Title

Improved energy performance of small-scale pneumatic dryers used for processing cassava in Africa

Author names and affiliations

Marcelo Precoppe*[,1] • Thierry Tran[2,3] • Arnaud Chapuis[2,3] • Joachim Müller[4] • Adebayo Abass[1]

*Corresponding author. E-mail: m.precoppe@cgiar.org

[1]International Institute of Tropical Agriculture (IITA), CGIAR Research Program on Roots, Tubers and Bananas (RTB). Address: Plot 25, Coca-Cola Road, Mikocheni B, PO Box 34441, Dar es Salaam, Tanzania.

[2]CIRAD, UMR Qualisud, CGIAR Research Program on Roots, Tubers and Bananas (RTB). Address: Kasetsart University, Research and Development Building, 10900 Bangkok, Thailand.

[3]CIRAD, UMR Qualisud, CGIAR Research Program on Roots, Tubers and Bananas (RTB). Address: Avenue Agropolis, 34398 Montpellier, France

[4]University of Hohenheim, Institute of Agricultural Engineering. Address: Garbenstraße 9, 70599 Stuttgart, Germany

Improved energy performance of small-scale pneumatic dryers used for processing cassava in Africa

Marcelo Precoppe[1] • Thierry Tran[2,3] • Arnaud Chapuis[2,3] • Joachim Müller[4] • Adebayo Abass[1]

Summary Cassava (*Manihot esculenta*) is the most important staple food in sub-Saharan Africa. However, the shelf-life of the crop is short and, for this reason, the roots are usually processed into more stable products like cassava flour by village-based enterprises. Most of these enterprises use small-scale locally built pneumatic dryers, but such dryers still need further development, so the objective of this research was to improve their energy performance. Experiments were conducted at two cassava processing centres, one in Tanzania and one in Nigeria. Sensors were installed on the dryers, product samples were collected and the mass and energy balance of the equipment analysed, allowing the dryers' minimum air mass flow rates to be calculated. The air mass flow rates of both dryers were then reduced to a level approximating the minimum value. In Tanzania, the air mass flow rate of the dryer was reduced by 24%, while in Nigeria it was reduced by 14%. In both locations, the modifications decreased the dryers' heat input without jeopardising evaporation rates, and so not affecting the final moisture content of the dry products. Air temperatures at the dryer outlets decreased and relative humidity increased, while enthalpy remained unchanged. The energy required to evaporate 1 kg of water decreased by 20% in Tanzania and by 13% in Nigeria. The modification also improved energy efficiency by 25% in Tanzania and by 14% in Nigeria. However, in Nigeria, where yellow cassava flour was being used, the dryer modifications resulted in greater product colour losses.

Keywords Flash dryer · Energy efficiency · Heat input · Specific energy consumption · Minimum air flow rate

---

✉ Marcelo Precoppe
m.precoppe@cgiar.org
Plot 25, Coca-Cola Road, Mikocheni B, PO Box 34441, Dar es Salaam, Tanzania

[1] International Institute of Tropical Agriculture (IITA), CGIAR Research Program on Roots, Tubers and Bananas (RTB), Dar es Salaam, Tanzania

[2] CIRAD, UMR Qualisud, CGIAR Research Program on Roots, Tubers and Bananas (RTB), Bangkok, Thailand

[3] CIRAD, UMR Qualisud, CGIAR Research Program on Roots, Tubers and Bananas (RTB), Montpellier, France

[4] University of Hohenheim, Institute of Agricultural Engineering, , Stuttgart, Germany

Nomenclature

Notation

a_s	specific air consumption (kg kg^{-1})
a_w	water activity
E	electrical power consumption (kW)
Q_{st}	heat of sorption (kJ kg^{-1})
h	enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg h^{-1})
MC	moisture content on wet basis ($\%_{wb}$)
P	pressure (kPa)
$\dot{Q}$	heat rate (kJ h^{-1})
q_E	specific electricity utilisation (MJ kg^{-1})
q_s	specific energy consumption (MJ kg^{-1})
q_U	specific heat utilisation (MJ kg^{-1})
SLR	solid loading ratio (kg kg^{-1})
T	temperature (°C)
v	air velocity (m s^{-1})
X	moisture content on dry basis (kg kg^{-1})
Y	absolute humidity (kg kg^{-1})

Greek letters

η	energy efficiency (%)
φ	relative humidity (%)

Subscripts

1	dryer inlet
amb	ambient
dm	dry matter
dp	dry product
ex	cyclone exhaust
in	input
out	dryer outlet
w	water
wp	wet product

1. Introduction

Cassava (*Manihot esculenta* Crantz) is a perennial root crop that belongs to the Euphorbiaceae family (Breuninger, Piyachomkwan, & Sriroth, 2009). The plant is native to the central region of South America, but nowadays is cultivated throughout the humid tropics (Beeching, 2013). Cassava roots have a low protein, vitamin and mineral content, but are rich in carbohydrates, and for this reason the plant is the main source of calories for many people in the tropical regions (Breuninger et al., 2009), and particularly for those living in Africa (Wheatley, Chuzel, & Zakhia, 2003).

During the 15th century, Portuguese traders learned from Brazilian native people how to process cassava into flour, and by the 16th century the Portuguese had taken the plant to Africa, the aim being to supply the slave ships with flour (Lebot, 2009). Because originally cassava was grown exclusively to supply these ships, it was not until the 18th century that the plant began to be consumed by the local African population (Beeching, 2013). Cassava was then quickly accepted and, by the end of 19th century, the root had become a key source of carbohydrate (Lebot, 2009). Since that time, cassava has mostly been grown by smallholder farmers (Beeching, 2013). Tolerance to dry spells, as well as resistance to pests and diseases, plus an ability to grow in impoverished soil, are all features of cassava that explain its rapid adoption in Africa (Breuninger et al., 2009).

However, cassava has a short shelf-life, and two days after harvest becomes unsuitable for human consumption (Lebot, 2009). For this reason, the roots are processed into flour or other dry products, which can be used later as the basis for a variety of dishes (Falade & Akingbala, 2011). During the cassava flour making process, the roots are peeled, grated, pressed, dry and milled (Wheatley et al., 2003). Cassava processing centres in Africa are usually village-based small- and medium-sized enterprises, and their expansion is constrained by a lack of appropriate, affordable and efficient processing equipment (Lebot, 2009). Developing efficient small-scale cassava processing equipment is; therefore, required, to reduce production costs and contribute to the expansion of village-based cassava processing enterprises across Africa. The expansion of such village-based agro-processing activities can promote entrepreneurship and employment, and bring additional income to rural areas (Orsat, Raghavan, & Sosle, 2008).

One of the most suitable types of dryer available for drying grated cassava is the pneumatic dryer, which is also known as a flash dryer (Brennan, 2011), and such dryers are commonly used to dry granular material in the chemical, pharmaceutical and food industries (Rotstein & Crapiste, 1997). The wet product enters the drying duct at the feeding point and is entrained by the hot airstream (Kemp, 1994). Both negative- and positive-pressure conveying systems are used in pneumatic dryers (Mills, Jones, & Agarwal, 2004). In a negative-pressure system, the blower is located downstream of the material separator, while in a positive-pressure system the blower is located upstream of the material feeding point (Fan & Zhu, 1998). During transport, heat is transferred from the hot air to the particles through convection, drying the material as it moves (Kudra, 2012). At the end of the drying duct, a cyclone is commonly used to separate the entrained dry product from the drying air (Rotstein & Crapiste, 1997). The large surface area of the product particles results in high drying rates and short residence times (Levy & Borde, 2014), and this allows heat sensitive materials to be dried at relatively high temperatures, without overheating taking place (Mujumdar, 2008).

