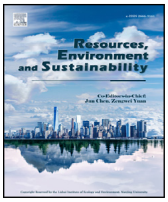
Resources, Environment and Sustainability 13 (2023) 100117

Contents lists available at ScienceDirect

Resources, Environment and Sustainability

journal homepage: www.elsevier.com/locate/resenv



Research article

Development of a pilot scale energy efficient flash dryer for cassava flour

Suraju A. Adegbite [a,*], Wahabi B. Asiru [a], Murat Sartas [b], Thierry Tran [c], Alejandro L. Taborda [c], Arnaud Chapuis [d,e], Makuachwuku Ojide [f], Adebayo Abass [b]

[a] Federal Institute of Industrial Research Oshodi (FIIRO), Lagos, Nigeria
[b] International Institute of Tropical Agriculture (IITA), CGIAR Research Program on Roots Tubers and Bananas (RTB), Nigeria
[c] International Center for Tropical Agriculture (CIAT), Cali, Colombia
[d] Qualisud, Univ Montpellier, Avignon Université, CIRAD, Institut Agro, IRD, Université de La Réunion, Montpellier, France
[e] CIRAD, UMR QualiSud, Sénégal
[f] Alex Ekwueme Federal University Ndufu-Alike (AE-FUNAI), Ebonyi State, Nigeria

ARTICLE INFO

Keywords:
Flash dryer
Energy efficiency
Specific energy consumption
High quality cassava flour

ABSTRACT

Cassava's transformation into an industrial raw material necessitates new processing techniques that improve quality while lowering processing costs. Drying has been identified as a major bottleneck in the production of high-quality cassava flour (HQCF) and expansion of its industrial application in Sub-Sahara African. This has triggered efforts towards developing an energy-efficient flash dryer for cassava flour/starch production at a small scale. A scaled-up version of the prototype flash dryer installed at the International Center for Tropical Agriculture (CIAT), Cali, Colombia, was built at the Federal Institute of Industrial Research, Oshodi, (FIIRO), Lagos, Nigeria based on numerical modeling. Excel tools developed by the CGIAR (RTB) scientists were used to design the components and built using locally sourced materials. The automation system of the flash dryer allows for operational flexibility, increased energy efficiency and reduced cost. It features a longer drying tube (22.5 m), a compact and improved heat exchanger, a larger blower for higher air velocity, and a high air/product ratio, thereby optimizing the drying efficiency. The dryer was evaluated with mechanically dewatered cassava mash (wet cake) dried into high quality cassava flour at air temperature of 180 °C and velocity of 13 m/s. The initial moisture content of the wet cake was 47.06 % wb, which was reduced to 9.6 % wb of dried product. Using a capacity of 298.0 kg of wet cake per hour, an output of 186.34 kg of dried product was achieved, resulting in an energy efficiency of 80.8 % and specific energy consumption of 2570 kJ/kg product of final product and 4560 kJ/kg water of evaporated water. These results revealed that the dryer is efficient and suitable for small-scale enterprises. Its use can reduce the production costs and expand the global market opportunity for cassava flour.

1. Introduction

Cassava's tolerance to biotic and abiotic challenges such as disease, flood, drought, and low soil fertility is critical to the food security of rural economies in sub-Saharan Africa. Among its many uses, cassava root is a famine-reserve crop, a rural staple, an urban convenience food, an industrial raw material, a cash crop, and a source of foreign exchange. In addition, its potential use in packaging, textile, and food processing contributes to the development of small industries that provides jobs and wealth income to rural dwellers. Cassava is currently one of the most widely grown tropical root crops due to its starchy tuberous roots, which are high in nutritional energy (Onwueme, 1978; Agordjo, 2012). It contributes considerably to the economy of many tropical countries by being processed into a variety of products (Apea-Bah et al., 2011), and it also plays an important role in the diets of the majority of Nigerians (Soyoye et al., 2015). According to Classifications (2023), the global total cassava production increased from 262.85 million metric tons (MT) in 2011 to 296.22 million MT in 2020 with Nigeria being the highest contributor to the global output (20.26%) followed by the Democratic Republic of Congo (DRC) and Thailand contributing 13.85% and 9.79% respectively. On the other hand, the global total cassava export from the major producers was 14.79 million metric tons (MT) in 2000 and 12.03 million metric tons (MT) in 2020. China is the highest global importer of cassava product (49.33%) with an import value of $531.00 million by March, 2022 followed by USA (25.61%) and Netherlands (6.18%) with an expenditure of $8.16 million and $1.06 million respectively during the same period. The leading exporter of cassava in 2021 was Thailand (85%) followed by Indonesia, Lao and Brazil contributing 6.43%, 1.92% and 1.36% respectively. Nigeria,

---

* Corresponding author.
E-mail address: adegbitesirojdeen@yahoo.com (S.A. Adegbite).

https://doi.org/10.1016/j.resenv.2023.100117
Received 30 October 2022; Received in revised form 5 March 2023; Accepted 6 March 2023

being a lead producer in the world does not contribute to global export of processed cassava products (Ndaliman, 2008; Classifications, 2023).

Cassava's transition into an industrial raw material necessitates innovative processing techniques to increase product quality and reduce processing costs. However, this transition requires the use of efficient processing equipment to deliver the quantity that meets the industrial demand, the required regularity and competitive price. For industrial or human use, the drying of cassava roots is a critical step (Duggan et al., 2008). By evaporation, drying removes moisture from solids to increase their shelf life, reduce transportation costs and make storage easier (Aghbashlo et al., 2008). The most energy-intensive process step in the production of high-quality cassava flour is drying, and keeping it under control is critical to ensuring the quality of the finished product (Tran et al., 2022) since the roots must be processed within 24 to 48 h of harvesting to reduce its toxicity and increase its shelf life, according to Ndaliman (2008). When cassava is processed into high-quality cassava flour, value is added to the product, its shelf life is extended, and transportation is made easier by the processing of cassava into high-quality cassava flour (Tran et al., 2022). Drying is a common problem that small and medium-sized enterprises (SMEs) face when processing cassava starch (Suherman et al., 2015). Roots are traditionally dried in the sun, but a dryer is needed to produce a higher-quality and much more hygienic product (Tran et al., 2022). There are numerous advantages to using mechanical drying equipment rather than sun drying for drying fine granule products. As a result of the increased granule surface area, the drying process proceeds significantly more quickly. In the food sector, advanced dryers are available and in use, but these are not suitable for smallholder farmers to adopt (Sriroth et al., 2000). Cassava drying has been hampered by a lack of suitable dryers that can be used by smallholder farmers, which has limited the growth of the small-scale cassava sector in Africa (Nweke, 2004). Dryers that are suited for use by small-scale farmers is still in the early stages of development, they are inefficient and the resulting product is of substandard quality (Da et al., 2013). Mechanical dryers for the production of high-quality cassava flour are available in a variety of forms, including the tunnel dryer, the rotary dryer, and the flash dryer. A pneumatic conveying dryer, also known as a flash dryer, is the most cost-effective and extensively used drying method for solids that have been dewatered or are naturally low in moisture (Mujumdar et al., 2014; Levy and Borde, 2014). One of the most frequent types of continuous convective drying systems is the "flash dryer", which utilizes an entrained fluidized bed to achieve its drying results (Brennan, 2011).

