



EFFECT OF COMBINED MULTI-PURPOSE SMART DRYER (MPSD) AND FERMENTATION ON THE DRYING QUALITY OF SWEET POTATO CHIPS

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ABSTRACT

This study used a Multi-purpose Smart Dryer (MPSD) equipped with an automatic gas-electric hybrid heating system and IoT-based temperature control to dry Sweet Potato Chips (SPC) from two varieties, namely Bima Pasru (BP) and Gatot Kaca (GK). The chips were subjected to two treatments during flour production: Fermented and non-fermented. Sweet Potato Flour (SPF) production includes cleaning, peeling, slicing, soaking in sodium bisulfate solution, drying, and milling (80 mesh). The MPSD is compared to Direct Sunlight (DS) drying as a control. The drying indicators, i.e., Temperature (T) and Relative Humidity (RH), work well. Temperature ranges from 35°C to 55°C, while RH decreases from 85% to 20% during drying. The drying speed of MPSD ranges from 2%/hour to 3%/hour, which is more efficient than traditional DS (1%/hour). The MPSD consumes about 12 kWh to dry chips from 72% to 7.3% water content. Drying time ranged from 17 to 19 hours, shorter than 40 hours of DS drying. Drying efficiency ranged from 33% to 36%. The MPSD, especially when combined with fermentation pre-treatment, offers an efficient, weather-resilient, and farmer-level-appropriate method for producing high-quality SPF.

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Introduction

The sweet potato (*Ipomoea batatas*) is a tuber that grows well in tropical and subtropical regions. It adapts easily to local environments, is resistant, and has relatively low production costs, making it suitable for both small- and large-scale farming (El Sheikha & Ray, 2017). Sweet Potato (SP) is a plant rich in fibre, protein, fats, polyphenols, carotenoids, and other nutrients (Sun *et al.*, 2017; Ishiguro, 2019; Mu & Singh, 2019; Mu & Zhang, 2019; Mu *et al.*, 2019).

Sweet potato is a highly versatile crop transformable into a wide range of food products, including staple food, snack food (Mu *et al.*, 2019), dietary items (Takamine *et al.*, 2019), fermented products (Takamine, 2019), and even for bioethanol production (Kim & Hamdy, 1985). Tubers and flour are widely used in food processing (Nuraeni & Fauziah, 2016; Mu *et al.*, 2019), while leaves are consumed as vegetables (Chao *et al.*, 2013). Cultivated extensively across tropical and subtropical regions, sweet

potato holds substantial economic value (Dereje *et al.*, 2020) and industrial potential (El Sheikha & Ray, 2017), as highlighted in global market reviews (Kassali, 2011).

The Bima Pasru (BP) variety stands out for its natural sweetness and caramelisation characteristics. Consumers widely favour it, and it has a high productivity of up to 15 tons per hectare with three annual harvests (Nurud *et al.*, 2022). The flour is processed into cookies, noodles, ice cream, and other food products (Wibowo & Aini, 2005; Tortoe *et al.*, 2017). Many consumers in Indonesia, China, South Korea, Japan, and Hong Kong favour the Bima Pasru (BP) variety of sweet potato (Solihin *et al.*, 2016; Diniyah *et al.*, 2023). Average land productivity reaches 15 tons per hectare, with three harvests per year (Nurud *et al.*, 2022). In addition to being consumed directly (baked, fried, and boiled), BP sweet potato is processed into flour. The flour can then be processed into various products, including snacks, cookies, pastry products (Tortoe *et al.*, 2017), noodles (Wibowo & Aini, 2005), ice cream, and various other foods (Diniyah *et al.*, 2022). In addition, several researchers have studied the potential of sweet potato as a functional food and medicine that benefits health (El Sheikha & Ray, 2017).

Researchers worldwide are extensively studying the drying methods. For example, Hatamipour *et al.* (2007) have observed the drying characteristics of six varieties of sweet potato honey using different dryers. Doymaz (2016) has reported using infrared drying for sweet potato chips. Other drying methods applied to sweet potatoes include convective air drying (Joykumar & Pandey, 2012), solar drying for slices (Diamante & Munro, 1993), and more. Ramesh *et al.* (2006) observed the quality changes in flour from different drying methods. Other researchers have studied the effects of drying methods using solar dryers, ultrasound (Rashid *et al.*, 2022), microwave (Yan *et al.*, 2013), infrared drying (Doymaz, 2012), vacuum-belt drying (Xu *et al.*, 2013), hot air drying (Bechoff *et al.*, 2009; Orikasa *et al.*, 2010), drum-drying (Soison *et al.*, 2014), and convective air drying

(Joykumar & Pandey, 2012), on the quality of sweet potato slices (Yan *et al.*, 2013), flour (Ramesh *et al.*, 2006), antioxidants (Yang *et al.*, 2010), and amylose/amylopectin produced from the drying process (Guo *et al.*, 2014). However, these methods often face limitations such as weather dependency, high energy requirements, or limited adaptability to various crops.