The drying of cassava in pneumatic dryers occurs through convection and diffusion, but it is the latter process that determines the drying rate, and; therefore, drying occurs on the falling-rate period (Salgado-Cervantes, Lebert, Garcia-Alvarado, Muchnik, & Bimbenet, 1994). For this reason, the shape and size distribution of the particles play a fundamental role in the drying kinetics; however, during the pneumatic drying of cassava, these properties are constantly changing due to particle shrinkage and agglomeration (Aichayawanich, Nopharatana, Nopharatana, & Songkasiri, 2011).

Pneumatic dryers are simple to construct and can have a low capital cost (Mujumdar, 2008). In addition, due to the small number of moving parts therein, the maintenance of such equipment can also be low (Levy & Borde, 2014), a characteristic that is important when considering village-based small- and medium-sized enterprises (Goletti & Samman, 2007). State-of-the-art industrial pneumatic dryers are available, and are used to process cassava in many tropical countries (Sriroth, Piyachomkwan, Wanlapatit, & Oates, 2000); however, these industrial, large-scale dryers are not suitable for use with village-based agro-processing activities (Chua & Chou, 2003; Orsat et al., 2008). Existing, locally built small-scale pneumatic dryers still need further development (Da et al., 2013), as they tend to be energy inefficient, resulting in high fuel consumption rates (Precoppe, Chapuis, Müller, & Abass, 2015). The objective of this research was to improve the energy performance of small-scale pneumatic dryers being used to process cassava in Africa. Experiments were conducted in two different countries and, although the dryers had the same dimensions, they were operated at different temperatures, using distinct transport modes and applying different feeding rates.

2. Materials and methods

2.1 Processing equipment and drying procedure

Experiments were conducted at two cassava processing centres, one located in Tanzania, East Africa and the other in Nigeria, West Africa. In both locations, the pneumatic dryers were of the single-pass type and contained a heating unit, a product feeder, a vertical drying duct and a cyclone separator. The drying ducts of the dryers at both locations were of the same dimensions: 0.38 m in diameter and 15 m length. In Tanzania, the system was negatively pressured while in Nigeria the system was positively pressured. In addition, in Nigeria, at the feeding point, the drying duct was narrower; with a diameter of 0.24 m. Fig 1 illustrates the dryers, depicting (a) the blower at the cyclone's exhaust outlet in Tanzania, and (b) the blower at the base of the drying duct in Nigeria. In both locations, the heating unit was composed of a diesel burner and a double-pipe heat exchanger, but the temperature was controlled differently at each location. In Tanzania, the temperature was controlled manually by adjusting the fuel rate according to the temperature measured at the air inlet. In Nigeria; meanwhile, the air temperature was controlled automatically by a fuel on/off regulation system connected to a thermostat.

In Tanzania and in Nigeria, the processing centres' normal drying procedures were followed during the experiments. In both locations, before adding the material to the dryer, the cassava roots were peeled by hand, grated with a rotary drum rasper and mechanically dewatered with a hydraulic press. After pressing, and in order to obtain a free-flowing material, the cassava was disintegrated using another rotary drum rasper, before being introduced to the dryer without having blended with any of the dry product. In Tanzania, locally grown white cassava of the Kiroba variety was used, while in Nigeria, locally grown yellow cassava of the UMUCASS 36 variety was used. In Tanzania, the cassava was mechanically dewatered to a moisture content of about $40\%_{wb}$, while in Nigeria it was pressed to a moisture content of about $50\%_{wb}$. A wet product feeding rate of 180 kg h^{-1} and an inlet temperature of 135 °C was the target in Tanzania, while in Nigeria the aim was a wet product feeding rate of 280 kg h^{-1} and an inlet temperature of 310 °C. The target final moisture content for the dry product were $10\%_{wb}$ in Tanzania and $11\%_{wb}$ in Nigeria.

2.2 Experimental design

First, in both locations the original dryers – called here the unmodified dryers – were evaluated based on each processing centre's usual drying operations. The mass and energy balances of the dryers were analysed and the minimum allowable air mass flow rates calculated. The dryers' blower speeds were then reduced by replacing the driver pulleys with smaller ones, so adjusting the dryers' air mass flow rates close to the minimum values. The dryers with the reduced air mass flow rates – named the modified dryers – were in turn also evaluated based on each processing centres' usual drying operations. As suggested by Baker (2005), data collection started only after the dryers had been operating for at least two hours, to ensure steady state conditions. For each dryer, data were recorded over a 1.5 hour period with three replications, once a day, over three consecutive days. On each day, three sets of wet and dry product sample were collected, one set every 20 minutes.

2.3 Data collection

Sensors were installed in the dryers according to International Standard 11520-1 (ISO, 1997), and following the guidelines described by Strumiłło, Jones, and Żyłła (2014). Fig 1 shows the measurements performed on the dryers. Ambient air temperature (T_{amb}) and ambient air relative humidity (φ_{amb}) were measured with a thermometer-hygrometer (HC2-SC05; Rotronic, Bassersdorf, Switzerland). Ambient pressure (P_{amb}) was measured with a pressure transmitter (PAB41X-C-800–1200; Omega Engineering Inc., Stamford, CT) and air temperature at the dryer inlet (T_1) was measured with a type K thermocouple (XSIB-K-3-1-10; Omega Engineering Inc., Stamford, CT). Air temperature and air relative humidity at the dryer outlet (T_{out}; φ_{out}) were measured with a thermometer-hygrometer (HC2-IC1; Rotronic, Bassersdorf, Switzerland), and air temperature plus air relative humidity at the cyclone exhaust (T_{ex}; φ_{ex}) were measured with another thermometer-hygrometer (HC2-S; Rotronic, Bassersdorf, Switzerland). Air pressure at the cyclone exhaust (P_{ex}) was measured with a pressure transmitter (PAB41X-C-800–1200; Omega Engineering Inc., Stamford, CT), while air velocity at the same location (v_{ex}) was measured with a set of three vane anemometers (MiniAir6 Mini, Schiltknecht, Gossau, Switzerland) placed at different radial positions in the cross-sectional area of the cyclone exhaust. Wet product temperature (T_{wp}) and dry product temperature (T_{dp}) were measured with thermometers (HC2-SC05; Rotronic, Bassersdorf, Switzerland), while wet product mass flow rate ($\dot{m}_{wp}$) and dry product mass flow rate ($\dot{m}_{dp}$) were measured with digital balances (LP7161; Avery, Windsor, United Kingdom). All the sensors were connected to a computer, with measurements synchronously recorded every 10 seconds. Electrical energy consumption (E) was measured with a digital kilowatt-hour meter (DTS223; Volex, Maldon, United Kingdom) from which data were manually recorded every 10 min. Air relative humidity at the dryer inlet (φ_1) was not directly measured, due to the elevated temperatures found at this location, but was calculated using T_{amb}, φ_{amb} and T_1.