In a flash dryer, the time spent in direct contact between the drying medium and the dried material is minimal (usually few seconds only). Since heat-sensitive and easily oxidized products like cassava (Goto, 1969) cannot be exposed to process temperatures for prolonged durations, this property makes it excellent for drying these materials and also removing external moisture (Rotstein and Crapiste, 1997). Higher intake temperatures can be employed in flash dryers than in many other dryers without overheating the product because of this unique attribute of the flash dryer. When compared to other dryers, flash dryers can be used to dry some products at temperatures as high as 700 °C. The dryer's energy efficiency (Nimmol et al., 2020) and the dried product's quality (Bonazzi et al., 2009), are both directly impacted by the air temperature. High drying air temperatures typically yield improved energy efficiency (Tran et al., 2022). Suherman et al. (2015) investigated the drying kinetics of cassava starch and found that increasing the air temperature significantly improved its energy performance. It is important to note that high drying air temperatures can have a negative impact on product quality, particularly for solids rich in starch. For cassava drying, the temperature of the solid must remain below 64.3 °C in order to avoid starch gelatinization (Breuninger et al., 2009). Dryer designs therefore need to be adapted to the product, as each has its own set of characteristics (Levy and Borde, 2014). The design of a dryer is particularly dependent on the product's initial and final moisture content, temperature sensitivity, and particle size of the product being dried (Levy and Borde, 2014; Jayaraman and Gupta, 2014). In addition, it is necessary to customize dryer designs to meet the needs of specific target audiences (Chua and Chou, 2003).

Cassava flour preparation is a common African method for preserving and enhancing the nutritional value of the cassava root (Graffham et al., 2000). Because of this, cassava flour produced using conventional methods is typically of poor quality, rendering it unsuitable as a substitute for wheat flour in baked products. As a result, the development of sustainable technologies is critical to making cassava processing viable (Chapuis et al., 2017). Due to a rising demand for long-lasting cassava products by urban populations, the use of flash drying to produce high-quality cassava flour and starch at low cost is becoming increasingly important. As a result, small-scale flash drying is a promising solution for meeting the high demand for cassava starch and flour. Equipment manufacturers in Nigeria have therefore attempted to develop this technology to expand cassava value chains in conjunction with experts from research institutions and private investors in Nigeria (Tran et al., 2022).

As a result, several flash dryers design for cassava drying have evolved. However, most of these flash dryers' configurations and operating conditions are suboptimal, resulting in high energy consumption and operating costs. Because the margins in high-quality cassava flour and starch production are so small, these high costs can mean the difference between profitability and loss, and thus technology adoption. An investigation of flash dryer performance in several cassava-producing countries suggests that small-scale flash dryers in Nigeria and Vietnam tend to use more energy and have a higher production cost than large-scale flash dryers in Thailand and Brazil (Tran et al., 2022). Thus, the focus of this study was to increase the drying performance of locally made flash dryers in Nigeria to lower the production costs of cassava starch and high-quality cassava flour. Hence, a small-scale energy efficient flash dryer for the production of cassava starch and high-quality cassava flour was developed.

The flash dryer installed at FIIRO was based on a prototype flash dryer designed by RTB scientists, which has proven to be as energy efficient as large-scale industrial dryers (Tran et al., 2022). The prototype, which was developed using numerical modeling to determine key design features of an energy efficient flash dryer, is an innovation to optimize energy efficiency and costs, including a longer drying tube for full drying optimization, a compact and improved heat exchanger in comparison to current models with suboptimal efficiency, a larger blower for higher air velocity, and a high air/product ratio. In addition, an excel tools which is users' friendly for designing key components of flash dryer is peculiar to this innovation. The small-scale flash dryer's drying performance is comparable to that of large-scale industrial dryers and shows better energy efficiency with decreased fuel consumption. Therefore, the goals of this project are to develop a two-ton energy-efficient flash dryer based on the prototype flash dryer designed by RTB scientists and to evaluate the dryer for high quality cassava flour drying.

2. Materials and methods

2.1. Design of the flash dryer

The excel tools developed by the CGIAR (RTB) scientists were used to design the flash dryer components. The diameter and length of the drying tube, cyclone, and heat exchanger components were all dimensioned using the users' friendly guide (excel tools) for designing flash dryers. The excel tools is available for equipment manufacturers and can be found online at https://flashdryer.cirad.fr/content/download/4153/31242/version/1/file/outil+diagnostique+v0.3.xlsm (http://www.rtb.cgiar.org/blog/publication/dryingoptimization-for-thesustainable-development-ofcassava-industry/).

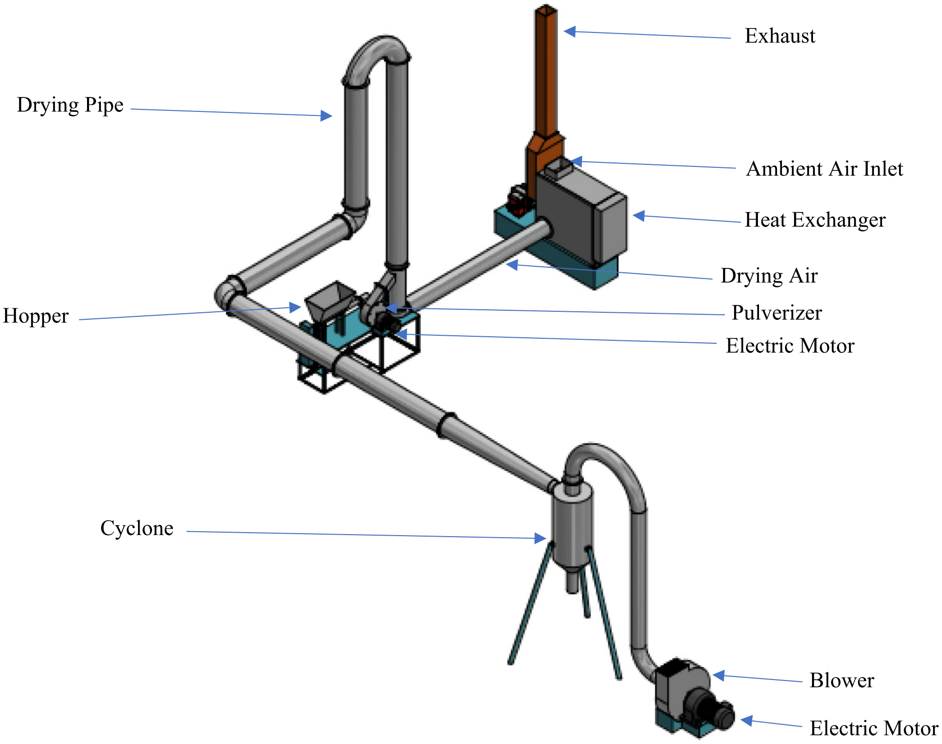


Fig. 1. Isometric view of the flash dryer.

