryer (J) |
| $EUR$ | Energy utilization rate (-) |
| $F_R$ | Heat removal factor (-) |
| $h_{amb}$ | Ambient air enthalpy (kJ/kg) |
| $h_{ci}$ | Collector inlet air enthalpy (kJ/kg) |
| $h_{co}$ | Collector outlet air enthalpy (kJ/kg) |
| $h_{di}$ | Cabin inlet air enthalpy (kJ/kg) |
| $h_{do}$ | Cabin outlet air enthalpy (kJ/kg) |
| $q_{Tc}$ | Total energy rate incident on the collector's glass cover (W) |
| $q_{Td}$ | Total rate of solar energy incident on the drying cabin (W) |
| $q_{T,PV}$ | Total rate of solar energy incident on the PV panel (W) |
| $q_{uc}$ | Rate of useful heat available in the collector (W) |
| $q_{ud}$ | Rate of useful heat for drying in cabin (W) |
| $SEC$ | Specific energy consumption (kWh/kg) |
| $SMER$ | Specific moisture extraction rate (kg/kWh) |
| $T_a$ | Absorber plate temperature (K) |
| $T_{amb}$ | Ambient air temperature (K) |
| $T_{amean}$ | Mean air temperature (K) |
| $T_{ci}$ | Air temperature at the collector inlet (K) |

| | |
|---|---|
| $T_{co}$ | Air temperature at the collector outlet (K) |
| $t_d$ | Drying time (s) |
| $T_{di}$ | Air temperature at cabin inlet (K) |
| $T_{do}$ | Air temperature at cabin outlet (K) |
| $T_{IR}$ | Infrared radiation source temperature (K) |
| $T_p$ | Product temperature (K) |
| $T_{wb}$ | Wet bulb temperature (K) |
| $U_l$ | Overall heat transfer coefficient ($W/m^2K$) |
| $V_{mx}$ | Maximum voltage (V) |
| $I$ | Instantaneous solar radiation ($W/m(m^2)2$) |
| $i_{mx}$ | Maximum current (A) |
| $IR$ | Infrared |
| $\dot{m}_a$ | Air mass flow rate (kg/s) |
| $m_p$ | Product mass (kg) |
| $m_w$ | Quantity of evaporated water (kg) |
| $P_{compr}$ | Compressor power (W) |
| $P_{elec}$ | Electrical power (W) |
| $P_f$ | Fan power (W) |
| $P_{IR}$ | Infrared power (W) |
| $P_{mec}$ | Mechanical power (W) |
| $P_{pump}$ | Heat pump power (W) |
| $P_{PV}$ | Photovoltaic panel power (W) |
| $PV$ | Photovoltaic panel |
| $PVT$ | Photovoltaic thermal panel |
| $q_a$ | Rate of heat absorbed by the plate (W) |
| $q_{IR}$ | Rate of IR radiation (W) |
| $q_l$ | Rate of heat lost or transferred (W) |
| $q_{pump}$ | Rate of useful heat output from the pump (W) |
| $Y_{amb}$ | Air humidity at ambient conditions ($kg_{water}/kg_{air}$) |
| $Y_{di}$ | Absolute air humidity in the cabin inlet ($kg_{water}/kg_{air}$) |
| $Y_{do}$ | Absolute air humidity in the cabin outlet ($kg_{water}/kg_{air}$) |
| $Y_{sat}$ | Air humidity at saturation conditions ($kg_{water}/kg_{air}$) |
| $\alpha$ | Absorptance (-) |
| $\Delta H$ | Latent heat of vaporization of free water (J/kg) |
| $\Delta H_{des}$ | Heat of desorption of moisture (J/kg) |
| $\eta_D$ | Drying efficiency (-) |
| $\eta_{E,c}$ | Collector energy efficiency (-) |
| $\eta_{E,d}$ | Drying energy efficiency (-) |
| $\eta_{eff,c}$ | Collector effective efficiency (-) |
| $\eta_{elec,PVT}$ | PVT collector electrical efficiency () |
| $\eta_{pick-up}$ | Pick-up efficiency (-) |
| $\eta_{T,c}$ | Collector thermal efficiency (-) |
| $\eta_{T,d}$ | Solar drying thermal efficiency (-) |
| $\eta_{T,d,max}$ | Maximum solar drying thermal efficiency (-) |
| $\eta_{T,PVT}$ | PVT collector thermal efficiency (-) |
| $\eta_{total,PVT}$ | PVT collector overall efficiency (-) |
| $\tau$ | Transmittance (-) |

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