Wet product and dry product samples were taken to the laboratory and analysed for their moisture content, water activity, colour and particle size. The moisture contents of the wet and dry product samples were determined gravimetrically following standard S358.2 (ASABE, 2008) and using a convection oven to dry the product at 103 ± 2 °C for 24 hours. Measurements were performed in triplicate and averaged for data processing purposes. In Tanzania, the oven model was DL-53, manufactured by VWR (Radnor, PA), while in Nigeria the oven model was 655F, manufactured by Fisher Scientific (Waltham, MA).

Water activity of the dry product samples was measured using a water activity meter (HC2-AW; Rotronic, Bassersdorf, Switzerland), with the humidity-temperature probe placed on top of the sample holder according to the standard 978.18 (AOAC, 1998b). Measurements were performed at a controlled ambient temperature of 23 ± 1 °C, carried out in triplicate and averaged.

The colour of the dry product samples was measured with a chroma-meter (CR-400; Minolta, Osaka, Japan) calibrated against a standard white plate, following standard E1347 (ASTM, 2004b) and using a D65 illuminant with a 2° observer. Measurements were performed in triplicate and averaged. The tristimulus values were converted to CIELAB colour space. Using this scale, L^* represents the lightness dimension, a^* represents the red to green dimension and b^* represents the yellow to blue dimension. In addition, whiteness index was calculated for the samples produced in Tanzania, as white cassava flour was produced there, while yellowness index was calculated for the samples produced in Nigeria, as yellow cassava flour was produced at that location. The formulas presented in standard E313 (ASTM, 2004a) were used to calculate these indices.

Particle sizes for the wet and dry product samples were measured using a nested set of 8 sieves of International Standards Organization (ISO) size, and following the procedures described under method 965.22 (AOAC, 1998a). Again, measurements were performed in triplicate and averaged. In Tanzania, the sieve shaker model was HAVER EML 200 manufactured by Haver & Boecker (Oelde, Germany), while in Nigeria the sieve shaker model was OCTAGON 200 manufactured by Endecotts (London, United Kingdom). Values were reported as weighted average diameters, as suggested by Klinzing (1981). Similar equipment was used to grate the cassava at both locations. In Tanzania, the average diameter of the wet product particle was 473.0 ± 29.3 µm and of the dry product particle, 335.7 ± 57.6 µm. In Nigeria, the average diameter of the wet product particle was 779.3 ± 88.3 µm and of the dry product particle, 414.8 ± 38.4 µm. The particle characteristics of wet and dry cassava material are further described by Romuli, Abass, and Müller (2016).

2.4 Statistical analysis

Measurements taken on the same day were treated as repeat measures, and to model their correlation a random effect was used with the aid of mixed models. The distribution of the residuals was assessed using normal probability plots. One-way analysis of variance (ANOVA) was performed to detect differences between the unmodified and modified dryers. Means were pairwise compared, using least significant difference (LSD) to detect critical differences at a 95% confidence interval. The results of the multiple comparison method were reported using superscript lower-case letters, with common letters indicating no significant differences. Analyses were performed using SAS 9.4 (SAS Institute Inc., Cary, NC) software.

3. Calculations

3.1 Minimum air mass flow rate calculation and modifications made to the dryers

The minimum air mass flow rate $(\dot{m}^{*}_{\mathrm{air}})$ was determined by taking into consideration the aerodynamic and heat demand of the dryers. The calculation was constrained, to assure that air velocity at the drying remained higher than the terminal velocity of the largest particle, as measured by Romuli et al. (2016). The calculation was also constrained to assure that the thermal energy required to dry the product was delivered. To determine $\dot{m}^{*}_{\mathrm{air}}$ measurements taken from each unmodified dryer were used. First, both the lowest allowable air temperature at the dryer outlet (T^{*}_{out}) and the highest allowable relative humidity at the dryer outlet $(\varphi^{*}_{\mathrm{out}})$ were calculated, then, based on these calculations, the highest possible absolute humidity (Y^{*}_{out}) was determined and used to calculate $\dot{m}^{*}_{\mathrm{air}}$, as shown in Eq. 1:

$$\dot{m}^{*}_{\mathrm{air}} = \frac{\dot{m}_{\mathrm{w}}}{Y^{*}_{\mathrm{out}} - Y_{\mathrm{amb}}} = \frac{\dot{m}_{\mathrm{dm}}\left(X_{\mathrm{wp}} - X_{\mathrm{dp}}\right)}{Y^{*}_{\mathrm{out}} - Y_{\mathrm{amb}}} \qquad (1)$$

Where: $\dot{m}_{w}$ is the water evaporation rate and Y_{amb} is the absolute humidity of the ambient air. The value for $\dot{m}_{w}$ was calculated based on the product mass flow rate on a dry basis ($\dot{m}_{dm}$) and the difference between the wet product moisture content on a dry basis (X_{wp}) and the dry product moisture content on a dry basis (X_{dp}), as suggested by Kudra (2009).

The calculations of T^{*}_{out} and φ^{*}_{out} took into consideration the air enthalpy at the dryer outlet (h_{out}), and also the equilibrium moisture content (MC^{*}_{dp}) of the dry product, as determined by the cassava sorption isotherms (Aviara & Ajibola, 2002). The value of h_{out} was calculated from T_{out} and φ_{out} measured for the unmodified dryers. MC^{*}_{dp} was determined using the modified Halsey model (Iglesias & Chirife, 1976) and the parameters for desorption presented by Aviara and Ajibola (2002). The values for T^{*}_{out} and φ^{*}_{out} were then calculated, with h^{*}_{out} constrained to be equal to h_{out} and MC^{*}_{dp} equal to 10%$_{wb}$.

In Tanzania, the air mass flow rate ($\dot{m}_{air}$) of the unmodified dryer was 3084.7 kg h^{-1}, and the air velocity (v_{air}) at the drying duct feeding point was 9.4 m s^{-1}. At the outlet, T_{out} was 62.6 °C, φ_{out} was 26.4% and as a consequence, Y_{out} was 0.0389 kg kg^{-1} and h_{out} was 164.7 kJ kg^{-1}. The value obtained for T^{*}_{out} was 47.6 °C, and the value for φ^{*}_{out} was 62.0%, resulting in a Y^{*}_{out} value of 0.0452 kg kg^{-1} and an $\dot{m}^{*}_{air}$ value of 2005.0 kg h^{-1}. Based on these results, the driver pulley connected to the blower was replaced by a smaller one. A standard size pulley was used instead of having one manufactured to the exact size that would produce $\dot{m}^{*}_{air}$. As a consequence, after installing the smaller pulley, the air mass flow rate remained approximately 300 kg h^{-1} above the calculated value. The modification reduced $\dot{m}_{air}$ to 2331.9 kg h^{-1}, while v_{air} at the drying duct's feeding point decreased to 7.2 m s^{-1}.