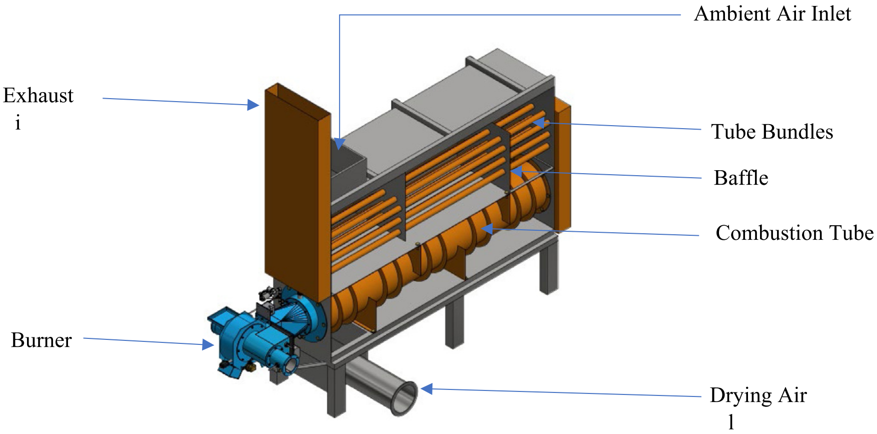


Fig. 2. Isometric view showing the internal components of heat exchanger.

2.2. Flash dryer development

Based on the design of a prototype flash dryer (100 kg/h) for cassava starch installed at the International Center for Tropical Agriculture (CIAT), Cali, Colombia (Tran et al., 2022), the flash dryer for this study (186.34 kg/h) was developed. Thus, it is a scaled-up version of the prototype flash dryer that was installed at CIAT. Computer Aided Design (CAD) software, Autodesk Inventor 2012, was used to generate the flash dryer's engineering drawings, followed by the construction of the dryer based on the dimensions specified in the excel tools.

2.2.1. Description of the flash dryer

The dryer is a negative and single cyclone system comprising of a heat exchanger, drying duct, feeding hopper, cyclone, blower, and a control panel (Fig. 1). The drying duct had a diameter of 0.25 m and a length of 22.5 m, with a capacity of 2.0 tons per 10 h of operation. The radius of the bend connecting each section was 0.6 m. Sensors were installed at various points to collect real time data of the drying parameters thus allowing automation and making the dryer both versatile and flexible in operation. The control panel is made up of programmable logic controllers (PLCs), which log data and display it on a screen (human machine interface) or computer system. The dryer's heat exchanger, a novel concept, is energized by diesel to generate heat and is made up of a combustion tube and a series of tubes with turbulators on top for the return of flue gas. The heat exchanger is a counter-current, and two-pass flow, with outside dimensions of 1.5 m in length and 0.6 m in width giving it the compact feature. The ignition (on and off) system controlled by a preset drying temperature range (Fig. 2) gives it the energy efficiency feature.

Plate 1a and b show the flash dryer and the heat exchanger installed at the cassava processing pilot plant of Federal Institute of Industrial Research, Oshodi, Lagos, Nigeria. Wet product to be dried was fed into the dryer via a screw auger/feeder powered by an electric motor. The feeder motor's speed can be varied by selecting the desired speed range on the screen, which is accomplished via a drive in the control panel. A pulverizer powered by a separate motor disperses the wet material

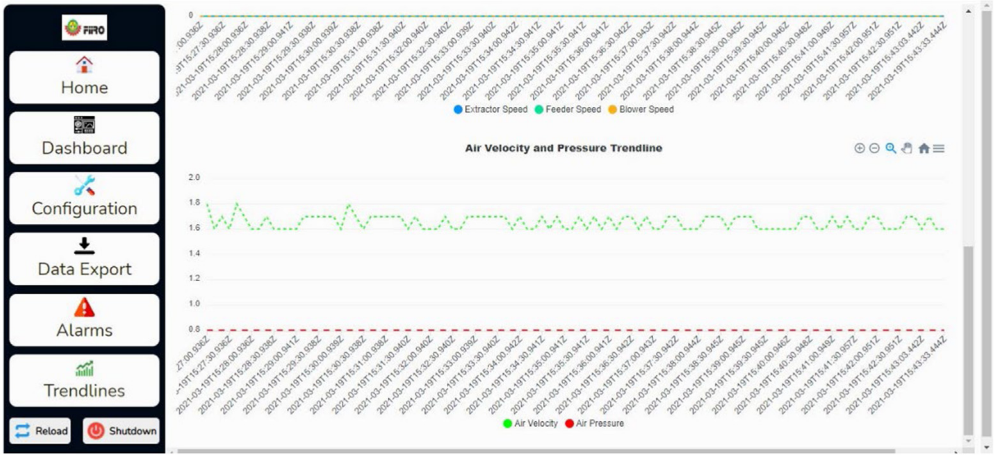


Fig. 3. The air velocity and the air pressure being displayed on the screen.

Plate 1. (a): The drying duct with control panel. (b): The heat exchanger with the fuel tank.

into the hot airstream for drying in the drying duct. The material is conveyed through the drying duct into the cyclone, where the dried material is separated from the wet exhaust air and discharged. A 15 hp electric motor drives a centrifugal blower located after the cyclone to induce negative airflow.

