



# Literature review of cocoa drying technologies and their role in increasing added value

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## Abstract

Cocoa is a major Indonesian export commodity, yet predominantly exported as raw beans, limiting value addition. This review examines cocoa drying technologies and their translation into economic value. Proper drying reduces moisture to safe levels, prevents fungal contamination and aflatoxin, and preserves quality attributes such as flavor and polyphenols. Temperature control (optimum 50–55°C) is critical to avoid defects like case-hardening. Traditional sun drying is cost-effective and develops desirable flavor but suffers from inconsistency and contamination risk. Mechanical methods offer speed and control but can reduce quality if mismanaged. Hybrid solar and greenhouse dryers achieve higher efficiency, faster drying, and more consistent quality, leading to higher-grade beans. Drying directly impacts economic value through bean grade, market price, and premium market suitability, especially when integrated with fermentation and storage. However, adoption of advanced dryers is hampered by high costs, limited technical knowledge, and structural constraints. Emerging innovations such as energy-efficient systems, circular use of by-products, and digital agriculture offer sustainable opportunities. Optimizing drying technology is therefore essential for enhancing cocoa quality, value addition, and Indonesia's global competitiveness.

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## 1. Introduction

Cocoa is a plantation commodity that plays an important role as a contributor to Indonesia's foreign exchange, after palm oil and rubber. In 2018, cocoa plantations reached 1,678,300 hectares, with total production reaching 593,800 tons (BPS, 2019). This commodity is exported in various forms, from raw materials to semi-finished products to finished products. Indonesia is also one of the main players in the global cocoa market, with a position as the fourth largest cocoa bean producer in the world after Ivory Coast, Ghana, and Ecuador. A decade earlier, the value of Indonesian cocoa exports was recorded at USD 1,413,535. However, more than 82% of these exports are still dominated by raw cocoa beans, while the remainder is in the form of processed products such as cocoa powder, cocoa butter, cocoa paste, and various cocoa-based food products. Until 2010, the majority of Indonesian cocoa exports were still in the form of beans, including those sent to Malaysia and Singapore. The cocoa beans are used as raw material in the production of cocoa butter in the processing industries of the two countries, which impose an import tariff of 0%. Meanwhile, the development of the domestic downstream cocoa industry tends to stagnate (1).

In order to increase the added value of cocoa commodities, the government has designated cocoa and its derivative products as one of the priority commodities in the national industry through Presidential Decree No. 2 of 2018 concerning the 2015–2019 National Industrial Policy. This policy aims to reduce the dominance of raw material exports in the form of cocoa beans and encourage increased exports of semi-finished and finished products. Cocoa product development is focused on various processed products such as cocoa butter, cocoa powder, cocoa-based drinks and foods, as well as functional food products. Domestic industry is also encouraged to process cocoa beans as raw materials into products with higher added value. If this effort is successful, Indonesia will not only gain economic added value, but will also be able to increase its competitiveness in the global market. So far, Indonesia has played a greater role as a supplier of raw materials for the cocoa processing industry in other countries. In fact, the potential to develop the domestic downstream cocoa industry is very large and can still be optimized (1).

The low added value in the agricultural sector reflects an indication of less-than-optimal government performance in the 2014–2019 period, considering that increasing the added value of agricultural commodities is one of the main targets in the 2014–2019 National Medium-Term Development Plan (RPJMN). In the next government period, namely 2020–2024, with the same leadership, increasing the added value of agriculture was again set as the main target in the 2020–2024 RPJMN. If there are no more significant efforts from the government to increase the added value of the agricultural sector, then the results achieved will potentially not be much different from the previous period (2).

Based on a review of previous literature, natural drying produces superior flavor profiles; however, it is prone to inconsistency due to variable moisture content and process errors that can compromise quality. When integrated with fermentation, natural drying can increase the added value of cocoa beans (3). In contrast, controlled drying methods, such as solar dryers and hybrid systems resulting in yield higher-grade beans with greater market value (4). These methods also better preserve polyphenols, prevent case-hardening (5), inhibit mold growth, and minimize polycyclic aromatic hydrocarbon (PAH) contamination when smoke contact is avoided (6). Despite these advantages, no study has comprehensively examined the quality parameters of cocoa drying in relation to its economic value. Therefore, this literature review aims to evaluate existing drying technologies and their potential to enhance the economic value of cocoa.

## **2. Materials and Methods**

The method employed in this study is a literature review analyzing relevant scientific publications published between 2020 and 2025 concerning cocoa drying technologies and their contribution to value addition in the cocoa supply chain. The reviewed literature focuses on the influence of drying methods on cocoa bean quality, drying efficiency, preservation of bioactive compounds, postharvest safety, and the resulting economic impacts, including bean grading, market price, and downstream processing potential. Particular attention is given to drying practices and technological development within the Indonesian cocoa sector, considering climatic conditions, smallholder farming systems, and local processing challenges.