Indarto *et al.* (2024) engineered a dryer (MSSD, standing for Multi Seed Smart Dryer) for grain seeds. The MSSD is integrated with control and IoT systems. In this research, the MSSD was modified to form a Multi-purpose Smart Dryer (MPSD) with a similar system. While maintaining the original features (such as real-time monitoring, temperature and humidity control, and programmable operation), the MPSD has been adapted to accommodate a broader range of agricultural commodities. This modified dryer features a modular drying chamber, adjustable airflow and heat distribution systems, and flexible trays, making it suitable for drying diverse products such as fruits, tubers, seeds, and herbs.

The development of MPSD addresses the need for a versatile, energy-efficient, and farmer-friendly drying solution, particularly for tropical climates with unpredictable weather, where traditional sun drying poses significant limitations regarding hygiene, drying time, and quality consistency. Previous studies have shown that different drying methods significantly influence SP products' drying characteristics and quality attributes (Badiora *et al.*, 2023; Goncalves *et al.*, 2023; Kgonothi *et al.*, 2024; Ntsowe & Balole, 2025). The drying method combined with pre-treatment is expected to significantly affect drying performance and improve the quality characteristics of sweet potato products.

After harvesting, the Bima Pasru (BP) and Gatot Kaca (GK) sweet potato varieties are classified into three quality types: A, B, and C. Type A is transferred to industry, and Type B is classified as rejected quality. Type C is generally discarded or used as animal feed and sold cheaply. However, these lower-grade

sweet potatoes hold untapped potential. When processed into flour, they can become valuable raw materials, particularly for smallholder farmers and agro-based SMEs seeking to enhance product value and reduce waste. Unfortunately, current postharvest processing practices, especially drying, remain a significant bottleneck.

Drying is vital in flour production and directly affects product quality and processing efficiency. Drying is the initial stage that determines flour quality, so innovation in drying methods is needed to improve flour quality, process efficiency, and cost efficiency, and ultimately increase farmers' income. However, many existing methods are inefficient, heavily dependent on weather conditions, consume significant energy, and fail to produce consistent results. Although previous studies have introduced a range of drying technologies, many are crop-specific, expensive to operate (Ntsowe *et al.*, 2025), or not feasible for small-scale use (Rashid *et al.*, 2022).

This study addresses that gap by developing and testing a Multi-purpose Smart Dryer (MPSD), a system adapted from the IoT-integrated Multi-seed Smart Dryer (MSSD) developed by Indarto *et al.* (2024). The MPSD is designed to be versatile and user-friendly for drying various agricultural products, including sweet potato chips. Key performance indicators such as temperature control, relative humidity, drying rate, energy usage, and efficiency are systematically evaluated. The quality of the dried chips and the resulting flour is also analysed.

Materials and Methods

In this research, two local varieties (Figure 1) of Sweet Potatoes (SP), namely Bima Pasru (BP) and Gatot Kaca (GK), were used to test the performance of MPSD. Febria *et al.* (2023) described the agronomic properties of these two cultivars in more detail in an official document. The raw potatoes (BP and GK) were harvested from specific plots. The plots were part of a field experiment programme organised by the National Agency of Research (or BRIN in

Indonesia) (Febria *et al.*, 2024). During this field experience, BRIN released two local varieties for public use.

The release of two local varieties was expected to enrich the national sweet potato resources. All machines, tools, and materials used for processing sweet potatoes were prepared, including a washer, peeler, slicer, soaking tub (stainless steel, 100 L, locally fabricated), centrifuge draining basket (BB Industrial Centrifuge, China), a modified Multi-purpose Smart Dryer (MPSD), grinder (Brightsail Machinery, China), analytical balance (OHAUS, USA), knives, a kWh meter (Scheider Electric, France), sodium bisulfite $\text{Na}_2\text{S}_2\text{O}_5$ (PT. Adimitra Prima Lestari, Indonesia), and two sweet potato varieties commonly grown in Indonesia: Bima Pasru and Gatot Kaca.

The procedures consisted of three main stages: (a) Design modification and functional test, (b) treatment and processing of SPF, and (c) quality analysis of both dried slices and flour produced.

Design Modification

Figure 2 shows the design of the MPSD used in this study. The dryer's dimensions were set to 130 x 50 x 100 cm. It was designed to meet the demand of most farmers in rural areas. These dimensions were practical for drying many products (for example, grain seeds, potato slices, etc.). The drying chamber consisted of 10 tray units. Each tray measured 100 x 50 cm. The trays were arranged vertically. Three light lamps and three fans were installed on the left side of the dryer. In this design, total energy consumption was set at 450 watts to match the common constraint that most seed farmers have only 450 watts of electric power installed in their homes. However, the drying function was not reduced (Indarto *et al.*, 2024).

A functional test was conducted at the Instrumentation Laboratory of FTP-UNEJ (Faculty of Agricultural Technology – University of Jember). The functional test was performed by running the dryer without product



Figure 1: Harvesting of sweet potatoes from BRIN Plots on 19 October 2024

(empty dryer) for 12 hours. In this case, each component and feature on the prototype was tested using standard procedures to evaluate each element's performance.

A watt meter (Taffware© Plug style: 2-pin German) was used to assess the heater, blower,

and exhaust fans during the drying process. The data logger recorded the temperature and Relative Humidity (RH) during drying. The Initial Water Content (IWC) and Final Water Content (FWC) were measured using the gravimetric method (Indarto *et al.*, 2024).