2.3. Dryer fabrication

The dryer was constructed according to the specifications using the excel tools software. Materials used in the dryer's fabrication were sourced locally, taking into account the environmental, economic, and availability of the dryer to small-holder farmers in order to reduce post-harvest loss. Additional criteria for material selection included their capacity to tolerate extreme temperatures and stresses as well as their food grade for sections that come into touch with the products they are intended to dry. The drying duct was built of 1.2 mm thick stainless steel whereas the hopper, feeder and cyclone were made of 3 mm thick stainless steel. The heat exchanger's combustion tube was constructed of 4 mm thick stainless-steel sheet, while the return tube bundles were made with 60 mm diameter pressure pipe and turbulators were constructed of 1.2 mm thick mild steel sheet. For the heat exchanger's framework, 100 mm square pipe was used, while 5 mm mild steel sheet was used for the housing. The drying duct and the heat exchanger were thermally insulated using a 50 mm thick fiber glass shielded with 1.2 mm galvanized sheet for the drying duct and 3 mm thick mild steel sheet for the heat exchanger.

2.4. Human Machine Interface (HMI)

Human Machine Interface (HMI) is the screen on the control panel where the desired drying condition can be pre-set for drying process as shown in Fig. 3. When the dryer is controlled by a computer system, an android phone via wireless connection within a 10 m radius, or the cloud via internet connection, a similar interface is displayed. The dryer's versatility stems from its operational flexibility. The desired drying conditions can be entered using the control panel's HMI or a computer/android phone. After the drying operation, the data for the drying parameters can be downloaded in excel format to determine dryer performance. Fig. 3 depicts the trend lines for air velocity and pressure. The blower's power induced the air velocity to range between 16 and 18 m/s, while maintaining an air pressure of 0.8 bars during the measurement period. It is also seen in the figures that two sets of data were captured within a second.

2.5. Performance test and evaluation

2.5.1. Materials for the dryer evaluation

Dewatered cassava cake, plastic containers, weighing scale, moisture analyzer, stop watch, computer, and diesel to fire the heat exchanger were used for the performance test.

Cassava processing: TME 419 cassava roots were purchased from a local farm in Ikorodu, Lagos State, Nigeria. The cassava roots were peeled, washed by hand, and grated in a mechanical cassava grater powered by a 5 hp electric motor. They were then dewatered using a dewatering press equipped with a 20-ton hydraulic jack. A mechanical granulator was used to granulate the dewatered cake into granules. The quantity and moisture content of the granules were measured and recorded.

Drying test: The dryer was preheated for about 15 min to reach a steady target temperature of 180 °C before introducing the material for drying. The drying parameters were adjusted within the set ranges on the computer system or control panel's screen (temperature 180–200 °C), air velocity (13–16 m/s), relative humidity (20%–30%). The drying progress was monitored during which temperature, humidity, air velocity, relative humidity and pressure were recorded at 10-s intervals and downloaded to the computer system as an excel file. Using a digital industrial weighing scale, fuel consumption was measured gravimetrically (LP7161; Avery Weigh-Tronix, Windsor, UK).

Type K thermocouples were installed in the drying duct before the feeder, the exhaust pipe, and the heat exchanger's combustion chamber to measure the temperatures of the hot air inlet, exhaust flue gas, and the direct flame in the heat exchanger. A pressure sensor mounted on the drying duct before the feeder was used to measure the inlet air pressure P (KPa). All of these sensors were connected to the control panel's PLC. Temperature/relative humidity sensors were installed on the hopper, the drying duct just before the cyclone, and the blower to measure the temperature and relative humidity of the wet cake, outlet air, and exhaust air respectively. The air velocity was measured with a velocity sensor positioned near the blower. A product sensor was also installed in the hopper and synchronized with the exhaust air temperature to increase product feeding when the temperature exceeds a pre-set value for optimum energy utilization and to prevent heat loss. A digital industrial balance was used to measure the feed rate of the wet product, m_{wp} (kg wet product/h), and the output rate of the dried product, m_{dp} (kg dried product/h). The dried samples were collected at the cyclone outlet and weighed gravimetrically. The moisture content of the wet and dried samples was determined using the gravimetric and oven dried method by drying for 24 h at 103 °C (AOAC, 1990; ASABE, 2008).

2.5.2. Sample color determination

The color of the cassava flours was measured using a Minolta CR-310 tristimulus colorimeter (Minolta Camera Co. Ltd, Osaka, Japan), recording L, a*, and b* values as reported by Wrolstad and Smith (2010). L denoted lightness (from 0 = darkness/blackness to 100 = perfect/brightness); a* denoted the extent of green color (from negative = green to positive = redness); and b* denoted blue (from negative = blue to positive = yellow).

2.5.3. Thermal analysis of the dryer performance

The dryer's psychrometric calculations were done using the British Standard (Anon, 2022) while the dryer's energy performance was determined by Precoppe et al. (2020) and Kudra (2009) as follows:

Determination of moisture content on dry basis

Eq. (1) was used to determine the feed and product's dry basis moisture content

$$M = \frac{m}{1-m} \tag{1}$$

where m is the moisture content on a wet basis (wb), and M is the moisture content on a dry basis (db)

Eq. (2) was used to calculate the solid mass flow rate (m_{dm}) on a dry basis, m_{dm} (kg h^{-1}).

$$m_{dm} = m_{ws} - m_{ws}\left(\frac{x_{ws}}{1+x_{ws}}\right) \tag{2}$$

where m_{ws} (kg h^{-1}) is the mass flow rate of wet cassava grits, x_{ws} (kg kg^{-1}) is the moisture content of wet cassava grits in dry basis, and x_{ds} (kg kg^{-1}) is the moisture content of dried cassava grits in dry basis.

Eq. (3) was used to calculate the rate of water evaporation (m_w).

$$m_w = m_{dm}\left(x_{ws} - x_{ds}\right) \tag{3}$$

Eqs. (4), (5), and (6) were used to calculate the air mass flow rate (m_{air}).

$$\text{Air inlet cross sectional area } (A) = L \times B \tag{4}$$

$$\text{Volumetric flow rate } (V_{air}) = A \times Vel \tag{5}$$

While the air mass flow rate (m_{air}) was calculated using Eq. (6)

$$m_{air} = \rho \times V_{air} \tag{6}$$

where L is the length (0.3 m), B is the width (0.2 m), ρ is the air density (1.2 kg/m^3) and V_{air} is the volumetric flow rate (3456 m^3 h^{-1}) and *Vel* is the air velocity (13 m s^{-1})

Absolute humidity (ω) was determined using Eqs. (7) and (8).

Eqs. (7) and (8) were used to calculate absolute humidity (ω).

$$p_v = \varnothing p_g @29.2\ ^\circ\text{C} \tag{7}$$

$$\omega = \frac{0.622\varnothing P_v}{P - \varnothing P_v} \tag{8}$$

where $\varnothing$ is the relative humidity (0.79), P is the partial pressure of moist air (101.325 Kpa), and Pv is the partial pressure of water vapor (4.0708).

