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Analysis of the Effectiveness of Fluidized Bed Dryer in Black Tea Processing Using the OEE Approach

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Abstract

This study evaluated the operational effectiveness of the Fluidized Bed Dryer (FBD) machine in the traditional black tea drying process using the Overall Equipment Effectiveness (OEE) framework, which includes availability, performance efficiency, and quality rate, as defined in ISO 22400-2:2014. Data collected from January to June 2023 indicated an average OEE of 83.66%. Although availability was consistently high (94–100%) and product quality maintained at 100% throughout the month, performance efficiency varied considerably, dropping to 69% in January and 66% in April, primarily due to operational delays and unstable machine utilization. These results indicate that performance efficiency was the main factor affecting OEE and total productivity. It recommends implementing condition-based maintenance procedures and real-time process monitoring systems to minimize unexpected downtime and enhance operational stability. Better regulation of input load, airflow, and drying temperature was crucial to ensure consistent performance and support product standardization in accordance with SNI 2891:2016, ultimately enhancing the competitiveness of the black tea processing industry.

Keywords: Overall Equipment Effectiveness, Fluidized Bed Dryer, Black Tea Processing, Performance Efficiency

1. Introduction

The tea industry in Indonesia played an important role in the national agro-economy, with black tea being its primary export product. Drying was a crucial stage in the tea production process, as it affected product stability, preservation of flavour, colour, and overall quality. The use of modern drying technology, such as the Fluidized Bed Dryer (FBD), illustrated the industry's efforts to enhance thermal efficiency and process uniformity. The FBD system operated based on the principle of fluidization, which allowed for consistent airflow and heat distribution, resulting in more uniform drying and reduced cycle duration.

However, despite its various benefits, equipment performance often fluctuated due to irregular operations, process disruptions, and inadequate maintenance procedures. Recent research has increasingly examined the impact of drying techniques on product quality in tea and herbal processing. When properly regulated, hot air drying enhanced the functional characteristics of black tea compared to conventional sunlight drying [1]. Exergetic and techno-economic assessments of industrial tea drying systems highlighted the importance of optimizing energy use and dryer design to improve system efficiency [2]. Additionally, advancements in pre-treatment methods such as the use of pulsed electric fields proved effective in enhancing polyphenol extraction from fresh tea leaves before drying [3]. Similar results regarding the impact of drying treatments on the preservation of phenolic compounds in herbal products emphasized the importance of precision in the thermal process [4].

However, despite these studies providing significant insights into quality and thermal dynamics, most overlooked the comprehensive aspects of equipment performance evaluation. In industrial practice, Overall Equipment Effectiveness (OEE) became a commonly used indicator to evaluate equipment utilization and production efficiency. Normalized by ISO 22400-2:2014, OEE encompassed three main metrics: availability (percentage of planned time the machine was operational), performance efficiency (ratio of ideal cycle time to actual cycle time), and quality rate (percentage of products free from defects). Various studies demonstrated the effectiveness of OEE in identifying operational losses and providing direction for maintenance improvements, particularly in the food and beverage industry [5–7]. For example, OEE was used to assess production limitations on oven machines [5] and filling lines for beverage packaging [6]. Further research also modified OEE to include failure mode analysis and maintenance optimization [7,8]. Although there were such developments, the utilization of OEE in tea processing remained limited, especially concerning equipment like FBD, which was crucial for product consistency and throughput.

Several studies conducted comprehensive OEE evaluations in the food, chemical, and other industries [9–12]. However, there is a lack of research that systematically applied OEE in the tea sector, particularly for black tea drying, where unbalanced air flow, variable feed load, and temperature instability affected performance efficiency. Therefore, this research aimed to fill that gap by evaluating the operational effectiveness of the FBD system used in black tea processing using the OEE framework.

This research had three main objectives: first, it measured and evaluated the three elements of OEE availability, performance efficiency, and quality rate during a specific production period; second, it detected operational inefficiencies impacted dryer performance; and third, it recommended improvements through condition-based maintenance and real-time process monitoring. The contributions of this research included: the establishment empirical OEE benchmarks for tea drying systems, confirmation the application of ISO 22400-2:2014 standards in agro-industrial settings, and the provision practical recommendations to align equipment performance with national quality standards (SNI 2891:2016) and global best operational practices.

2. Methods

This research used the Overall Equipment Effectiveness (OEE) method to evaluate the operational effectiveness of the Fluidized Bed Dryer (FBD) in the orthodox style black tea drying process. OEE was a commonly used metric in the industry to measure machine relative to its maximum capacity during a specified production period. The three basic elements of OEE evaluated in this study were Availability (AV), Performance Efficiency (PE), and Product Quality Rate (RQP) [5,6].