In Nigeria, the air mass flow rate of the unmodified dryer was 1648.5 kg h^{-1} and v_{air} at the drying duct's feeding point was 18.8 m s^{-1} At the outlet, the T_{out} value was 65.8 °C, φ_{out} was 56.9% and, as a consequence, the Y_{out} value was 0.1101 kg kg^{-1} and the h_{out} value 354.8 kJ kg^{-1}. The T^{*}_{out} value obtained was 59.8 °C and φ^{*}_{out} was 75.9%, resulting in a Y^{*}_{out} value of 0.1129 kg kg^{-1} and an

$\dot{m}^*_{air}$ value of 1262.6 kg h^{-1}. The dryer was then modified, using a smaller pulley of standard size, and as a result, the air mass flow rate remained approximately 150 kg h^{-1} above the calculated value having been reduced to 1425.6 kg h^{-1}, while v_{air} at the drying duct's feeding point decreased to 16.4 m s^{-1}.

To assess the material's concentration in air, the solid loading ratio (SLR) was calculated. SLR is defined as the ratio between the product mass flow rate on a dry basis ($\dot{m}_{dm}$) and the air mass flow rate on a dry basis ($\dot{m}_{air}$): SLR=$\dot{m}_{dm}/\dot{m}_{air}$ (Mills et al., 2004). In this study, the value for $\dot{m}_{air}$ was calculated from the air density, air velocity and cross-sectional area of the cyclone exhaust.

3.2 Energy performance evaluation

Specific air consumption, specific energy consumption, energy efficiency and specific heat utilisation were all calculated. Specific air consumption (a_s) is defined as the ratio between the air mass flow rate ($\dot{m}_{air}$) and the water evaporation rate ($\dot{m}_w$): $a_s=\dot{m}_{air}/\dot{m}_w$ (Kudra, 2012; Kudra, Platon, & Navarri, 2009), while specific energy consumption (q_s) is defined as the ratio between the heat input to the dryer ($\dot{Q}_{in}$) and the water evaporation rate ($\dot{m}_w$), as shown in Eq. 2 (Baker, 2005; Kudra, 2012):

$$q_s = \frac{\dot{Q}_{in}}{\dot{m}_w} = \frac{\dot{m}_{air}\left(h_1 - h_{amb}\right)}{\dot{m}_w} \quad (2)$$

Where: h_1 is the enthalpy of the air at the dryer inlet and h_{amb} is the enthalpy of the ambient air.

Energy efficiency (η) is defined as the ratio between the heat used for moisture evaporation ($\dot{Q}_w$) and the heat supplied to the dryer ($\dot{Q}_{in}$), as shown on Eq. 3 (Kudra, 2012; Strumiłło et al., 2014):

$$\eta = \frac{\dot{Q}_w}{\dot{Q}_{in}} = \frac{\dot{m}_w \cdot Q_{st}}{\dot{Q}_{in}} \quad (3)$$

Where: Q_{st} is the starch heat of sorption, as presented by Al-Muhtaseb, McMinn, and Magee (2004). As suggested by Kudra (2009), to account for the energy required to overcome capillary forces, heat of sorption was used instead of the latent heat of vaporization.

To assess the electrical energy needed to obtain 1 kg of dry product, specific electricity utilisation (q_E) was calculated as the ratio between the electrical power consumed (E) and the dry product output rate ($\dot{m}_{dp}$): $q_E=E/\dot{m}_{dp}$. In addition, to access the thermal energy needed to obtain 1 kg of dry product, specific heat utilisation (q_U) was calculated as the ratio between the heat input to the dryer ($\dot{Q}_{in}$) and the dry product output rate ($\dot{m}_{dp}$): $q_U=\dot{Q}_{in}/\dot{m}_{dp}$.

4. Results and discussion

4.1 Dryer operating conditions

Ambient conditions can have an important influence on a dryer's energy performance (Kudra, 2009). In Tanzania, during data collection the average ambient air temperature (T_{amb}) was 29.3 ± 1.2 °C and the average ambient air relative humidity (φ_{amb}) was 60.0 ± 5.8%. In Nigeria, average T_{amb} was 34.2 ± 1.8 °C and average φ_{amb} was 44.1 ± 14.7%. According to the Köppen-Geiger system, both dryers were located in tropical savanna climates, the predominant climate type in sub-Saharan Africa (Hidore, 2005).

Table 1 and Table 2 show the air conditions at the dryer inlet and outlet during the operations in both Tanzania and Nigeria. The same drying settings for the unmodified and modified dryers were used at both locations. In Tanzania, no significant differences between dryers were observed in terms of the air temperature at the inlet (T_1); however, in Nigeria T_1 at the modified dryer's inlet was significantly higher. At this location, in both the modified and unmodified dryers, the thermostat that controls the heating unit was set at 310 °C. However, in the unmodified dryer, this target temperature was not reached, despite the fact that the diesel burner remained switched-on most of the time. Table 2 shows a wider standard deviation for T_1 with the unmodified dryer in Nigeria, the temperature ranging from 278.9 °C to 318.1 °C. Attempting to counteract this temperature fluctuation, the operator reduced and increased the wet product feeding rate ($\dot{m}_{wp}$), and this explains the higher standard deviations seen for $\dot{m}_{wp}$, as shown in Table 4. However, for the modified dryer in Nigeria, the value of T_1 was closer to the target temperature, ranging from 304.6 °C to 315.6 °C. For the drying of food, air temperatures are usually under 200 °C, and temperatures as high as 300 °C are only used with spray dryers (Kudra, 2009). For the drying of potato starch in industrial pneumatic dryers, the inlet temperature usually ranges from 160 °C to 165 °C (Grabowski, Marcotte, & Ramaswamy, 2003). For drying cassava starch in industrial pneumatic dryers, T_1 typically ranges from 170 °C to 200 °C (Sriroth et al., 2000). High inlet temperatures result in better energy efficiency, but T_1 should not exceed the limits imposed by the material being dried, otherwise product quality will be compromised (Kemp, 1994; Kudra, 2009).

Table 1 Air conditions at the dryer inlet and outlet for the unmodified and modified equipment in Tanzania

Dryer	Dryer inlet			Dryer outlet		
	Air temperature, T_1 (°C)	Air relative humidity, φ_1 (%)	Air enthalpy, h_1 (kJ kg^{-1})	Air temperature, T_{out} (°C)	Air relative humidity, φ_{out} (%)	Air enthalpy, h_{out} (kJ kg^{-1})
Unmodified	134.6^{a} ± 2.3	0.78^{a} ± 0.06	180.4^{a} ± 6.0	62.6^{a} ± 2.7	26.4^{a} ± 2.4	164.7^{a} ± 8.0
Modified	136.2^{a} ± 2.7	0.76^{a} ± 0.09	182.4^{a} ± 2.5	49.9^{b} ± 4.8	54.3^{b} ± 7.6	165.4^{a} ± 25.6

Different letters in the same column indicate significant differences at a 95% confidence interval

Table 2 Air conditions at the dryer inlet and outlet for the unmodified and modified equipment in Nigeria

Dryer	Dryer inlet			Dryer outlet		
	Air temperature, T_1 (°C)	Air relative humidity, φ_1 (%)	Air enthalpy, h_1 (kJ kg^{-1})	Air temperature, T_{out} (°C)	Air relative humidity, φ_{out} (%)	Air enthalpy, h_{out} (kJ kg^{-1})
Unmodified	301.6^{a} ± 12.7	0.03^{a} ± 0.01	377.8^{a} ± 14.6	65.8^{a} ± 1.4	56.9^{a} ± 6.0	354.8^{a} ± 17.4
Modified	311.1^{b} ± 3.9	0.02^{b} ± 0.00	366.9^{a} ± 6.5	61.6^{b} ± 1.0	69.4^{b} ± 5.4	354.2^{a} ± 12.5

Different letters in the same column indicate significant differences at a 95% confidence interval

In Tanzania and in Nigeria, air enthalpy at the dryer outlet (h_{out}) was not affected by the reduction in air mass flow rate, but air temperature at the dryer outlet (T_{out}) decreased and air relative humidity at the dryer outlet (φ_{out}) increased. In general, higher energy efficiencies can be attained by bringing the outlet air conditions closer to saturation (Kudra, 2009). T_{out} values were lower and φ_{out} values were higher at both locations when compared to the values reported by Kudra (2012), who used an industrial pneumatic dryer to process starch.