Eqs. (9) was used to calculate the enthalpy (h) of the ambient air and the enthalpy of the inlet air into the dryer.

$$h = C_p T + \omega_1\left(h_w + CP_w.T\right) \tag{9}$$

where $\boldsymbol{\omega}$ is the air humidity ratio (0.020389 kg H_2O/kg dry air), *Cp* is the specific heat capacity of air (1.005 kJ/kg °C), CP_w is the specific heat capacity of water vapor (1.82), h_w @ 0 °C is the specific enthalpy of water vapor (2500.9 kJ/kg), T_{amb} is the ambient temperature (29.2 °C), and T_2 is the inlet air temperature (180 °C). For steady conditions, air absolute humidity or humidity ratio ($\boldsymbol{\omega}$) equals 0.020389 kg H_2O/kg dry air.

Eq. (10) was used to calculate the heat input or energy rate (Q_{in}) into the dryer.

$$Q_{in} = m_{air}\left(h_1 - h_{amb}\right) \tag{10}$$

Eq. (11) was used to calculate specific energy consumption (q_s).

$$q_s = \frac{Q_{in}}{m_w} \tag{11}$$

The dryer's energy efficiency (η_e) was calculated using Eq. (12)

$$Energy\ efficiency\ (\eta_e) = \frac{Q_w}{Q_{in}} = \frac{m_w \cdot \lambda}{Q_{in}} \tag{12}$$

where λ is the heat of vaporization of water (2144.3 @ 180 °C)

3. Results

3.1. Dryer specification

Plate 1(a & b) shows the flash dryer's drying duct with the control panel and heat exchanger, while Table 1 shows the flash dryer's drying parameters during drying test, along with their mean value and standard deviation. Temperatures on the dryer were recorded at various locations, including the heat exchanger exhaust (215 ± 8.7 °C), the inlet pipe, just before the feeder (180 ± 4.3 °C), the drying column just before the cyclone (78 ± 1.8 °C), the blower exhaust (65.89 ± 4.9 °C), and at the hopper for the feed temperature (32 ± 2.1 °C), with the average temperature of the dried flour being 61.26 ± 8.8 °C. The inlet air temperature of the dryer can be varied because it is automated. In comparison to other dryers, flash dryers have a considerable advantage since they may use higher temperatures without scorching the product due to their quick contact times and rapid evaporation rates (Rotstein

Table 1
Drying parameters of the flash dryer.

Parameters	Unit	Mean ± SD
Average ambient temperature	°C	29.9 ± 2.1
Ambient air Relative humidity	%	65 ± 4.8
Inlet air temperature	°C	180 ± 4.3
Outlet air temperature	°C	65.89 ± 4.9
Outlet air relative humidity	%	42.8 ± 7.9
Mass of wet cassava grit	kg	298 ± 30.2
Moisture content of wet grit	% (w/w)	47.06 ± 5.2
Mass of dried flour	kg	186.34 ± 7.4
Moisture content of flour	% (w/w)	9.60 ± 3.4
Air mass flowrate	kg/h	4147.2 ± 9.8
Specific air enthalpy	kg/kg dry air	196.886 ± 4.9
Air velocity	m/s	13 ± 1.2

and Crapiste, 1997; Brennan, 2011; Levy and Borde, 2014). The air velocity in the drying pipe was 13 ± 1.2 m/s. Due to the length of the drying tube (22.5 m), this air velocity is suitable for pneumatic conveying of the product, since the minimum entrainment velocity and incipient fluidization velocity of cassava grits were 6.0 ± 0.5 m/s and 4.1 ± 0.4 m/s respectively (Precoppe et al., 2015). The shorter lengths of most small-scale flash dryers do not allow for optimal drying due to the product's extremely short resident time. Mujumdar (2007) proposed that the residence time in these small-scale dryers can be adjusted by changing the cross-sectional area of the drying duct, thereby reducing air velocity, or by varying the length of the drying duct (Brennan, 2011).

4. Discussion

4.1. The dryer performance

The specific energy consumption for the dryer was determined to be 2570 ± 300 kJ/kg product of final product and 4560 ± 148 kJ/kg water of evaporated water. Tran et al. (2022) studied the performance comparison of some flash dryers in some cassava producing countries and reported that the energy consumption were 1500–2000 kJ/kg starch for 200 ton/day in Thailand, 2000–3400 kJ/kg starch for 25–100 ton/day in Paraguay, 2600 kJ/kg starch for 50 ton/day in Colombia, 5000 kJ/kg starch for 2 ton/day in Vietnam and 3000–10 000 kJ/kg for 1–2 ton/day in Nigeria. In addition, Precoppe et al. (2015) reported the performance of a cassava pneumatic dryer in Tanzania, with specific energy consumption decreasing from 5750 to 4600 kJ/kg_{water} before and after modification as a result of reduction in air velocity from 9.8 m/s to 7.2 m/s. Hence, the energy consumption of 2570 kJ/kg flour obtained for the developed small-scale flash dryer compared favorably with the large-scale flash dryers with better improvements in performance when compared to existing small-scale flash dryers. In general, the specific energy consumption of flash dryers ranges from 3000 kJ/kg_{water} (Mujumdar, 2007) to 9000 kJ/kg_{water} (Satpati et al., 2019), and for cassava drying with flash dryers, the values range from 3420 kJ/kg_{water} to 5750 kJ/kg_{water} as reported by Saravacos and Kostaropoulos (2016). The ideal energy consumption is 2500 kJ/kg water (Schlünder et al., 1987), but the actual energy consumption for the developed dryer was higher, possibly due to heat losses and the material's internal resistance to moisture transport (Precoppe et al., 2016). Moreover, water diffusivity is the primary determinant of drying rate in the cassava drying process (Strumiłło et al., 2014), hence the dryer's resistance to water flow is critical.