The FBD system examined in this study was widely used in various sectors, including food processing, pharmaceuticals, and chemicals, due to its ability to dry materials evenly. The operational concept involved suspending solid particles in an upward flow of hot air, which facilitated efficient heat transfer and moisture extraction [7,8].

Table 1. Heat Exchanger Specifications

Specification	Description
Number of units	2 units
Capacity	180 kg
Fuel type	Palm shell biomass
Motor voltage	380 V
Current	21.8 A
Power	15 HP / 11 kW

Table 1 presents the parameters of the heat exchanger unit used as a heating source in the FBD system. This technology utilized palm kernel biomass as a sustainable fuel source. It comprised two heat exchangers with a combined capacity of 180 kg, operated using a centrifugal fan driven by an electric motor, which ensured a consistent output of hot air.

The main FBD unit used in this research had been manufactured by TEHA and acquired in 1994. This machine was designed for processing tea with a maximum capacity of 350 kg/hour, using a combustion furnace that used palm kernel shells as the main heat source. The use of biomass ensured energy efficiency while also supporting environmental sustainability.

Table 2. FBD Machine Specifications

Specification	Description
Brand	TEHA
Year of acquisition	1994
Dimensions	8.093 x 1.55 x 2.5 m
Capacity	350 kg/hour
Voltage	360 V, 3-phase
Heat source	Palm shell furnace

FBD operated through a series of thermodynamic and mechanical processes to achieve efficient and uniform tea drying. First, the freshly harvested tea leaves were placed into the drying chamber, forming a layer of material. Next, hot air was circulated upward through the layer, creating fluidization conditions where the tea particles became suspended and agitated. This fluidization process ensured that each particle was evenly exposed to hot air, which enabled a constant heat transfer throughout the material. After some time, the moisture in the tea leaves gradually evaporated. The rising water vapor was carried away by the airflow, removing the moisture content and resulting in evenly dried tea leaves. This technique ensured a shorter drying duration while maintaining product quality through controlled heat distribution.

The advantages of this FBD included reduced drying duration, consistent drying quality, and minimal material damage [9,10].

2.1. *Availability*

Availability (AV) quantifies the ratio of actual operational time to planned production time.

$$AV = \frac{\text{loading time} - \text{downtime}}{\text{loading time}} \times 100\% \quad (1)$$

2.2. *Performance Efficiency (PE)*

Assesses the machine's speed relative to its ideal performance:

$$PE = \frac{\text{Processed Amount} \times \text{Ideal Cycle Time}}{\text{Operation Amount}} \times 100\% \quad (2)$$

2.3. *Rate of Quality Product (RQP)*

Represents the proportion of defect-free products:

$$RQP = \frac{\text{Processed amount} - \text{Defect amount}}{\text{Processed amount}} \times 100\% \quad (3)$$

2.4. *Overall Equipment Effectiveness (OEE)*

Overall Equipment Effectiveness (OEE) offers a thorough assessment of machinery performance.

$$OEE = AV \times PE \times RQP \quad (2.4)$$

These indicators were calculated weekly over a six-month period to assess operational trends and identify performance barriers [11–17]. This technique adhered to recognized standards in industrial engineering and allows for replication in similar processing systems.

The FBD system used in this study operated through a series of thermodynamic and mechanical processes to achieve efficient and uniform tea drying. Freshly picked tea leaves were initially placed into the drying chamber to form a layer of material. Subsequently, hot air was circulated upward, creating fluidization conditions that allowed the tea particles to become suspended and agitated. This process ensured that each particle was evenly exposed to heat, enabling consistent heat transfer. During this process, the moisture within the tea leaves gradually decreased. The resulting steam was carried away by the airflow, removing the moisture content and produced evenly dried tea leaves.

3. Results and Discussion

This study aimed to evaluate the operational effectiveness of the Fluidized Bed Dryer (FBD) in drying black tea using the Overall Equipment Effectiveness (OEE) framework, which included availability, performance efficiency, and product quality level, as defined in ISO 22400-2:2014. The results of this study aligned with the research objectives, emphasized the identification of the main causes of operational losses and suggested operational improvements. These findings were analyzed in relation to the dynamics of thermal processes, tea industry standards, and existing literature, to provide a thorough and scientifically validated analysis.