Table 3 and Table 4 show product characteristics during the drying operations in Tanzania and Nigeria respectively. Before pressing, the average moisture content of the material was 61.7 ± 1.4%$_{wb}$ in Tanzania and 68.7 ± 2.8%$_{wb}$ in Nigeria. Typical mature cassava roots have average moisture content in the range from 60%$_{wb}$ to 70%$_{wb}$, though it depends on the variety and growing environment (Breuninger et al., 2009).

Table 3 Wet and dry product temperature and moisture content levels, and mass flow rates, for the unmodified and modified dryers in Tanzania

Dryer	Wet product			Dry product		
	Moisture content, MC_{wp} ($\%_{wb}$)	Temperature, T_{wp} (°C)	Feeding rate, $\dot{m}_{wp}$ (kg h^{-1})	Moisture content, MC_{dp} ($\%_{wb}$)	Temperature, T_{dp} (°C)	Output rate, $\dot{m}_{dp}$ (kg h^{-1})
Unmodified	$39.4^{a} \pm 0.9$	$30.0^{a} \pm 2.0$	$183.0^{a} \pm 0.3$	$10.2^{a} \pm 0.5$	$56.6^{a} \pm 3.1$	$123.4^{a} \pm 2.2$
Modified	$38.7^{a} \pm 2.1$	$27.1^{b} \pm 1.4$	$183.3^{a} \pm 0.4$	$10.3^{a} \pm 0.9$	$51.6^{b} \pm 2.5$	$125.3^{a} \pm 3.5$

Different letters in the same column indicate significant differences at a 95% confidence interval

Table 4 Wet and dry product temperature and moisture content levels, and mass flow rates, for the unmodified and modified dryers in Nigeria

Dryer	Wet product			Dry product		
	Moisture content, MC_{wp} ($\%_{wb}$)	Temperature T_{wp} (°C)	Feeding rate, $\dot{m}_{wp}$ (kg h^{-1})	Moisture content, MC_{dp} ($\%_{wb}$)	Temperature T_{dp} (°C)	Output rate, $\dot{m}_{dp}$ (kg h^{-1})
Unmodified	$48.0^{a} \pm 3.0$	$28.4^{a} \pm 1.0$	$285.4^{a} \pm 29.2$	$10.7^{a} \pm 0.4$	$42.4^{a} \pm 2.5$	$165.9^{a} \pm 16.2$
Modified	$47.8^{a} \pm 1.7$	$26.5^{b} \pm 2.0$	$288.6^{a} \pm 11.0$	$11.0^{b} \pm 0.8$	$43.8^{a} \pm 1.7$	$169.2^{a} \pm 8.2$

Different letters in the same column indicate significant differences at a 95% confidence interval

Water removal using mechanical devices is considerably more energy efficient than using a dryer (Baker, 2005; Kudra, 2009; Strumiłło et al., 2014), and in the cassava starch drying industry, the material is usually dewatered to at least a 40$\%_{wb}$ moisture content (Sriroth et al., 2000). Table 3 and Table 4 show that a greater reduction in the material moisture content took place during the mechanical dewatering process in Tanzania than in Nigeria, even though similar hydraulic presses were used at both locations.

Table 3 and Table 4 show that the reduction in air mass flow rates for the dryers in Tanzania and in Nigeria did not increase the moisture content of the dry product. For cassava flour, a final moisture content of 12$\%_{wb}$ is usually the target (Wheatley et al., 2003). Regarding the dry product temperature (T_{dp}), in Tanzania a lower T_{dp} was observed for the modified dryer; however, in Nigeria this was not observed, likely because of the higher T_1 used in the modified dryer. For potato starch, usually the dry product leaves the dryer at a temperature of 40 °C (Grabowski et al., 2003). In addition, Table 3 and Table 4 show that the dry product temperature was higher in Tanzania, despite the fact that in Nigeria a higher T_1 was applied. This is explained by the higher MC_{wp}, higher $\dot{m}_{wp}$ and lower $\dot{m}_{air}$ used in Nigeria, resulting in a higher evaporation rate.

In both locations, air mass flow rate reductions did not decrease the dry product output rate ($\dot{m}_{dp}$). Despite having the same drying duct dimensions, the two dryers were operated under different regimes. In Nigeria, air temperature at the dryer inlet (T_1) was higher than in Tanzania, and the wet product feeding rate ($\dot{m}_{wp}$) was also higher. However, the air mass flow rate ($\dot{m}_{air}$) was lower in Nigeria. Kudra (2012) reported an $\dot{m}_{dp}$ value for starch almost 30 times higher in a pneumatic dryer with a drying duct of similar length but approximately twice the diameter. Drying duct dimensions vary considerably among pneumatic dryers, because their development has been mainly empirical (Kemp, 1994). Sriroth et al. (2000) reported industrial pneumatic dryers being used to process cassava starch with a pipe length ranging from 40 m to 60 m, a diameter ranging from 1 m to 2 m, and a $\dot{m}_{dp}$ ranging from 8000 kg h^{-1} to 10000 kg h^{-1}.

In Tanzania, the solid loading ratio was 0.036 ± 0.001 kg_{dm} kg_{air}^{-1} for the unmodified dryer, but increased significantly (α=0.05) to 0.048 ± 0.001 kg_{dm} kg_{air}^{-1} after the dryer had been modified by decreasing the air mass flow rate. Likewise, in Nigeria, the solid loading ratio was 0.090 ± 0.011 kg_{dm} kg_{air}^{-1} for the unmodified dryer, but increased significantly (α=0.05) to 0.106 ± 0.008 kg_{dm} kg_{air}^{-1} after modification. Despite the increase in air mass flow rates, the conveying modes stayed as dilute phase systems, and in both locations the solid loading ratios were below 15 kg_{dm} kg_{air}^{-1}, the threshold normally used to distinguish between dilute and dense phase systems (Klinzing, Rizk, Marcus, & Leung, 2010).