Based on the evaluation, the dryer has an energy efficiency rating of 80.8 ± 50%. This result shows that the dryer is efficient for a small-scale operation when compared to some existing dryer. For instance, Adegbite et al. (2018) reported that the energy efficiency of some locally manufactured flash dryer models ranged from 50.93 to 63.27%. Also, Precoppe et al. (2015) reported the performance of a cassava pneumatic dryer in Tanzania, with energy efficiency increasing from 43.1 to 54.0% before and after modification. The energy efficiency of flash dryers ranges from 40% to 75% (Cervantes et al., 1992), whereas for cassava flash drying, it ranges from 43% to 69% (Precoppe et al., 2016). In addition, convective dryers typically have an energy efficiency of between 20 and 60% (Strumiłło et al., 2014). Cassava starch was also dried using a tray drier with an energy efficiency of 16 to 31%, according to Aviara et al. (2014). Generally speaking, the efficiency of convective dryers is defined by the rate at which heat is transferred between a solid and hot air (Kudra, 2009); the higher this rate of heat transfer, the better the dryer's energy efficiency (Azadbakht et al., 2017). This high level of energy efficiency recorded in this study can be attributed to the fact that the material is suspended in the air, which allows for optimal solid-hot air contact and efficient heat transmission (Pakowski and Mujumdar, 2014), longer length of the drying duct of 22.5 m, which allows optimum energy utilization and efficient heat exchanger. It is vital that the drying duct be long enough to provide the particles adequate time to dry while being transported in flash dryers (Chapuis et al., 2017), as this has an impact on their energy efficiency (Nimmol et al., 2020). This is unlike the conventional locally manufacture flash dryer which the length of the drying duct is typically range between 7 to 15 m length (Tran et al., 2022).

Furthermore, the dryer's exhaust air temperature was synchronized with a product sensor located at the feed hopper, which increased the feed rate when it exceeded a pre-set threshold, ensuring maximum energy utilization and preventing heat loss. Earlier studies have shown that various small-scale flash dryers have some drawbacks (Adegbite et al., 2018). This innovation addresses those shortcomings. For example, Precoppe et al. (2020) discovered that lowering the fluctuation in the drying air temperature and eliminating the variance in the feeding rate of wet solid can improve dried product uniformity. Because of the mismatch between the drying air temperature and the temperature set at the thermostat of most small-scale flash dryers, he believes that adopting a more responsive temperature control system, such as the one presented in this automated system, can improve drying uniformity. Similarly, Satpati et al. (2019) reported that in flash dryers, a feed rate control system improves both the consistency of dried product moisture content and the dryer's energy efficiency. All of these suggestions were taken into account when developing the flash dryer.

Furthermore, the water evaporation was 105.38 ± 2.7 kg/h and the fuel consumption were 9.2 ± 4.2 kg/h. The increased evaporation rate can be attributed to the greater volume of material and the higher rate of heat input value and this is also influenced by material characteristics, moisture content, and the level of contact between the material and the drying medium (Kudra, 2009). Consequently, the dryer was well-designed, based on its energy performance metrics. The developed flash dryer is estimated to cost $20,000,[1] as shown in Table 3 in the Appendix A. When compared to domestically made flash dryers in Nigeria, this estimated cost is relatively less expensive. According to Ojide et al. (2022), the average price of imported flash dryers was around US$68,500 per unit, whereas those made domestically were around US$22,802 per unit.

4.2. Product moisture content and color

The L*, a*, b* parameters and moisture content of dried cassava flour are shown in Table 2. After pressing, the moisture content of cassava cake was 47.07%. This moisture level was close to the values reported by Precoppe et al. (2015) and Tivana et al. (2010), both of whom used a similar pressing system. However, Gevaudan et al. (1989) reported lower moisture content after pressing, suggesting that the mechanical dewatering processes could be improved. It is possible to mechanically remove 20%–30% of the water before drying, which is a crucial step in energy efficiency due to lower quantity of water

---

[1] Exchange rate as of December, 2022: US $1 = 452.13 NGN (Central Bank of Nigeria, 2022).

Table 2
Product quality parameters.

Wet product moisture content (% wb)	Dried product moisture content (% wb)	Dried product L* value	Dried product a* value	Dried product b* value
47.06 ± 5.2	9.60 ± 3.4	82.23 ± 6.8	−1.28 ± 0.2	6.58 ± 1.7

to be dried (Strumillo et al., 2014). By using an effective cassava pressing machine, the original moisture content can be further lowered to roughly 30%, resulting in lower drying costs. Mechanical dewatering reduces the initial moisture content, which, according to Strumiłło et al. (2014) results in significant energy savings. However, if the mechanical dewatering system is improved, the feed rate should be increased to prevent energy loss in order to achieve higher drying capacity. The 9.60% final moisture content of the product confer to it a long shelf life in storage and acceptable to most end-users and market operators in terms of long-term marketing (Marina et al., 2019).

Also, an important quality attribute of flour is its white color, which affects appearance and consumer acceptability of products made from it Wrolstad and Smith (2010). A high degree of whiteness is desirable according to Van Hall (2000). The whiteness of cassava flour is an indicator that no fermentation and microbial contamination had occurred in the cassava roots prior to processing into flour. It was also indicative of thorough peeling since natural pigments from peels may affect the color of flour (Taylor and Anyango, 2011). As color is the aesthetic appeal of finished products from flour and reducing amino acid content of flours greatly affects the color of finished products made from them. The result indicated that the flour obtained from the drying operation had a L (lightness index) of 82.23 which is slightly lighter in color when compared to 89.71 obtained for wheat flour (Wrolstad and Smith, 2010) though close to the values reported by Precoppe et al. (2015) but, nevertheless within the threshold for consumers' acceptance. Also, the sample appearance values a and b are close to the values reported by Precoppe et al. (2016). As a result, the product is more likely to be acceptable by customers.

4.3. Limitation of the study and recommendation for future work

Testing revealed that the small-scale flash dryer developed based on the RTB prototype flash dryer design was both energy efficient and cost effective. However, since the drying settings could be varied for drying optimization to improve the drying performance, further testing of the dryer under additional drying conditions is necessary in order to determine most economical drying condition. Additionally, and considering that the technology is currently in the scaling stage, a comparison of the dryer's capacity and production cost with the commercially-used flash dryers in Nigeria is recommended to proof its comparative economic advantage. This will facilitate the adoption of the technology by cassava processors.

5. Conclusion

Cassava roots processed into high-quality cassava flour as a key industrial raw material have the potential to jumpstart rural industrialization, increase cassava market value, and improve farmers' earnings and livelihoods. As a result, an improved energy-efficient flash dryer has been developed. The dryer's performance in tests has been found to be satisfactory. The moisture content of cassava mash was reduced from 47.06% (wb) to 9.60% (wb) of dried product. The maximum drying capacity of 298 kg of wet cake per hour was achieved, with an output of 186.34 kg of dried product, resulting in an energy efficiency of 80.8% and specific energy consumption of 2570 kJ/kg product of final product and 4560 kJ/kg water of evaporated water. The dryer's drying performance and capacity indicate that the dryer is highly efficient and best suited for small-scale enterprises. The total production cost of the equipment is $20,000 which include the heat exchanger and the other components of the drying system. When this innovative technology is adopted, the production costs can be reduced, the standardization of cassava products may be facilitated, and the global market opportunity for cassava will expand.