The analysis was conducted through structured stages of literature collection, selection, synthesis, and interpretation. Scientific articles, review papers, and technical reports were collected from reputable electronic databases, including Scopus, ScienceDirect, and Google Scholar, using keywords related to cocoa drying, solar drying, mechanical drying, greenhouse drying, cocoa quality, moisture reduction, polyphenol retention, and value addition. The selection process prioritized studies discussing drying performance, temperature optimization, energy efficiency, drying kinetics, quality preservation, and the relationship between drying conditions and economic value. Comparative analysis was further conducted to evaluate the advantages and limitations of traditional sun drying, mechanical dryers, and hybrid drying systems in terms of product quality, sustainability, and feasibility for industrial and smallholder applications. This approach was intended to provide a comprehensive understanding of how drying technology optimization can improve cocoa quality, reduce postharvest losses, enhance market competitiveness, and support sustainable value addition in the Indonesian cocoa industry.

### 3. Results and Discussion

#### 3.1. Characteristics of cocoa and the importance of drying

Cocoa beans undergo significant changes during fermentation, with moisture content decreasing from approximately 61% to 52% (wb) before drying, ultimately reaching a fermented bean moisture range of 5.6–7% (wb) (8). Fermentation also enhances the yield of certain nutrients, including fat, while polyphenol content remains notably high in certain cultivars, depending on the cultivation system employed (9,10). Cocoa beans ideally reach an equilibrium moisture content below 7%, consistent with the established target of  $\leq 7$ –8%, a threshold supported as acceptable for producing high-quality cocoa products (11).

Inadequate moisture management during storage poses several risks. Elevated water content increases the likelihood of fungal contamination, particularly by *Aspergillus spp.* (12). Under high humidity conditions, aflatoxin-producing species such as *Aspergillus flavus* and *A. parasiticus* have been detected in raw cocoa materials, raising significant food safety concerns (13). Furthermore, slow or uneven drying can trigger re-fermentation, promote spoilage, and generate undesirable volatile compounds that negatively affect flavor (14).

The relationship between drying and fermentation is deeply interconnected and influences both flavor development and processing efficiency. Pre-drying applied before or during the early stages of fermentation can modify the flavor profile, enhancing fruity and sour characteristics (15). Additionally, partial pulp removal, analogous to pre-drying has been shown to substantially accelerate the drying process, reducing drying time from 144 hours to as little as 4.3 hours while simultaneously improving taste quality (16). Conversely, excessively high drying temperatures ( $\geq 60$ – $95^{\circ}\text{C}$ ) can damage the flavor profile, introduce burnt off-notes, and compromise the accuracy of cut test results (17). Finally, the degree of fermentation itself influences drying behavior: beans that have undergone complete fermentation develop a tissue structure that facilitates water diffusion, resulting in a more uniform and efficient drying process (18).

#### 3.2. Cocoa drying technology

Several cocoa drying technologies, namely traditional drying including OSD (Open Sun Drying), have the potential risk of contamination and limitations in controlling temperature

and relative humidity (RH), so that product quality becomes less consistent (4). The advantages are being able to produce a taste profile that is close to certain traditional standards and the disadvantages are having a high risk of contamination and a low level of uniformity (19). Mechanical drying includes drying with a convection oven can speed up the process, but has the potential to damage the color, reduce the quality of the taste, and reduce the content of total phenolic compounds (20). Tray dryers can speed up the drying process and maintain hygiene, but the uneven heat distribution often causes the product quality to be uneven (21). This technology has the advantage of not being dependent on weather conditions and has a relatively short drying time (20). However, this technology potentially reduces polyphenol content and aroma quality if used at too high a temperature (22). The last one it modern drying technology, namely solar-electric hybrid drying, which can increase the drying rate by up to 20% while reducing energy consumption by 56.6% (23). Variations in drying methods can be seen in Table 1.

**Table 1. Variations in cocoa drying methods.**

Methods	Energi Efficiency	Drying Time	Product Quality	Operating Cost	Ref.
OSD (traditional)	Very low; unstable	4–14 days	Variable; risk of mold, unstable flavor	The lowest	(24)
Oven / Tray Dryer	High (large consumption)	1–2 days	Risk of phenolic and aroma degradation	High	(21)
Hybrid Solar Dryer	High; efficiency 52–94%	2–3 days	High quality; phenolics are better preserved	Low–medium	(25)
Greenhouse Dryer	Medium–high	2–3 days	Brown beans >95%	Low	(3)
Vacuum Dryer	Medium	Fast; high diffusion	Best quality for color & pH	High (expensive technology)	(26)

### 3.3. Increasing the added value of cocoa

The highest added value is at the downstream stage, namely the processing of fermented dry cocoa beans into cocoa powder, which produces an added value of around 20.06%, while instant beverage products can reach up to 71.86% (27). The application of technology in the fermentation, drying, quality classification and storage stages can increase farmers' income while improving efficiency in the value chain (28). Utilization of by-products such as pulp, honey, fruit skin, and cocoa bean skin can significantly increase farmers' income while reducing industrial waste (29). Integration of the value chain along with the implementation of the OVOP (One Village One Product) model can increase competitiveness and added value through improving the quality of raw materials, innovation, product diversification, and marketing modernization (30). Drying determines the grade and selling value, using a greenhouse drying method is able to produce cocoa beans with grade 1 quality and a water content of 5–8%, thus directly increasing price competitiveness (3). Suboptimal drying process can reduce market value, defects such as smoke-taint, and over-dried beans. Meanwhile, uneven drying could reduce quality and prices, both in local and international markets. Optimal drying can increase the selling price by up to USD 2.8/kg, as reported in a study of local convection drying in Cameroon (31). Indonesia has a large

market potential for cocoa powder and butter, but not finished chocolate products (32). Consistent cocoa quality, such as moisture content <7% and optimal fermentation, opens up opportunities to access the premium market (11).