4.2 Energy performance

Table 5 and Table 6 show the energy performance indices for the dryers in Tanzania and Nigeria. In both locations, the heat input rate at the dryer inlet ($\dot{Q}_{in}$) was significantly lower after the reduction in air mass flow rates had been made, though in Nigeria, T_1 for the modified dryer was higher than in the unmodified dryer. Despite the reduction in $\dot{Q}_{in}$, drying forces were not jeopardised and the evaporation rate ($\dot{m}_w$) did not decrease, which also explains the improvements in specific air consumption (a_s), specific energy consumption (q_s) and energy efficiency (η). The q_s for particulate material usually ranges from 5 to 8 MJ kg_{water}^{-1} (Strumiłło et al., 2014), but lower values can be achieved within pneumatic dryers (Levy & Borde, 2014). For example, Kudra (2012) reported a q_s of 4.7 MJ kg_{water}^{-1} for starch being processed in an industrial pneumatic dryer.

Table 5 Energy performance indices for the unmodified and modified dryers in Tanzania

Dryer	Heat input rate, $\dot{Q}_{in}$ (kW)	Water evaporation rate, $\dot{m}_w$ (kg_{water} h^{-1})	Specific air consumption, a_s (kg_{air} kg_{water}^{-1})	Specific energy consumption, q_s (MJ kg_{water}^{-1})	Energy efficiency, η (%)	Electrical power consumption, E (kW)
Unmodified	95.2^a ± 2.8	59.6^a ± 2.2	51.8^a ± 2.2	5.75^a ± 0.18	43.1^a ± 1.4	3.96^a ± 0.08
Modified	73.9^b ± 1.0	58.0^a ± 3.5	40.4^b ± 2.8	4.60^b ± 0.27	54.0^b ± 3.1	2.87^b ± 0.05

Different letters in the same column indicate significant differences at a 95% confidence interval

Table 6 Energy performance indices for the unmodified and modified dryers in Nigeria

Dryer	Heat input rate, $\dot{Q}_{in}$ (kW)	Water evaporation rate, $\dot{m}_w$ (kg_{water} h^{-1})	Specific air consumption, a_s (kg_{air} kg_{water}^{-1})	Specific energy consumption, q_s (MJ kg_{water}^{-1})	Energy efficiency, η (%)	Electrical power consumption, E (kW)
Unmodified	136.2^a ± 6.8	119.4^a ± 17.6	14.1^a ± 2.2	4.18^a ± 0.58	60.2^a ± 7.4	3.43^a ± 0.02
Modified	119.6^b ± 5.0	119.4^a ± 7.8	12.0^b ± 0.9	3.62^b ± 0.29	68.8^b ± 5.7	3.13^b ± 0.02

Different letters in the same column indicate significant differences at a 95% confidence interval

The energy efficiency (η) of pneumatic dryers usually ranges from 50% to 75% (Strumiłło et al., 2014), and Table 5 and Table 6 show that in both locations a significant improvement was achieved for η. The value for the starch isosteric heat of sorption used to calculate $\dot{Q}_w$ in both locations was 2476 kJ kg^{-1}, close to the upper limit of the latent heat of evaporation that, depending on the temperature, ranges from 2200 kJ kg^{-1} to 2500 kJ kg^{-1} (Kemp, 2012).

In pneumatic dryers, electricity usage is a significant component of the production costs, due to the large amount of electrical energy required to power the blowers (Kudra, 2009). Table 5 and Table 6 show that in both locations, the smaller driver pulley used to modify the dryers reduced the amount of mechanical power demanded from the electric motor, and, as a consequence, a significant reduction in electrical power consumption was achieved. In addition, Table 7 shows that the specific electricity utilisation (q_E), that is, the electric energy needed to produce 1 kg of dry product, decreased significantly in both locations.

Table 7 Specific electricity utilisation and specific heat utilisation for the dryers in Tanzania and in Nigeria

Dryer	Dryers in Tanzania		Dryers in Nigeria	
	Specific electricity utilisation q_E (MJ kg_{dp}^{-1})	Specific heat utilisation q_U (MJ kg_{dp}^{-1})	Specific electricity utilisation q_E (MJ kg_{dp}^{-1})	Specific heat utilisation q_U (MJ kg_{dp}^{-1})
Unmodified	$0.116^a \pm 0.002$	$2.78^a \pm 0.12$	$0.075^a \pm 0.008$	$2.98^a \pm 0.39$
Modified	$0.082^b \pm 0.002$	$2.12^b \pm 0.07$	$0.067^b \pm 0.004$	$2.55^b \pm 0.20$

Different letters in the same column indicate significant differences at a 95% confidence interval

Table 7 also shows that the specific heat utilisation (q_U), that is, the energy needed to produce 1 kg of dry product, decreased significantly in both locations after the modifications had been made. Despite these improvements, the values reported by Sriroth et al. (2000) show that industrial pneumatic dryers require even less energy to produce 1 kg of cassava starch. One of the reasons for this is the higher heat losses that occur in small-scale dryers, due to their less favourable surface-to-volume ratios (Kemp, 2012). Comparing the q_U values of the dryers in Tanzania and Nigeria, it can be seen that more energy was needed to produce 1 kg of dry product in Nigeria than in Tanzania, despite the higher η of the dryers in Nigeria. The reason for this was the elevated moisture content of the wet products in Nigeria, which resulted in a larger amount of water having to be evaporated to achieve the desired final moisture content.

4.3 Product quality

Table 8 and Table 9 show the quality parameters for the dry products obtained from the dryers in Tanzania and in Nigeria respectively. Water activity indicates the availability of water for microbial growth and chemical reactions (Carrín & Crapiste, 2008). Despite the fact that the dryer modifications did not significantly increase the moisture content of the dry product, a rise in water activity (a_w) was observed both in Tanzania and in Nigeria. This can be explained by the sigmoid shape of the cassava desorption isotherm (Aviara & Ajibola, 2002). In the range of the dry product, a small change in the product's moisture content leads to a large change in water activity. Nevertheless, a_w values here remained at a level where, according to Beuchat (1983), deteriorative chemical and biochemical reaction rates are minimal and where there is no microbiological growth.

Table 8 Water activity, plus CIELAB colour space and whiteness index for the dry products obtained from Tanzania

Dryer	Dry product water activity, a_w	Dry product L^* value	Dry product a^* value	Dry product b^* value	Whiteness index
Unmodified	$0.51^a \pm 0.05$	$91.6^a \pm 0.9$	$-1.2^a \pm 0.3$	$7.3^a \pm 0.6$	$45.5^a \pm 5.0$
Modified	$0.57^b \pm 0.04$	$91.3^a \pm 1.2$	$-1.3^a \pm 0.2$	$7.1^a \pm 1.0$	$45.5^a \pm 3.0$

Different letters in the same column indicate significant differences at a 95% confidence interval

Table 9 Water activity, plus coordinates of the CIELAB colour space and yellowness index for the dry products obtained from Nigeria

Dryer	Dry product water activity, a_w	Dry product L^* value	Dry product a^* value	Dry product b^* value	Yellowness index
Unmodified	$0.55^a \pm 0.04$	$90.4^a \pm 1.3$	$0.5^a \pm 0.3$	$23.1^a \pm 1.6$	$41.4^a \pm 2.5$
Modified	$0.61^b \pm 0.05$	$91.9^b \pm 0.7$	$0.0^b \pm 0.3$	$20.7^b \pm 2.2$	$36.7^b \pm 3.2$

Different letters in the same column indicate significant differences at a 95% confidence interval

In Tanzania, the modifications to the dryer had no impact on product colour, but in Nigeria, the dry product from the modified dryer was significantly less yellow. The loss of colour during drying is a well-known phenomenon (Carrín & Crapiste, 2008), and is particularly pronounced with carotenoid rich materials (Stefanovich & Karel, 1982) like yellow cassava. The significant loss of colour when using the modified dryer here could be attributed to the elevated T_1 used, and such a loss of colour could reduce consumer acceptance. Colour is the most important factor influencing the appearance of food (Araya-Farias & Ratti, 2008; Mendoza, Dejmek, & Aguilera, 2006), and appearance is the main element determining consumer acceptance of a food product (Fernández, Castillero, & Aguilera, 2005; Louka, Juhel, Fazilleau, & Loonis, 2004).