CRediT authorship contribution statement

Suraju A. Adegbite: Methodology, Data curation, Laboratory analysis, Writing – original draft, Artwork. **Wahabi B. Asiru:** Supervision. **Murat Sartas:** Supervision, Funding acquisition. **Thierry Tran:** Conceptualization, Supervision. **Alejandro L. Taborda:** Conceptualization. **Arnaud Chapuis:** Conceptualization, Artwork. **Makuachwuku Ojide:** Conceptualization. **Adebayo Abass:** Conceptualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

CIAT, IITA, FIIRO, AE-FUNAI, and the flash drying team are commended for their support in making the study a reality. Others, who made significant contributions, as indicated in Authors' contributions, are the paper's authors. All authors have read and agreed to the published version of the manuscript.

Funding

This research was undertaken as part of the CGIAR Research Program on Roots, Tubers and Bananas (RTB). RTB is funded by CGIAR Trust Fund contributors (https://www.cgiar.org/funders/). Therefore, the fund provided for this study is acknowledged with thanks.

Appendix A

See Table 3.

Table 3
Estimated cost of the flash dryer.

S/N	Particulars	Amount (₦)	Amount ($)
1	Cost of purchased component parts	4,425,340	9787.76
2	Cost of components fabrication	1,800,000	3981.16
3	Cost of machined jobs	970,000	2145.40
4	Cost of non-machined jobs	943,000	2085.68
5	Value Added Tax (10% of the total cost)	904,260	2000
	Total	**9,042,600**	**20,000**

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resenv.2023.100117.

References

Adegbite, S.A., Abass, A., Olukunle, O.J., Olalusi, A.P., Asiru, W.B., Awoyale, W., 2018. Mass and energy balance analysis of pneumatic dryers for cassava and development of optimization models to increase competitiveness in Nigeria. Curr. J. Appl. Sci. Technol. (ISSN: 2457-1024) 32 (3), 1–11, 2019; Article no. CJAST.46215.

Aghbashlo, M., Kianmehr, M.H., Arabhosseini, A., 2008. Energy and exergy analyses of thin-layer drying of potato slices in a semi-industrial continuous band dryer. J. Dry. Tech. 26, 1501–1508.

Agordjo, S.M., 2012. Influence of Age and Cultivar on Yield and Quality of Starch/Flour Extracted from Cassava (Manihot Esculent Crantz) (Unpublished MSc thesis). Department of Crop and Soil Sciences, KNUST, Kumasi, submitted for publication.

Anon, https://www.engineeringtoolbox.com access on 3rd February, 2022.

AOAC, 1990. Official Methods of Analysis of the AOAC. Vol. 2, fifteenth ed. Association of Official Analytical Chemists Inc., USA.

Apea-Bah, F.B., Oduro, I., Ellis, W.O., Safo-Kantanka, O., 2011. Factor analysis and age at harvest effect on the quality of flour from four cassava varities. World J. Dairy Food Sci. 6 (1), 43–54, (2011).

ASABE, 2008. ASAE S358.2 DEC 1988 (r2008) moisture measurements – forage. In: ASABE (Ed.), ASABE Standards 2008: Standards Engineering Practices Data. ASABE, St. Joseph, MO, pp. 670–672.

Aviara, N.A., Onuoha, L.N., Falola, O.E., Igbeka, J.C., 2014. Energy and exergy analyses of native cassava starch drying in a tray dryer. J. Energy 73, 809–817.

Azadbakht, M., Aghili, H., Ziaratban, A., Torshizi, M.V., 2017. Application of artificial neural network method to exergy and energy analyses of fluidized bed dryer for potato cubes. J. Energy 120, 947–958.

Bonazzi, C., Broyart, B., Courtois, F., 2009. Dryer modelling. In: Ratti, C. (Ed.), Advances in Food Dehydration. CRC Press, Boca Raton, FL, USA, pp. 355–399.

Brennan, J.G., 2011. Evaporation and dehydration. In: Brennan, J.G., Grandison, A.S. (Eds.), Food Processing Handbook, second ed. Wiley-VCH Verlag Gmbh, Weinheim, Germany, pp. 77–130.

Breuninger, W.F., Piyachomkwan, K., Sriroth, K., 2009. Tapioca/cassava starch: Production and use. In: BeMiller, J., Whistler, R. (Eds.), In Starch: Chemistry and Technology, third ed. Acadmic Press, San Diego, CA, USA, pp. 541–568.

Cervantes, M.S., Garcia Alvarado, M.A., Kubiak, K.N.W., 1992. Modeling of water activity and enthalpy of water sorption in cassava chips. J. Dry. Technol. 12, 1743–1752.

Chapuis, A., Precoppe, M., Méot, J.M., Sriroth, K., Tran, T., 2017. Pneumatic drying of cassava starch: Numerical analysis and guidelines for the design of efficient small-scale dryers. J. Dry. Tech. 35 (4), 393–408.

Chua, K.J., Chou, S.K., 2003. Low-cost drying methods for developing countries. Trends Food Sci. Technol. 14, 519–523.

2023. Classifications on economic statistics and trend of cassava production. In: HS 2017. https://www.tridge.com, access on January 9th, 2023.

Da, G., Dufour, D., Giraldo, A., Moreno, M., Tran, T., Velez, G., Sanchez, T., Le-thanh, M., Marouze, C., Marechal, P.A., 2013. Cottage level cassava starch processing systems in Colombia and Vietnam. J. Food Biol. Tech. 6, 2213–2222.

Duggan, E., Noronha, N.O., Riordan, E.D., O'Sullivan, M., 2008. Effect of resistant starch on the water binding properties of imitation cheese. J. Food Eng. 84, 108–115.

Gevaudan, A., Chuzel, G., Didier, S., Andrieu, J., 1989. Physical properties of cassava mash. Int. J. Food Sci. Technol. 24, 637–645.

Goto, F., 1969. Determination of gelatinization property of highly concentrated starch suspension by brabender plastograph. Part 2. Examination of gelatinization curve obtained by plastograph. Starch Starke 21, 267.

Graffham, A.J., Dziedzoave, N.T., Ayernor, G.S., 2000. Final Technical Report of the CPHP Project Entitled Expanded Markets for Cassava Starches and Flours in Ghana. Report of the Natural Resources Institute (R6504).

Jayaraman, Gupta, 2014. Final Technical Report of the CPHP Project Entitled Expanded Markets for Cassava Starches and Flours in Ghana. Report of the Natural Resources Institute (R6504).

Kudra, T., 2009. Energy aspect in food dehydration. In: Ratti, C. (Ed.), Advances in Food Dehydration. CRC Press, Boca Raton, FL, USA, pp. 423–445.

