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Foam mat drying of cassava and associated properties: comparison between white-flesh and yellow-flesh varieties

Dissertation

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Declaration

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Oluwatoyin Ayetigbo

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1 General Introduction

1.1 Cassava (*Manihot esculenta*, Crantz)

1.1.1 Overview: origin, cultivation locations and agronomy

Cassava is known by various names in different locations of the world: as *yucca*, *manioc, manihot* (Ukwuru & Egbonu, 2013), *mandioca*, *macaxeira, tapioca* and *aipim* (OECD, 2016). It belongs to the *Euphorbiaceae* family of plants. The origin of cassava can be traced to the South-American continent, especially, to Brazil, where wild populations of *Manihot esculenta* Flabellifolia have been determined as the ancestral progenitor of the domesticated cassava (Olsen & Schaal, 1999). In the 16th century, cassava was introduced to Africa through trades with Portuguese traders from Brazil as barter items for goods. Portuguese and Spanish traders also exchanged cassava with the Asian continent through trade at about the same time. Three major regions based on three continents are well known for the cultivation of cassava on a commercial scale, which are: West Africa, South-East Asia and South America, in countries like Nigeria, Colombia, Brazil, Costa Rica, Peru, Thailand, Indonesia, Venezuela, China, etc.

Cassava is a staple food crop for about 500 million people in the tropic and subtropics regions. It is an energy dense crop with the capacity of supplying higher carbohydrate per hectare ratio than the main cereal crops such as corn, millet, and sorghum (Julie A. Montagnac, Davis, & Tanumihardjo, 2009a). The adaptability of cassava to soils with low fertility, drought, disease and pest makes it efficient to cultivate commercially in marginally fertile soils at low costs (Ukwuru & Egbonu, 2013). Cassava can also be stored, traditionally, underground prior to planned harvest, thus reducing storage requirements. In spite of these facts, cassava is highly susceptible to rapid post-harvest physiological deterioration, and therefore, requires immediate processing. The crop can be propagated by stem cuttings or seed, although, the seeds are rarely produced and often dormant. Details on agronomic practices and requirement for cassava are available in the literature (OECD, 2016).

1.1.2 Global, regional and local production of cassava

Among the many crops cultivated in the world, cassava plays a substantial role in food security and livelihoods, especially in Nigeria (Figure 1-1), which is the largest producer of cassava in the world (Figure 1-2). According to the Food and Agricultural Organisation (FAO, 2019a), statistics show that in Nigeria, the total amount of area harvested for cassava has increased from about 0.78 million ha to 6.8 million ha between 1961 to 2017, total production has increased eight folds from 7.4 million to 59.5 million tonnes, while yield has only marginally increased within this period (Figure 1-3). As at 2017, Nigeria accounted for 69 %, 34 % and 26 % of the area dedicated to cassava cultivation, and contributed 62 %, 33 % and 20 % of the total production, compared to the West African region, Africa and the world, respectively (Table 1-1). However, the average yield of cassava was still about 20 % lower than the average yield worldwide.