4.4 Further modifications to the dryers

Decreasing the air mass flow rate of a dryer can bring energy savings (Kudra, 2009) and involves minimal investment (Strumiłło et al., 2014). However, it is also important to ensure that heat demand is fully supplied (Rotstein & Crapiste, 1997) and that air velocity at the drying duct remains sufficient to convey the product (Kudra, 2012; Levy & Borde, 2014). In both locations, the reduction in air mass flow rates did not jeopardise the pneumatic conveying of the material. In cases where the air velocity does fall below the terminal velocity of the largest particle, Jumah and Mujumdar (2014) suggest installing a venturi at the feeding point, to improve product dispersion and fluidisation.

Further improvements to the energy performance of the dryers studied here could still be achieved. For example, the divergence seen between the moisture contents of the dry products obtained from the modified dryers and the value predicted by the sorption isotherm suggests that equilibrium between the air and the materials was not achieved. This could be addressed by using a longer drying duct to increase the residence time and allow more complete mass and heat transfers to take place between the air and the materials. Adding thermal insulation to the ducts would also reduce heat losses and contribute positively to the dryers' performance (Strumiłło et al., 2014). Furthermore, instrumentation of the dryers would allow better process control, and so bring improvements in terms of energy efficiency and product quality (Baker, 2005). The absence of a proper control system here resulted in a non-uniform drying operation, and this explains the high standard deviations seen in the measured parameters. However, as much as instrumentation of the dryers is important, given the scale of the drying operations involved, it is imperative to keep equipment costs low, and for the dryers to be able to be repaired locally (Orsat et al., 2008).

5. Conclusions

The experiments carried out in this study confirmed that the energy performance of pneumatic dryers can be improved by reducing the mass flow rate of the drying air. The minimum air mass flow rate was calculated based on air enthalpy at the dryer outlet and on the product sorption isotherm. In addition, the calculation took into consideration the terminal velocity of the largest particle, to ensure there were no negative effects on the pneumatic conveyance of the cassava particles. Air mass flow was reduced by simply replacing the blower's driver pulleys with one of a smaller diameter. In Tanzania, the air mass flow rate was lowered by 24% and in Nigeria by 14%. Consequently, the specific energy consumption, i.e., the amount of energy required to evaporate 1 kg of water, was reduced by 20% in Tanzania and 13% in Nigeria, resulting in energy efficiency improvements of 25% in Tanzania and 14% in Nigeria. Insulating the dryer ducts could further improve the energy performance of such dryers and reduce the influence of the local weather on drying conditions, though the ambient air temperature in such areas of Africa is usually high.

A difference found between the moisture content of dry cassava and the value predicted from the sorption isotherm indicates that no equilibrium was achieved between the drying air and cassava. Therefore, the energy performance of the dryers could be further improved by using longer drying ducts to increase the cassava residence time and; thus, achieve thermodynamic equilibrium at a lower air temperature.

The modifications made to the dryers had no impact on the colour of the dry cassava in Tanzania; however, in Nigeria, the dry cassava was significantly less yellow. This difference could be attributed to the elevated temperature of the drying air in Nigeria.

The modifications made to the dryers in both countries increased water activity of the dry product both in Tanzania and in Nigeria. However, even with the increased water activity levels, it remained low enough for safe storage.

6. Acknowledgments

This work was supported by the CGIAR Research Program on Roots, Tubers and Bananas (RTB). We should express our gratitude to Ukaya Farm (Tanzania) and Niji Farms (Nigeria) for taking part in the study, and would like to thank Mr. Audifas Gaspar (IITA−Tanzania) and Mr. James Oyelekan (IITA−Nigeria) for their assistance with the laboratory analysis. We would also like to thank Mr. Gary Morrison for proofreading the article.

7. References

Aichayawanich, S., Nopharatana, M., Nopharatana, A., & Songkasiri, W. (2011). Agglomeration mechanisms of cassava starch during pneumatic conveying drying. *Carbohydrate Polymers, 84*(1), 292-298.

Al-Muhtaseb, A. H., McMinn, W. A. M., & Magee, T. R. A. (2004). Water sorption isotherms of starch powders: Part 1: Mathematical description of experimental data. *Journal of Food Engineering, 61*(3), 297-307.

AOAC. (1998a). *Method 965.22: Sorting corn grits*. Gaithersburg, MD: AOAC International.

AOAC. (1998b). *Method 978.18: Water activity of canned vegetables*. Gaithersburg, MD: AOAC International.

Araya-Farias, M., & Ratti, C. (2008). Dehydration of foods: General concepts. In C. Ratti (Ed.), *Advances in Food Dehydration* (pp. 1-36). Boca Raton, FL: CRC Press.

ASABE. (2008). S358.2: Moisture measurements – Forages *ASABE Standards 2008: Standards Engineering Practices Data* (pp. 670-672). St. Joseph, MO: American Society of Agricultural and Biological Engineers.

ASTM. (2004a). *E313: Standard practice for calculating yellowness and whiteness indices from instrumentally measured color coordinates*. West Conshohocken, PA: ASTM International.

ASTM. (2004b). *E1347: Standard test method for color and color-difference measurement by tristimulus (filter) colorimetry*. West Conshohocken, PA: ASTM International.

Aviara, N. A., & Ajibola, O. O. (2002). Thermodynamics of moisture sorption in melon seed and cassava. *Journal of Food Engineering, 55*(2), 107-113.

Baker, C. G. J. (2005). Energy efficient dryer operation – An update on developments. *Drying technology, 23*(9-11), 2071-2087.

Beeching, J. R. (2013). *Manihot esculenta* (Cassava) *eLS* (pp. 1-7). Chichester, UK: John Wiley & Sons, Ltd.

Beuchat, L. R. (1983). Influence of water activity on growth, metabolic activities and survival of yeasts and molds. *Journal of Food Protection, 46*(2), 135-141.

Brennan, J. G. (2011). Evaporation and dehydration. In J. G. Brennan & A. S. Grandison (Eds.), *Food Processing Handbook, 2^{nd} Edition* (2^{nd} ed., pp. 77-130). Weinheim, Germany: Wiley-VCH.

Breuninger, W. F., Piyachomkwan, K., & Sriroth, K. (2009). Tapioca/cassava starch: Production and use. In J. BeMiller & R. Whistler (Eds.), *Starch* (3^{rd} ed., pp. 541-568). San Diego, CA: Academic Press.