3.1. Availability

The average availability of the FBD machine was 94% during the six-month observation period, with a maximum value of 100% achieved in February, April, and June, as shown in Table 3. This indicated that the machine was operational for most of the planned time. The high availability reflected adequate preventive maintenance and prompt remedial actions during those months. However, the reduction to 96% in January and 98% in March, along with 245 hours of unexpected downtime in January, indicated losses caused by restart delays and reactive maintenance. These infrequent but impactful downtimes significantly affected operational continuity and reduced OEE value. Similar patterns related to availability losses were also reported in the bread and plastic printing sectors, where inadequate maintenance integration reduced the optimal utilization of the system [6,10].

3.2. Performance Efficiency

Performance efficiency showed the highest monthly fluctuations, ranging from 66% in April to 100% in May and June, as seen in Table 4. The performance drop during January–April was primarily caused by process stagnation, irregular loading, and uneven fluidization caused by fluctuations in feed moisture and temperature. This inefficiency resulted in longer cycle times and suboptimal machine utilization. Figure 2 illustrates clear relationship between the decrease in performance efficiency and the decrease in OEE, confirming that performance efficiency (PE) was the most sensitive variable and had a significant impact on OEE. This aligned with the research findings of Temple and van Boxtel, which showed that small changes in fluidization velocity or particle properties hindered heat transfer and prolonged drying duration [16,18]. Additionally, Zeng et al. emphasized the importance of automatic control in regulating production rates and energy input in black tea drying systems [2]. The system analyzed in this study showed deficiencies in real-time control, resulting in performance instability despite high availability.

3.3. Quality Rate

Conversely, the product quality rate (RQP) constantly maintained a level of 100% over the study period, indicating that all processed batches adhered to the specified quality standards without necessitating any adjustments. No faults were identified in the goods examined. Consequently, the monthly defect quantity is 0 kg. This demonstrates effective temperature regulation and adequate safeguarding of product integrity. These results align with national standards, namely SNI 2891:2016, which establishes thresholds for moisture content, leaf uniformity, and sensory quality in black tea. Comparable findings were documented in drying trials conducted by Yang et al. and Oh et al., indicating that drying with meticulously regulated hot air preserved the taste, colour, and bioactive constituents in tea and herbal products [1,5]. Nonetheless, these figures suggest that exceptional product quality alone does not ensure maximum equipment efficiency. In January and April, despite the RQP remaining at 100%, the Performance Efficiency (PE) score fell below 70%, highlighting the need of assessing quality outcomes by factoring in process availability and operational velocity.

3.4. Overall Equipment Effectiveness

The OEE value ranged between 66.24% in January to 100% in June, with an average OEE of 83.66% (Figure 3). Although these figures were relatively high, they did not meet the 85% standard that is commonly used as a benchmark for ideal operations. This highlighted that although availability and quality remained very good, uncertainty in performance efficiency continued to be a significant constraint. Similar research in the beverage and chemical industries identified comparable challenges, where inefficiencies in cycle time reduced the benefits of uptime and consistent product quality [7,12,17]. These findings were consistent with previous assessments of food processing lines, which highlighted the need for integrated control systems and predictive maintenance to minimize performance variability [8,11].

The observed variation in performance efficiency, especially during the first operational months, suggested that system instability was likely due to irregularities in feed moisture, human loading procedures, and the lack of automated control. Operational inconsistencies were also reported in other thermal processing systems, including those in the beverage and chemical industries, where insufficient integration between mechanical input and thermal dynamics led to cycle time losses [7,12]. Moreover, prior research indicated that even with increased machine availability, inadequacies in process synchronization and management impeded overall productivity [8,11]. The FBD system evaluated in this study demonstrated similar challenges, highlighting the necessity of implementing real-time monitoring tools, automating airflow and temperature, and employing maintenance strategies aligned with predictive diagnostics to reduce performance efficiency fluctuations and ensured consistent throughput in agro-industrial applications.

Table 3. Availability of the Fluidized Bed Dryer for Tea drying

Period (Month)	Machine Preparation Time (hours)	Machine Downtime (hours)	Machine Operating Time (hours)	Availability (%)
January	30.5	24.5	689	96
February	30.5	0	641.5	100
March	33.33	10.67	700	98
April	29	0	691	100
May	33.33	10.67	700	98
June	30.5	0	690	100
Average				**94**