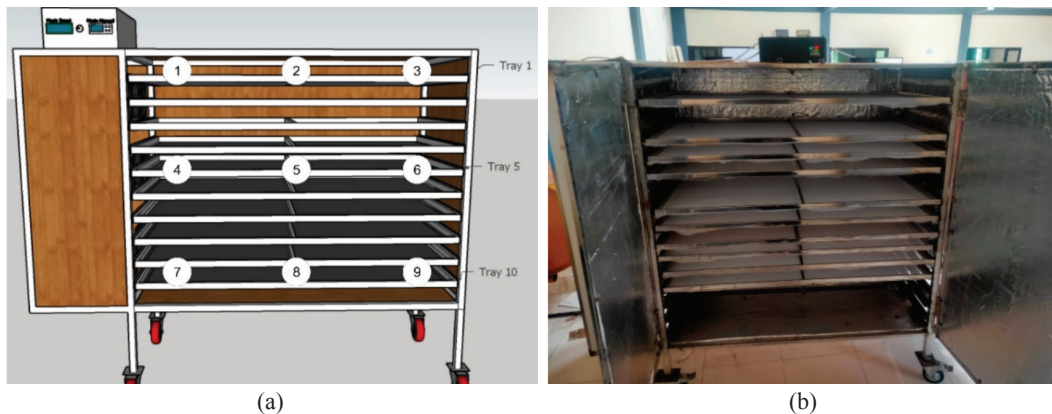


Figure 2: (a) Three-dimensional (3D) model of the multi-purpose dryer design showing the main structural components; (b) fabricated dryer unit as realised in the field after the manufacturing process

Treatment and Processing of SPF

Preparation of Chips

The harvested SP raw material was washed and peeled. The outer skin was peeled after washing. Then, peeled SP were sliced into uniform, tiny chips using an automatic slicer. After that, the SP chips were immersed in the soaking tub. The water in this soaking tub was mixed with sodium bisulfite ($\text{Na}_2\text{S}_2\text{O}_5$) proportionally (1:1) for 30 minutes; this treatment was referred to as Fermented (F) treatment. Other similar weights of SP were prepared as Non-fermented (NF). The chips were dried directly in MPSD (MP) or sun-dried on the floor (DS), without soaking. Both F and NF treatments are subject to the same weight.

Drying of Chips

The chips' initial water content and colour before entering the MPSD were measured in the laboratory. First, the SP chips were directly dried in the MPSD. Second, the chips were arranged uniformly in each MPSD tray. Third, another sample of chips (used as a control) was placed on the ground floor and dried using direct sunlight. Fourth, during drying, the temperature and RH of the drying chamber were measured using a sensor and recorded by the Data logger. Finally, the dry chips were collected from the MPSD and SDD. The final water content

and colour of dry chips were measured in the laboratory. All treatments and analyses were conducted in triplicate to ensure data accuracy and reliability.

Processing of Sweet Potato Flour (SPF)

The dried SP slices were milled using a high-speed grinder to produce Sweet Potato Flour (SPF). The resulting powder was sieved through an 80-mesh screen to obtain fine flour with consistent granularity. The 80-mesh flour from each treatment was stored in airtight containers at room temperature and subsequently sent to an accredited laboratory for proximate and functional property analysis. The SPF samples were sent to an accredited laboratory to measure several variables describing the quality of the produced SPF.

Performance Test

The performance of the Multi-purpose Smart Dryer (MPSD) was evaluated using four primary indicators: Water content, drying rate, energy consumption, and drying efficiency. Water content is a critical parameter, as it directly affects drying efficiency, shelf life, microbial stability, and the overall quality of the final flour product. In this study, water content

was measured using the gravimetric method, following standard AOAC procedures (AOAC, 2000) using Equation (1) as follows:

$$\%WC = \frac{W1-W2}{W1} \times 100\% \quad (1)$$

In this case:

$W1$ = Initial weight of cup and sample before drying in grams (gr)

$W2$ = Final weight of cup and sample after drying in grams (gr)

Drying Rate (DR) is an important parameter that reflects the speed at which moisture is removed from a material during the drying process. DR was calculated using the gravimetric method by monitoring the weight loss of the sample over time during the drying process, as described in Equation (2):

$$\text{Drying Rate } (DR) = \frac{Iw-Fw}{\Delta t} \quad (2)$$

Where:

DR = Drying rate (% db/hr)

Iw = Initial water content of the material (% db)

Fw = Final water content of the material (% db)

Δt = Drying time in hours (hr), and db = dry basis

Energy Consumption (EC) during the drying process represents the total amount of electrical energy the drying equipment uses to remove moisture from the product. EC during drying was measured using a calibrated digital kWh meter (Schneider PM1200) installed between the power source and the MPSD unit. Power readings were recorded at the beginning and end of each drying cycle.

The total EC is equivalent to the energy (power) $\times$ time of operation, which can be calculated as follows (Andika *et al.*, 2023):

$$EC = \frac{P \times t}{1000} \quad (3)$$

Where EC = Energy Consumption in kilowatt hours (kWh), P = Power consumption in watts (W), and t = drying time in hours (hr).