Carrín, M. E., & Crapiste, G. H. (2008). Convective drying of foods. In C. Ratti (Ed.), *Advances in Food Dehydration* (pp. 123-151). Boca Raton, FL: CRC Press.

Chua, K. J., & Chou, S. K. (2003). Low-cost drying methods for developing countries. *Trends in Food Science and Technology, 14*(12), 519-528.

Da, G., Dufour, D., Giraldo, A., Moreno, M., Tran, T., Velez, G., . . . Marechal, P.-A. (2013). Cottage level cassava starch processing systems in Colombia and Vietnam. *Food and Bioprocess Technology, 6*(8), 2213-2222.

Falade, K. O., & Akingbala, J. O. (2011). Utilization of cassava for food. *Food Reviews International, 27*(1), 51-83.

Fan, L.-S., & Zhu, C. (1998). *Principles of Gas-Solid Flows*. Cambridge, UK: Cambridge University Press.

Fernández, L., Castillero, C., & Aguilera, J. M. (2005). An application of image analysis to dehydration of apple discs. *Journal of Food Engineering, 67*(1–2), 185-193.

Goletti, F., & Samman, E. (2007). Post-harvest systems in world agriculture. In P. Golob, G. Farrel & J. E. Orchard (Eds.), *Crop Post-Harvest: Science and Technology, Volume 1: Principles and Practice* (pp. 1-34). Malden, MA: Blackwell Science Ltd.

Grabowski, S., Marcotte, M., & Ramaswamy, H. (2003). Drying of fruits, vegetables, and spices. In A. Chakraverty, A. S. Mujumdar, G. S. V. Raghavan & H. S. Ramaswamy (Eds.), *Handbook of Postharvest Technology: Cereals, Fruits, Vegetables, Tea, and Spices* (pp. 653-695). New York, NY: Marcel Dekker, Inc.

Hidore, J. J. (2005). Savanna climate. In J. E. Oliver (Ed.), *Encyclopedia of World Climatology* (pp. 635-636). Dordrecht, Netherlands: Springer.

Iglesias, H. A., & Chirife, J. (1976). Prediction of the effect of temperature on water sorption isotherms of food material. *International Journal of Food Science & Technology, 11*(2), 109-116.

ISO. (1997). *International Standard 11520-1:1997 Agricultural grain dryer – Determination of drying performance*. Geneva, Switzerland: International Organization of Standardization.

Jumah, R. Y., & Mujumdar, A. S. (2014). Dryer feeding systems. In A. S. Mujumdar (Ed.), *Handbook of Industrial Drying* (4^{th} ed., pp. 1025-1043). Boca Raton, FL: CRC Press.

Kemp, I. C. (1994). Scale-up of pneumatic conveying dryers. *Drying Technology, 12*(1-2), 279-297.

Kemp, I. C. (2012). Fundamentals of energy analysis of dryers. In E. Tsotsas & A. S. Mujumdar (Eds.), *Modern Drying Technology, Volume 4: Energy Savings* (Vol. 4, pp. 1–45). Weinheim, Germany: Wiley-VCH.

Klinzing, G. E. (1981). *Gas-Solid Transport*. New-York, NY: McGraw-Hill.

Klinzing, G. E., Rizk, F., Marcus, R., & Leung, L. S. (2010). *Pneumatic Conveying of Solids: A Theoretical and Practical Approach* (3^{rd} ed.): Springer.

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

Kudra, T. (2012). Energy performance of convective dryers. *Drying Technology, 30*(11-12), 1190-1198.

Kudra, T., Platon, R., & Navarri, P. (2009). Excel-based tool to analyze the energy performance of convective dryers. *Drying Technology, 27*(12), 1302-1308.
Lebot, V. (2009). *Tropical Root and Tuber Crops: Cassava, Sweet Potato, Yams and Aroids* (Vol. 17). Wallingford, CT: CABI.
Levy, A., & Borde, I. (2014). Pneumatic and flash drying. In A. S. Mujumdar (Ed.), *Handbook of Industrial Drying* (4th ed., pp. 381-392). Boca Raton, FL: CRC Press.
Louka, N., Juhel, F., Fazilleau, V., & Loonis, P. (2004). A novel colorimetry analysis used to compare different drying fish processes. *Food Control, 15*(5), 327-334.
Mendoza, F., Dejmek, P., & Aguilera, J. M. (2006). Calibrated color measurements of agricultural foods using image analysis. *Postharvest Biology and Technology, 41*(3), 285-295.
Mills, D., Jones, M. G., & Agarwal, V. K. (2004). *Handbook of Pneumatic Conveying Engineering*. New York, NY: Marcel Dekker, Inc.
Mujumdar, A. S. (2008). Drying: Principles and practice. In L. F. Albright (Ed.), *Albright's Chemical Engineering Handbook* (pp. 1667-1716). Boca Raton, FL: CRC Press.
Orsat, V., Raghavan, G. S. V., & Sosle, V. (2008). Adapting drying technologies for agri-food market development in India. *Drying Technology, 26*(11), 1355-1361.
Precoppe, M., Chapuis, A., Müller, J., & Abass, A. (2015). Tunnel dryer and pneumatic dryer performance evaluation to improve small-scale cassava processing in Tanzania. *Journal of Food Process Engineering*, in press.
Romuli, S., Abass, A., & Müller, J. (2016). Physical Properties of Cassava Grits before and after Pneumatic Drying. *Journal of Food Process Engineering*, n/a-n/a. doi: 10.1111/jfpe.12397
Rotstein, E., & Crapiste, G. H. (1997). Design and performance evaluation of dryers. In K. J. Valentas, R. P. Singh & E. Rotstein (Eds.), *Handbook of Food Engineering Practice* (pp. 121-162). Boca Raton, FL: CRC Press.
Salgado-Cervantes, M. A., Lebert, A., Garcia-Alvarado, M. A., Muchnik, J., & Bimbenet, J. J. (1994). Development of the characteristic drying curve for cassava chips in Monolayer. *Drying Technology, 12*(3), 685-696. doi: 10.1080/07373939408959984
Sriroth, K., Piyachomkwan, K., Wanlapatit, S., & Oates, C. G. (2000). Cassava starch technology: The Thai experience. *Starch - Stärke, 52*(12), 439-449.
Stefanovich, A. F., & Karel, M. (1982). Kinetics of beta-carotene degradation at temperatures typical of air drying of foods. *Journal of Food Processing and Preservation, 6*(4), 227-242.
Strumiłło, C., Jones, P. L., & Żyłła, R. (2014). Energy aspects in drying. In A. S. Mujumdar (Ed.), *Handbook of Industrial Drying* (4th ed., pp. 1077-1100). Boca Raton, FL: CRC Press.
Wheatley, C. C., Chuzel, G., & Zakhia, N. (2003). Cassava: Uses as a raw material. In B. Caballero (Ed.), *Encyclopedia of Food Sciences and Nutrition* (2nd ed., pp. 969-974). Oxford, UK: Academic Press.

Legends to figures

Figure 1 Schematics of the pneumatic dryers (a) in Tanzania and (b) in Nigeria, plus the location of the sensors (T, temperature; φ, relative humidity; P, pressure; v, air velocity; $\dot{m}$, mass flow rate; E, electric energy)