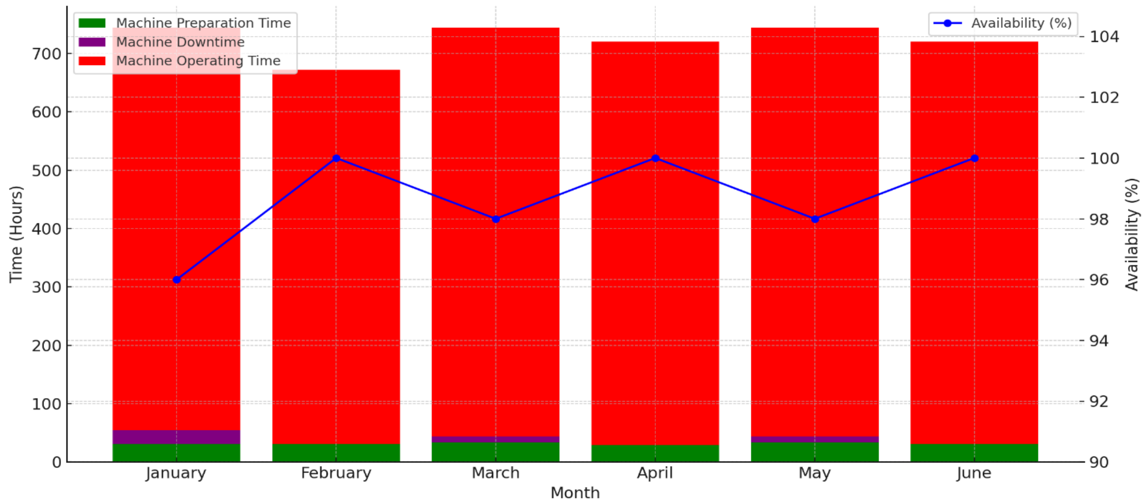

Figure 1. Availability profile of the Fluidized Bed Dryer machine in tea processing

Table 4. Performance Efficiency of Fluidized Bed Dryer for Tea Drying

Period (Month)	Ideal Cycle Time (hour/kg)	Machine Operating Time (hours)	Production Output (kg)	Average Performance Efficiency (%)
January	0.004	689	144,729	69
February	0.004	642	146,452	91
March	0.004	700	155,727	88
April	0.004	691	114,394	66
May	0.004	700	179,158	100
June	0.004	690	175,128	100
Average				**89**