Drying Efficiency (DE) is a key performance indicator used to evaluate how effectively a drying system converts the input energy into useful energy for moisture removal. High drying efficiency indicates that a greater proportion of the energy supplied to the dryer is used for evaporating water, rather than being lost as waste heat or used to heat dryer components.

Drying efficiency in this study is defined as the ratio of the total useful energy used to evaporate moisture and heat the Sweet Potato (SP) chips to the total energy input provided by the heating element of the MPSD unit. The calculation follows a thermodynamic energy balance approach, using Equations (4) to (7) below.

The energy to evaporate water from the chips is calculated as follows:

$$Q1 = W_o \times H \quad (4)$$

Where $Q1$ = Energy consumption to evaporate water from the chips in kilojoules (kJ), W_o = Water vapour load in (kg H_2O), H = Latent heat in kilojoules/kg of chips (kJ/kg).

The energy to heat the chips is calculated as follows:

$$Q1 = m \times Cp \times \Delta t \quad (5)$$

Where $Q2$ is the sum of energy to heat the chips, in kilojoules (kJ); m = Chips mass to be dried in (kg); Cp = Specific heat of the chips in (kJ/kg $^{\circ}C$); Δt = Temperature difference between chips before and after drying ($^{\circ}C$).

Therefore, energy is needed to evaporate water and heat the chips:

$$Q_{out} = Q1 \times Q2 \quad (6)$$

Efficiency of drying processes:

$$DE = \frac{Q_{out}}{Q_{in}} \times 100\% \quad (7)$$

Where, DE = Drying efficiency in (%), Q_{out} = Energy used to evaporate and dry the chips (kJ), Q_{in} = Energy produced by the source that enters the drying chamber (kJ).

Quality Analysis of SP-chips and SPF

Water content and colour are measured from SP chips using laboratory methods. SP chips and SPF water content were measured using a digital moisture meter (OHAUS MB25, USA). To conduct the measurement, a sample (typically 5–10 g) was placed in the measurement chamber, and the moisture meter detected the dielectric properties to estimate the moisture level, which was instantly displayed as a percentage on the device screen.

Colour measurement was performed using a colourimeter (CHN Spec CS10, China), an instrument that quantifies surface colour based on reflected light intensity. The device measures colour values in the CIE $L^*a^*b^*$ colour space, which is widely accepted in food quality assessment because it represents human visual perception. To conduct the measurement, the sample (either in powder or slice form) was placed on a flat surface to ensure uniform coverage. The colourimeter sensor was then positioned directly on the sample surface, and readings were taken at three to five locations to account for sample variability. The average L^* , a^* , and b^* values were recorded. Before measurement, the instrument was calibrated using standard reference materials to ensure accuracy.

Then, the SPF samples were prepared for Proximate Analysis (PA). The PA was conducted at the C-DAST laboratory at the University

of Jember and an accredited laboratory at the Faculty of Agricultural Technology, the University of Gadjah Mada. All procedures were performed using standardised methods based on the AOAC protocols (AOAC, 2000).

Statistical Analysis

The experimental data were analysed using descriptive statistics. All experiments were conducted in triplicate, and the results were expressed as mean values along with standard deviations. Comparative analysis among treatments was performed by evaluating trends and relative differences in drying performance parameters, including moisture content, drying rate, energy consumption, and drying efficiency. Graphical and tabular representations were used to illustrate the behaviour of each treatment during the drying process. No inferential statistical tests were applied, as the primary objective of this study was to evaluate the drying system's performance characteristics.

Results and Discussions

Water Content, Drying Rate, Energy Consumption, and Drying Efficiency

Table 1 presents a comparison of key parameters to evaluate the performance of the drying methods and their effect on product quality. Table 1 compares the measured properties of

Table 1: Comparison of SP chip and flour properties by different drying methods (mean $\pm$ SD, n = 3)

Treatment	IWC (%)	FWC (%)	Drying Time/DT (hour)	Drying Rate/DR (%/hour)	Energy Consumption (kWh)	Drying Efficiency (DE) (%)
GK-FMP	75.38 $\pm$ 2.28	7.81 $\pm$ 0.26	18	3.75	12.26	36.1
GK-NFMP	73.52 $\pm$ 1.66	6.46 $\pm$ 0.03	19	3.53	12.82	33.7
BP-FMP	71.78 $\pm$ 0.80	7.37 $\pm$ 0.16	17	3.79	12.2	34.6
BP-NFMP	67.11 $\pm$ 2.25	7.57 $\pm$ 0.56	18	3.31	11.41	35.1
GK-FDS	75.38 $\pm$ 2.28	7.59 $\pm$ 0.32	74	0.92		
GK-NFDS	73.52 $\pm$ 1.66	7.94 $\pm$ 0.06	50	1.31		
BP-FDS	71.78 $\pm$ 0.80	9.18 $\pm$ 0.09	47	1.33		
BP-NFDS	67.11 $\pm$ 2.25	9.51 $\pm$ 0.06	26	2.22		

chips from MPSD (GK-FMP; GK-NFMP; BP-FMP; BP-NFMP) and the chips measured from Direct Sunlight (DS) drying, i.e., (GK-FDS; GK-NFDS; BP-FDS; BP-NFDS). In this case, the DS treatment serves as the control.