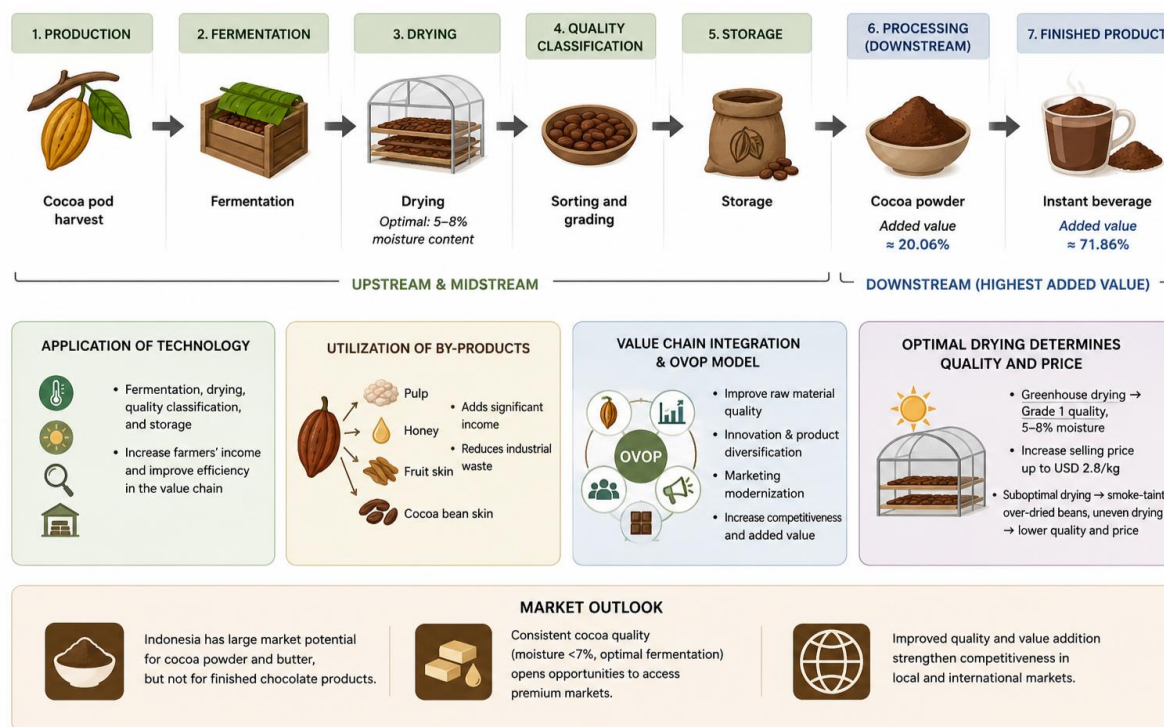


Figure 1. Cocoa value and added value.

### 3.4. Challenges and opportunities in technology development

Regarding costs and access, the implementation of post-harvest technology and increasing added value are still hampered by the high cost of machinery and limited access to modern equipment (33). In terms of human resources, limited technological literacy, lack of training, and minimal support from extension workers are the main factors hindering the adoption of artificial intelligence, precision agriculture, and digital systems (34). Social and structural factors such as uncertainty of land ownership, age of farmers, and migration also become obstacles in implementing innovations like agroforestry and the use of smartphone-based applications (35). The challenges regarding innovation and future trends in environmentally friendly technological approaches, such as the use of cocoa waste as biomaterials, organic compost, biofuel, and pectin, are now developing as major trends that support the implementation of a circular economy (36). Energy is becoming a dominant factor in post-harvest costs; innovations such as solar-powered systems, IoT-based monitoring, and smart grids can improve efficiency (37). The Smart Agriculture 5.0 framework uses blockchain and reinforcement learning to improve traceability and minimize crop failure (38).

## 4. Conclusions

Drying technology plays an important role in determining the quality and added value of cocoa by controlling water content, chemical quality, and taste. Optimal drying can

prevent contamination, maintain bioactive compounds, and increase sales value, while improper processes reduce quality and price. Modern methods such as hybrid solar and greenhouse dryers are superior in efficiency and quality consistency compared to traditional methods. However, technology adoption remains hampered by cost and human resource capacity. Therefore, the application of efficient and sustainable drying technology is the key to increasing the competitiveness and economic value of Indonesian cocoa.

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### **Data Availability Statement**

Available data are presented in the manuscript.

### **Conflicts of Interest**

Author declared no conflict of interest.

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