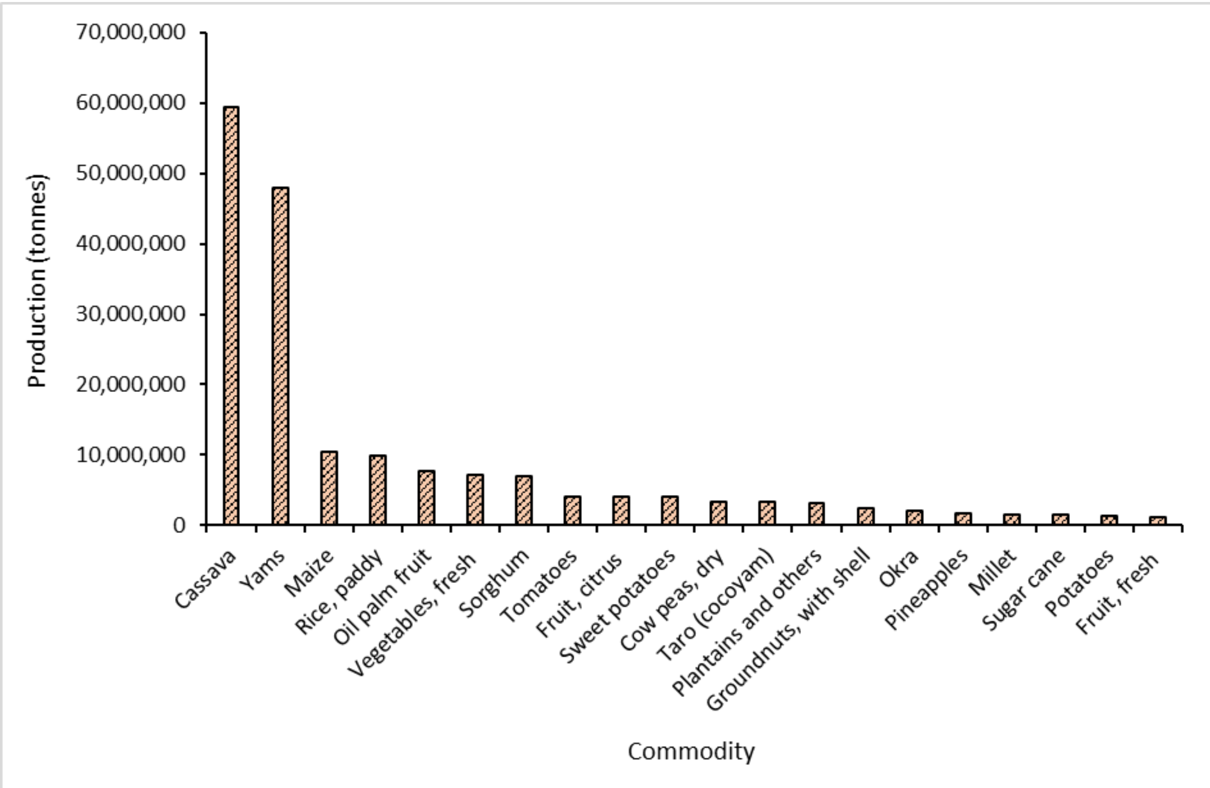

Figure 1-1: Production capacity of top 20 food commodities produced in Nigeria in 2017 (FAO, 2019c)