The data include drying performance indicators such as Drying Time (DT), Drying Rate (DR), Energy Consumption (EC), Drying Efficiency (DE), along with chip quality attributes including Initial Water Content (IWC) and Final Water Content (FWC).

Temperature and RH Distribution

Figure 3 shows the temperature distribution in the drying chamber. The temperature data is obtained from the DHT22 sensor and then recorded with a data logger. The temperature

increases from 35°C to 55°C during the drying. Although the temperature is set to 60°C to 62°C in the heating chamber, the temperature in the drying chamber rises only to 55°C. This decrease is caused by heat-transfer losses from the heater to the drying chamber.

Drying Time and Colour of SPF

Table 2 presents the colour test results for SPF samples. The drying method affects the colour characteristics of the GK and BP varieties (brightness, redness, and yellowness). Drying using the MPSD yields a relatively high brightness level (L^*) with a shorter drying time, demonstrating that this method accelerates the drying process and can maintain or even enhance brightness, particularly in samples subjected to fermentation.

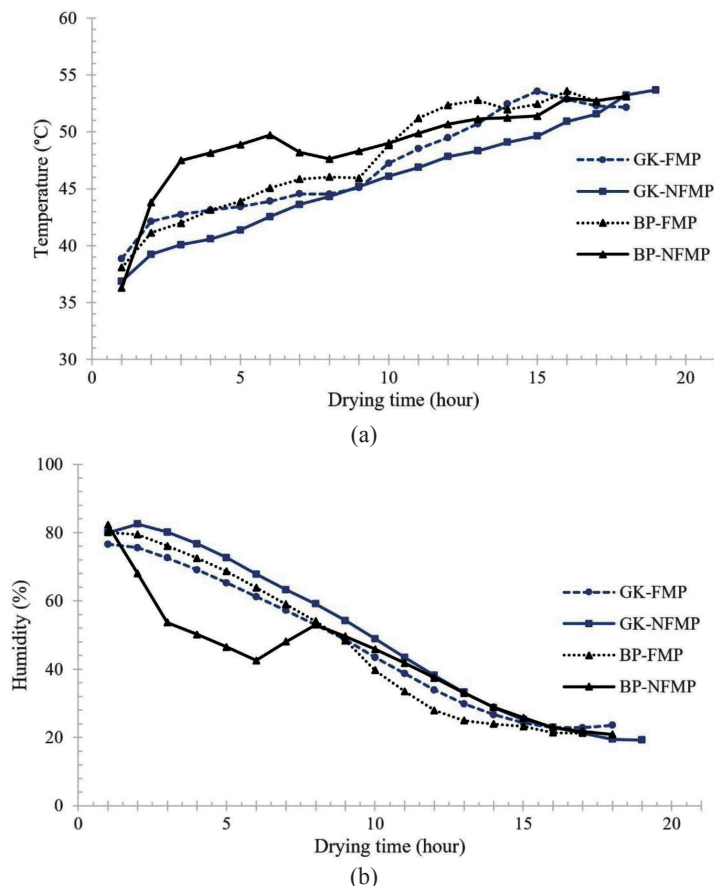


Figure 3: The temperature (a) and relative humidity (b) distribution in the drying chamber

Table 2: Colour parameters (L^* , a^* , b^*) of SP chips after drying (mean $\pm$ SD, $n = 3$)

Treatment	Brightness Level (L^*)	Red Level (a^*)	Yellow Level (b^*)
GK-FMP	73 $\pm$ 0.00	4.65 $\pm$ 0.07	17.7 $\pm$ 0.00
GK-NFMP	73.4 $\pm$ 0.00	5.1 $\pm$ 0.00	21.4 $\pm$ 0.14
BP-FMP	73.5 $\pm$ 0.00	5.3 $\pm$ 0.00	20.4 $\pm$ 0.00
BP-NFMP	71.3 $\pm$ 0.00	7.35 $\pm$ 0.07	25.56 $\pm$ 0.07
GK-FDS	73.6 $\pm$ 0.00	5.15 $\pm$ 0.00	17.95 $\pm$ 0.07
GK-NFDS	65.8 $\pm$ 0.00	6.2 $\pm$ 0.00	21.25 $\pm$ 0.07
BP-FDS	74.45 $\pm$ 0.00	5.05 $\pm$ 0.07	18.9 $\pm$ 0.00
BP-NFDS	73.8 $\pm$ 0.00	7 $\pm$ 0.00	24.7 $\pm$ 0.00

In contrast, the direct Sunlight Drying (DS) method yields the longest drying time, yet the brightness level remains relatively stable, especially in Bima Pasru (BP). Additionally, redness (a^*) in the DS method tends to be higher, which may be due to prolonged exposure

to direct sunlight, increasing browning intensity and concentrating surface pigments.

Table 3 shows the Proximate Analysis (PA) results, and Table 4 presents the physicochemical properties of sweet potato flour.