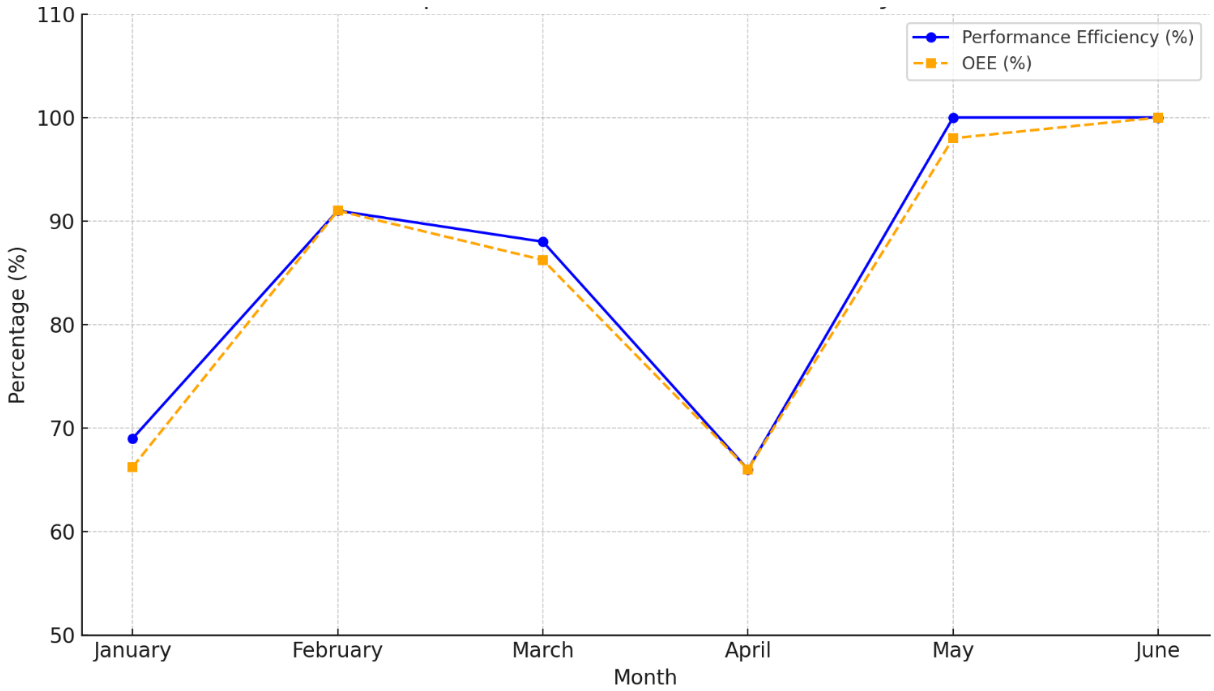

Figure 2. Relationship between the decrease in performance

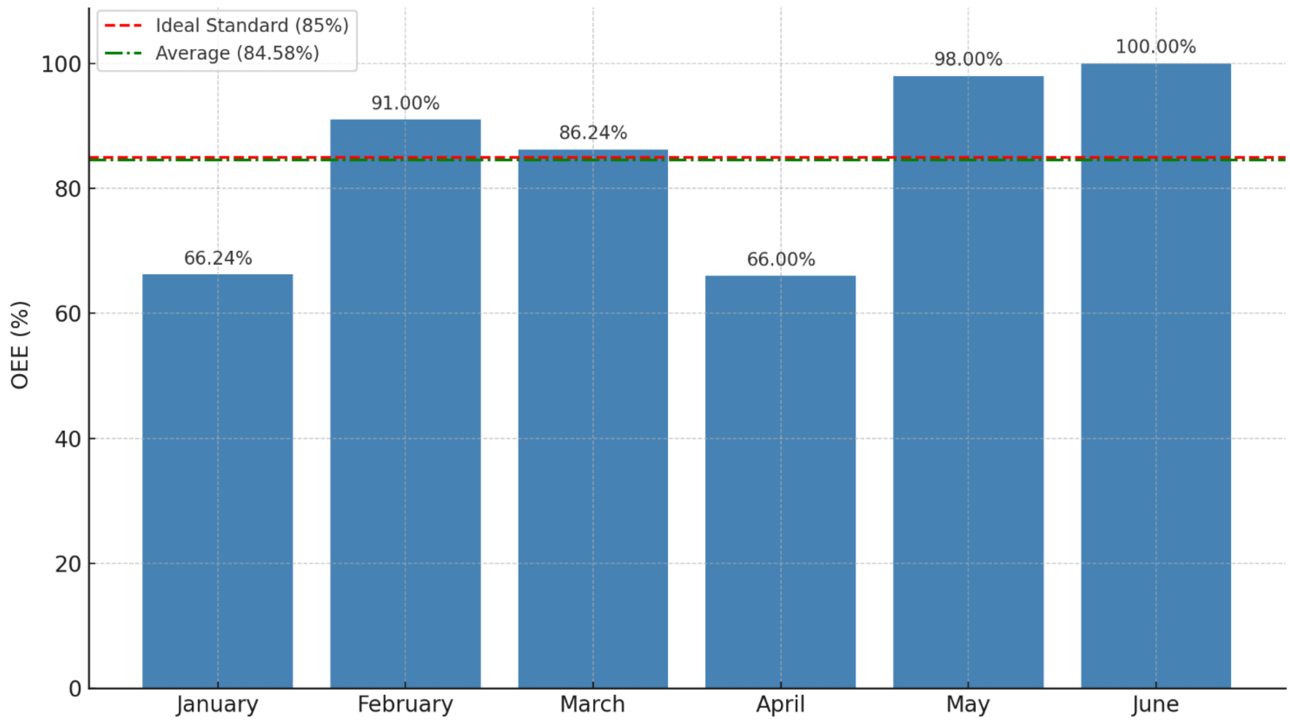

Figure 3. Monthly OEE of FBD

4. Conclusion

This study conducted a systematic evaluation of the performance of the Fluidized Bed Dryer (FBD) used in the production of orthodox black tea using the Overall Equipment Effectiveness (OEE) methodology, in accordance with ISO 22400-2:2014. The results obtained from the six-month operating period showed an average OEE of 83.66%, with consistently high availability (94%) and a product quality rate reaching 100%, despite significant variations in performance efficiency (66%–100%). This study identified that performance efficiency was the main factor affecting OEE variation, caused by longer cycle times and throughput imbalance, rather than machine downtime or product defects.

The detected inefficiencies indicated a discrepancy between the actual operational speed and the planned system capability. These findings supported the adoption of certain strategies, such as real-time process management, automatic control of air and temperature distribution, and condition-based maintenance to reduce performance degradation. These interventions were deemed necessary to ensure consistent equipment utilization, reduce process variability, and enhance the reliability of thermal drying operations in accordance with productivity and quality standards in black tea processing.

The recommendations from this study included the implementation of a digital performance monitoring system, including the use of sensors for predictive maintenance, as well as enhancing temperature and airflow control to maintain standardized product quality. Additionally, this research recommended that tea processing entrepreneurs prioritize of real-time monitoring technology to minimize unexpected downtime and optimize operational efficiency.

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