Levy, A., Borde, I., 2014. Pneumatic and flash drying. In: Mujumdar, A.S. (Ed.), Handbook of Industrial Drying, fourth ed. CRC Press, Boca Raton, FL, pp. 381–392.

Marina, V.Z., Baishali, D., Donald, G.M., Heather, L.M., Marianne, F.T., 2019. Assessment of moisture content measurement methods of dried food products small-scale operations in developing countries. A review. Trends Food Sci. Technol. 88, 484–496.

Mujumdar, A.S., 2007. Handbook of Industrial Drying. Published by Taylor & Francis Group, LLC.

Mujumdar, A.S., Jangam, S.V., Pikon, J., 2014. Drying of coal. In: Mujumdar, A.S. (Ed.), Handbook of Industrial Drying, fourth ed. CRC Press, Boca Raton, FL, USA, pp. 999–1099.

Ndaliman, M.B., 2008. Development of cassava grating machine a dual-operation mode leonardo journal. HHP://\textit{jascademicdirect.org}/AO9/1103-110.

Nimmol, C., Yodrux, A., Hirunwat, A., 2020. Rapid drying of high-moisture paddy using a pneumatic dryer with corrugated-surface drying sorghum. E3S Web Conf. 141, 1–5.

Nweke, F.I., 2004. New Challenges in the Cassava Transformation in Nigeria and Ghana. Environmental and Protection Technology Discussion. Discussion Paper 118, International Food Policy Research Institute, Washington D.C. USA, pp. 1–16.

Ojide, M.G., Adegbite, S., Tran, T., Taborda, L.A., Chapius, A., Lukombo, S., Totin, E., Sartas, M., Schut, M., Lopez-Lavalle, L.A.B., Dufour, D., Abass, A., 2022. Processor's Experience in the Use of Flash Dryer for Cassava-Derived Products in Nigeria. Frontiers in Sustainable Food Systems. Original Research, http://dx.doi.org/10.3389/fsufs.2021.771639.

Onwueme, I.C., 1978. The Tropical Tuber Crops: Yam, Cassava, Sweet Potatoes, Cocoyam. John Willey and Sons Limited, USA, pp. 234–243.

Pakowski, Z., Mujumdar, A.S., 2014. Drying of pharmaceutical products. In: Mujumdar, A.S. (Ed.), Handbook of Industrial Drying, fourth ed. CRC Press, Boca Raton, FL, USA, pp. 681–701.

Precoppe, M., Chapuis, A., Müller, J., Abass, A., 2015. Tunnel dryer and pneumatic dryer performance evaluation to improve small - scale cassava processing in Tanzania. J. Food Proc. Eng. 40, I.F. 0.830.

Precoppe, M., Komlaga, G.A., Chapuis, A., Müller, J., 2020. Comparative study between current practices on cassava drying by small-size enterprises in Africa. J. Appl. Sci. (10), 7863. http://dx.doi.org/10.3390/app10217863.

Precoppe, M., Tran, T., Chapuis, A., Müller, J., Abass, A., 2016. Improved energy performance of small-scale pneumatic dryers used for processing cassava in Africa. J. Biol. Eng. 151, 510–519, I.F. 1.997.

Rotstein, E., Crapiste, G.H., 1997. Design and performance evaluation of dryers. In: Valentas, K.J., Singh, R.P., Rotstein, E. (Eds.), Handbook of Food Engr. Practice. CRC Press, Boca Raton, FL, pp. 121–162.

Saravacos, G., Kostaropoulos, A.E., 2016. Food evaporation equipment. In: Handbook of Food Processing Equipment, second ed. Springer, Cham, Switzerland, pp. 367–419.

Satpati, B., Koley, C., Datta, S., 2019. Nonlinear model of pneumatic conveying dryer for economic process control. J. Dry. Technol. 1–22.

Schlünder, E.U., Spalding, D.B., Taborek, J., 1987. Heat Exchanger Design Handbook. VDI, Dusseldorf, Germany.

Soyoye, B.O., Olukunle, O.J., Alakhunmwen, O.J., 2015. Development and performance evaluation of a mini horizontal flash dryer. Agric. Engrg. Int. CIGR J. 17 (4), 211–228.

Sriroth, K., Piyachomkwan, K., Wanlapatit, S., Oates, C.G., 2000. Cass starch tech.: the thai experience. Starch Starke 52, 439–449.

Strumillo, C., Jones, P.L., Romuald, Zylla., 2014. Energy aspects in drying. In: Chapter in Handbook of Industrial Drying. On Pressing As a Means of Energy Conservation.

Strumiłło, C., Jones, P.L., Zyłła, R., 2014. Energy aspects in drying. In: Mujumdar, A.S. (Ed.), Handbook of Industrial Drying, fourth ed. CRC Press, Boca Raton, FL, USA, pp. 1077–1100.

Suherman, K., Cahyo, A., Kusworo, T.D., 2015. Experimental study on drying kinetic of cassava starch in a pneumatic drying system. Int. Conf. Chem. Mater. Eng. ICCME 1699, 1–6.

Taylor, J.R.N., Anyango, J.O., 2011. Sorghum flour and flour products: production, nutritional quality and fortification. In: Preedy, V.R., Watson, R.R., Patel, V.B. (Eds.), Flours and Breads and their Fortification in Health and Disease Prevention, first ed. Academic Press, New York, p. 127.

Tivana, L.D., Dejmek, P., Bergenståhl, B., 2010. Characterization of the agglomeration of roasted shredded cassava (*Manihot esculenta Crantz*) roots. J. Starch Stärke 62, 637–646.

Tran, Thierry, Abass, Adebayo, Taborda Andrade, Luis Alejandro, Chapuis, Arnaud, Precoppe, Marcelo, Adinsi, Laurent, Bouniol, Alexandre, Ojide, Makuachukwu, Adegbite, Suraju Adeyemi, Lukombo, Simon Singi, Sartas, Murat, Teeken, Bėla, Kuate, Apollin Fotso, Ndjouenkeu, Robert, Moreno, Martin, Belalcazar, John, Becerra Lȯpez-Lavalle, Luis Augusto, Dufur, Dominique, 2022. Cost-effective cassava processing: Case study of small-scale flash-dryer reengineering. In: Root, Tuber and Banana Food System Innovations. Springer, Cham, pp. 105–143.

Van Hall, M., 2000. Quality of sweet potato flour during processing and storage. Food Rev. Int. 16, 1–37.

Wrolstad, R.E., Smith, D.E., 2010. Color analysis. In: Nielsen, S. (Ed.), Food Analysis, fourth ed. Springer Science and Business Media, LCC, New York, pp. 573–586.