Table 3: Proximate composition of sweet potato flour (mean $\pm$ SD, $n = 3$)

Treatment	Water Content (%)	Ash (%)	Fat (%)	Protein (%)	Calory (kcal/100gr)	Carbohydrate (%)
GK-FMP	8.42 $\pm$ 0.06	0.57 $\pm$ 0.01	1.05 $\pm$ 0.02	1.68 $\pm$ 0.01	369.29 $\pm$ 0.30	88.28 $\pm$ 0.04
BP-FMP	8.29 $\pm$ 0.06	0.88 $\pm$ 0.01	0.93 $\pm$ 0.02	4.33 $\pm$ 0.01	367.99 $\pm$ 0.18	85.57 $\pm$ 0.11
GK-NFMP	7.65 $\pm$ 0.07	2.83 $\pm$ 0.01	0.98 $\pm$ 0.01	3.93 $\pm$ 0.01	362.96 $\pm$ 0.31	84.61 $\pm$ 0.06
BP-NFMP	7.22 $\pm$ 0.04	1.98 $\pm$ 0.00	0.47 $\pm$ 0.01	5.13 $\pm$ 0.07	365.53 $\pm$ 0.08	85.20 $\pm$ 0.11
GK-FDS	9.12 $\pm$ 0.08	0.51 $\pm$ 0.01	1.04 $\pm$ 0.01	1.64 $\pm$ 0.00	366.72 $\pm$ 0.28	87.69 $\pm$ 0.11
BP-FDS	10.11 $\pm$ 0.00	0.71 $\pm$ 0.01	1.03 $\pm$ 0.00	3.12 $\pm$ 0.00	361.84 $\pm$ 0.01	85.03 $\pm$ 0.01
GK-NFDS	8.10 $\pm$ 0.01	1.63 $\pm$ 0.02	0.82 $\pm$ 0.03	3.8 $\pm$ 0.00	365.17 $\pm$ 0.11	85.65 $\pm$ 0.04
BP-NFDS	10.11 $\pm$ 0.00	1.53 $\pm$ 0.01	0.62 $\pm$ 0.01	4.64 $\pm$ 0.00	356.56 $\pm$ 0.01	83.10 $\pm$ 0.04

Table 4: Physicochemical properties of sweet potato flour (mean $\pm$ SD, $n = 3$)

Treatment	pH Unit	Antioxidant (A.O.)	Water Holding Capacity (WHC)	Oil Holding Capacity (OHC)	Swelling Power
GK-FMP	4.2 $\pm$ 0.00		205.92 $\pm$ 0.86	99.27 $\pm$ 0.78	318.11 $\pm$ 0.47
BP-FMP	4.1 $\pm$ 0.00	2.89 $\pm$ 0.08	199.26 $\pm$ 0.93	78.95 $\pm$ 0.94	293.16 $\pm$ 0.54
GK-NFMP	6.1 $\pm$ 0.00		183.20 $\pm$ 0.95	77.15 $\pm$ 0.95	298.24 $\pm$ 0.77
BP-NFMP	5.9 $\pm$ 0.00	12.2 $\pm$ 0.07	183.32 $\pm$ 0.52	73.65 $\pm$ 0.23	167.11 $\pm$ 0.98
GK-FDS	4.3 $\pm$ 0.00		194.69 $\pm$ 0.93	96.13 $\pm$ 0.54	309.93 $\pm$ 0.64
BP-FDS	4.3 $\pm$ 0.00	4.06 $\pm$ 0.08	192.75 $\pm$ 0.13	89.55 $\pm$ 0.42	328.96 $\pm$ 0.87
GK-NFDS	5.7 $\pm$ 0.00		191.87 $\pm$ 0.76	83.17 $\pm$ 0.66	264.61 $\pm$ 0.08
BP-NFDS	6 $\pm$ 0.00	6.44 $\pm$ 0.08	186.05 $\pm$ 0.89	77.62 $\pm$ 0.42	287.11 $\pm$ 0.48

Discussion

This section presents and discusses the results of the drying process and quality evaluation of SPF produced from two local varieties, BP and GK, under different pre-treatment and drying methods. The analysis covers key performance indicators, including: Drying Time (DT), Drying Rate (DR), Water Content (WC), drying temperature and RH, Drying Rate (DR), Energy Consumption (EC), and Efficiency (EF).

Drying can reduce the water content in the chips from (67%–75%) at Initial Water Content (IWC) to (6.46%–7.81%) at Final Water Content (FWC); this value is still favourable for further saving, handling, and flouring processes (Table 1). The FWC value of chips is still below the maximum allowed by the standard (i.e. 14.5%) (Aydin *et al.*, 2009). In contrast, higher water content in chips can promote the development of fungi and other contaminants. Excessively high moisture content in flour can lead to easy contamination (Abdullah *et al.*, 2000; Bodor *et al.*, 2024). The findings are consistent with those reported by Abano and Amoah (2015), where dried sweet potato slices with a moisture content below 10% showed improved microbial stability and more storage life. Karim and Hawlader (2005) also emphasised that appropriate drying conditions can significantly reduce microbial risks while preserving product quality.

The drying rate measures the amount of water evaporated from the product per hour during drying (as visualised in Table 1). The Drying Rate (DR) of MPSD (MP) treatment ranges from 3.32%/hour to 3.79%/hour. It performs better than direct sunlight drying (DS). Table 1 shows that DS drying takes longer to reach the same FWC level as MPSD. As the drying rate decreases, the time required to dry the material increases. Additionally, several factors influence the drying rate, including temperature, airflow, chip thickness, ambient humidity, and initial moisture content. In this study, the MPSD maintained more stable, controlled temperature and airflow, promoting faster moisture removal.

Conversely, DS drying was affected by fluctuating sunlight intensity and inconsistent airflow, resulting in lower drying rates and longer drying times. Moreover, chip characteristics such as variety, presence of skin, and slice thickness also contributed to the observed variations. The result is consistent with previous findings by Bassey and Schmidt (1986), who noted that thinner slices and skinless chips exhibit faster drying behaviour due to a higher surface area and more efficient moisture diffusion. Fermentation significantly improves the drying rate only when combined with controlled drying environments (MPSD), where fermented samples consistently dried faster than non-fermented ones. However, fermentation in uncontrolled drying, such as DS, was less effective or counterproductive, likely due to surface moisture retention and environmental limitations.

An efficient PS-chip dryer uses less energy to achieve the desired FWC without excessive waste. The energy requirements during the drying process are lower for the MPSD (Table 1). This occurs because the MPSD optimises heat and air circulation, reducing drying time and therefore the energy needed to operate the system. Additionally, the MPSD uses components that require lower electrical power for energy-efficient system operation.

Drying Efficiency (DE) is calculated by comparing the heat required to dry the product with the actual heat used. The DE calculation (Table 1) is based on the thermal energy used to evaporate moisture from the material (SP) and the electrical power produced during the drying process. The higher the DE, the less energy is required for drying. Testing of the MPSD shows that as efficiency increases, less energy is needed for the drying process. The MPSD produces DE values of 36.05%, 33.66%, 34.58%, and 35.09%. This DE value is due to the relatively low energy requirement, the quick drying process, and the uniform temperature distribution that ensures the entire material dries thoroughly.

Figure 3 (a) shows that the MPSD provides a gradual and controlled rise in drying temperature, which is suitable for low-temperature drying of agricultural products. Variations in temperature across treatments indicate that both the type and pre-treatment influence drying characteristics. Among the treatments, BP-NFMP exhibited the highest and most rapid temperature increase, consistently reaching temperatures above those of other treatments after the 5th hour. This indicates a potentially faster drying reaction, likely due to differences in tissue composition compared with GK. In contrast, GK-FMP showed the least rapid temperature increase, suggesting more controlled heat transfer because the soaking treatment reduced the initial thermal conductivity or changed the surface characteristics of the slices.

Figure 3 (b) shows that RH gradually decreases from 84% to 20% during drying. Among the treatments, BP-NFMP shows the fastest drop in RH within the first 4 hours, suggesting a more rapid initial moisture release. In contrast, GK-FMP and GK-NFMP showed a more gradual decrease in humidity, indicating slower drying behaviour. Furthermore, non-fermented samples tended to reduce humidity faster than fermented ones because of differences in initial surface moisture and diffusion resistance.

The browning reaction significantly influences the chip colour, as reflected by lower L^* and higher a^* values in DS-treated samples. The shorter drying duration and controlled environment in the MPSD method effectively limit both enzymatic and non-enzymatic browning, making this method more suitable for preserving SPF's visual quality than sun drying. The data also indicate that fermentation reduces browning intensity in SP chips, as reflected by higher L^* values and lower a^* and b^* values than in non-fermented samples. This effect is more evident in samples dried using MPSD, where controlled temperature and humidity conditions complement the fermentation's ability to suppress enzymatic and non-enzymatic browning.

In contrast, the DS method, even in fermented samples, showed signs of browning, though to a lesser extent than their non-fermented counterparts. Fermentation protects against colour degradation; its effectiveness is significantly enhanced with a controlled drying environment. The browning reaction also affects the colour of sweet potato flour. When exposed to heat during drying, sweet potatoes contain polyphenoloxidase enzymes that cause a browning reaction. The longer the drying process, the more intensive the browning reaction, so the flour's colour becomes darker. The MPSD method is suitable for maintaining or enhancing brightness levels and allows for more efficient drying times than the DS method.

Fermentation treatment tends to reduce ash content, protein, and pH in both GK and BP varieties (Table 3). The reduction in ash content may be due to the solubilisation or leaching of mineral components during microbial activity in the fermentation process. Meanwhile, the protein degradation could result from the proteolytic activity of fermentation microorganisms, which break down protein molecules into peptides and amino acids (Nkhata *et al.*, 2018). Furthermore, the quality characteristics of the SP chip and SP flour are compared across treatments. The results are discussed in the context of existing literature to evaluate the effectiveness of the MPSD as a farm-level drying technology in tropical climates.

Additionally, decreased pH is a standard indicator of successful lactic acid fermentation, as lactic acid bacteria produce organic acids, primarily lactic acid, which acidify the substrate (Tamang *et al.*, 2020). This acidification can enhance preservation and contribute to enzymatic activity that modifies nutrient composition. Adegunwa *et al.* (2011) reported similar trends, noting that fermentation significantly reduced pH and protein content in cassava flour.

These results (Tables 3 and 4) suggest that fermentation alters sweet potato flour's physicochemical composition before drying and should be considered when determining its suitability for various food applications. First,

Fermentation (F) before drying tends to increase variables such as water content (A.O), fat content, calories, carbohydrate, Water Holding Capacity (WHC), Oil Holding Capacity (OHC), and swelling power. The results are similar for both GK and BP varieties. In contrast, fermentation decreased ash content, protein, and pH. The decrease in ash content, protein, and pH observed in the fermented treatments can be explained by the biochemical and physical changes occurring during fermentation (Table 4).

The decline in pH (from approximately 6 in non-fermented to around 4 in fermented samples is primarily due to the production of organic acids (e.g., lactic and acetic acids) by lactic acid bacteria or through sodium bisulfite treatment (Adejuwon *et al.*, 2021). This acidification is a hallmark of microbial or chemical pre-treatments designed to inhibit browning and improve preservation. Similarly, the reduction in ash content is mainly attributable to the leaching of minerals (potassium, calcium, and magnesium) into the soaking or fermentation medium. These minerals become dissolved and are typically discarded with the liquid, resulting in lower residual mineral levels in the flour (Ajayi *et al.*, 2016). Regarding protein content, fermentation promotes proteolysis (microbial enzymes break down proteins into peptides and free amino acids), which may dissolve into the medium or be consumed by microbes. As a result, the overall protein level in the dried sample declines (Dashen *et al.*, 2024). A more detailed analysis of Antioxidant (A.O.) activity shows that fermentation treatment in the BP variety decreases A.O. Fermentation treatment before drying improves some properties of GK and BP SP flour.

Second, drying using MPSD tends to decrease water content and holding capacity. MPSD drying does not change the significant properties of SPF such as ash, fat, protein, and carbohydrate content. Moreover, pH, oil-holding capacity, and swelling power also remain constant during the drying treatment (Table 4). Both BP and GK have higher water content than flour made without fermentation (Table 3);

during fermentation, water is absorbed by sweet potatoes, increasing the water content. This result matches Kurniadi *et al.* (2019), who state that fermentation increases the water content of sorghum flour compared to that made without fermentation. The ash content of fermented flour is lower than that of flour without fermentation (Table 3). Some minerals dissolve in the soaking water during fermentation, reducing the ash content. This result is similar to Aini *et al.* (2016), who state that fermentation in the manufacture of corn flour reduces minerals, and the longer the fermentation, the lower the mineral content (Jukonyte *et al.*, 2018). Fermentation reduces ash and protein content because soaking in the fermentation process decreases some water-soluble components. Some minerals and proteins in sweet potatoes are water-soluble compounds, so sweet potato chips' ash and protein content will decrease after fermentation. During fermentation, lactic acid bacteria form and produce lactic acid. Lactic acid is acidic, so it lowers the pH of sweet potato chips.

Third, fermentation increases water absorption capacity. During fermentation, water absorption occurs and the volume of sweet potatoes increases due to the inclusion of soaking water. According to Aini *et al.* (2016), this will increase water absorption. Water absorption capacity affects how easily flour homogenises when mixed with water. Flour with high water absorption will be easier to homogenise, thus accelerating gelatinisation. Fermented sweet potato flour has a higher oil absorption capacity than non-fermented flour. The results follow Aini *et al.* (2016), who state that the oil absorption capacity of corn flour increases with fermentation. During fermentation, changes in starch molecules influence this phenomenon. According to Indrastuti *et al.* (2018), the longer the fermentation time, the greater the degradation of macromolecules into simpler molecules. Macromolecules that were previously relatively compact become somewhat porous as they break down into simple molecules with lower molecular weights, making them looser and more readily able to absorb oil.

Conclusion

MPSD is a suitable drying method for processing Sweet Potato Flour (SPF) at the farmer level, especially in tropical regions like Indonesia, which are prone to adverse weather conditions and high rainfall. Combining the MPSD method with fermentation treatment (30 minutes at 25°C) is recommended as the optimal choice to improve yield and flour quality. This study showed that the Multi-purpose Smart Dryer (MPSD), operated at 35°C–55°C, significantly reduced drying time for sweet potato flour to 17–19 hours, compared to 48–72 hours with Direct Sunlight (DS), and achieved an energy consumption of 3.03–5.17 kWh. The MPSD also produced flour with a 6%–8% final water content, essential for extended shelf life and quality maintenance. Additionally, MPSD drying enhanced flour brightness, which can be further improved by applying fermentation before drying. This fermentation step also decreased initial moisture, speeding up drying and boosting efficiency. Overall, the MPSD, especially when combined with fermentation, offered an effective drying solution for sweet potato flour production at the farmer level in tropical climates.

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Conflict of Interest Statement

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare absence of conflicting interests with the funders.

Author Contributions Statement

NPL and II carried out the investigation, drafted the article, and executed the revisions. NI, EW, and IS conceptualised the central research

idea and provided the underlying theoretical framework. The research methodology was designed by Indarto, NI, EW, and IS, who also supervised the overall progress of the research. Finally, II anchored the review process, managed the final revisions, and approved the article for submission. All authors reviewed and approved the final manuscript.

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