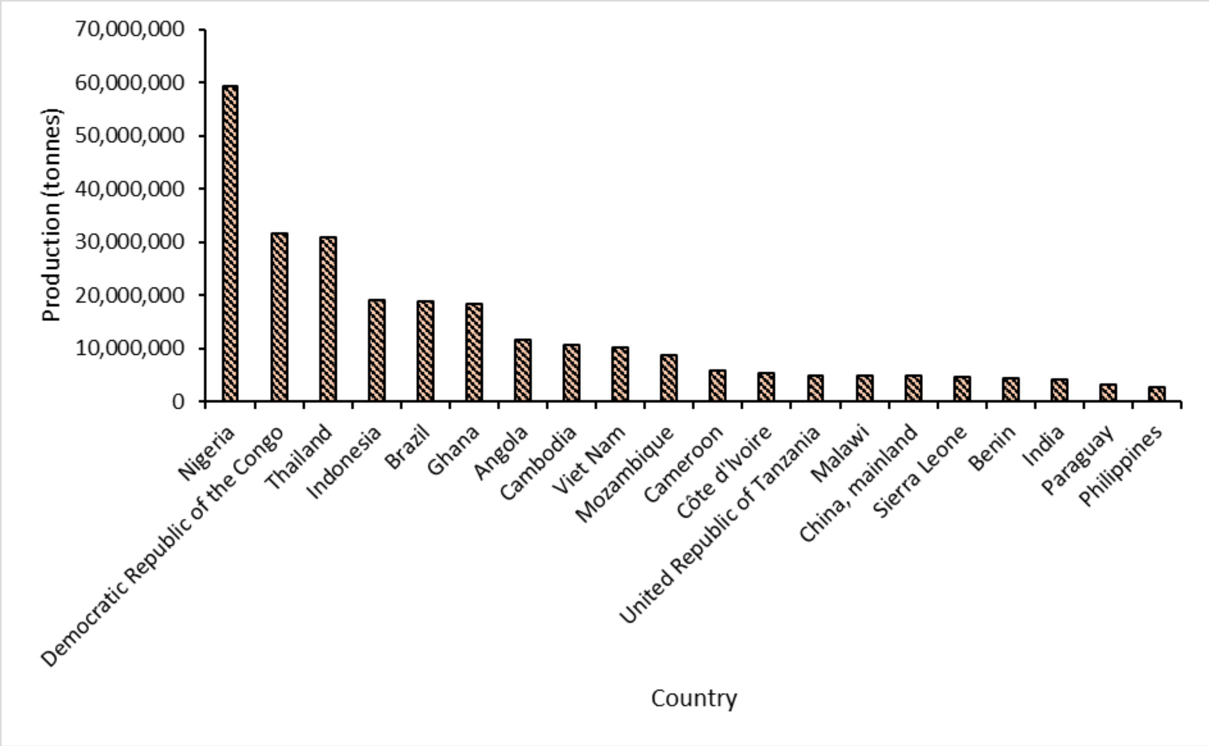

Figure 1-2: Production capacity of top 20 countries producing cassava in 2017 (FAO, 2019b)

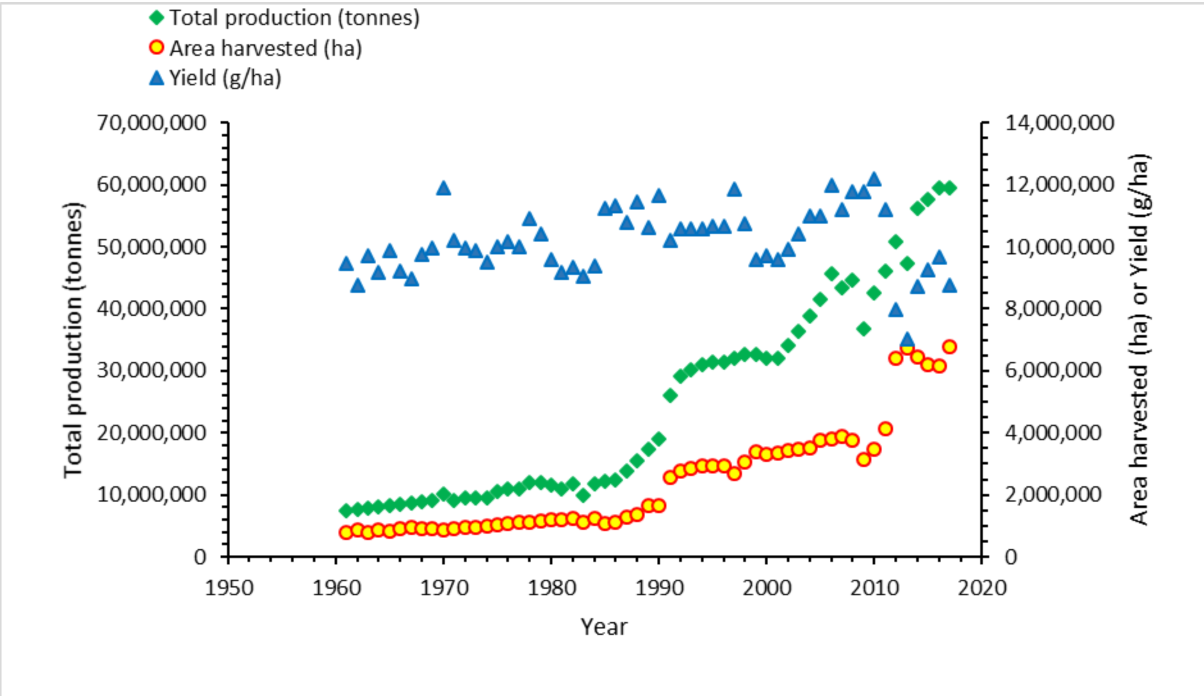

Figure 1-3: Area under cultivation, yield and total production profile (1961 - 2017) for cassava in Nigeria. Calculated as per standardized statistics (FAO, 2019a)

Table 1-1: Contribution of Nigeria to the regional, continental and global statistics on cassava (2017)

Location	Area harvested (ha)	Yield (g/ha)	Total production (tonnes)
Nigeria	6,792,349	8,757,800	59,485,947
West Africa	9,869,840	9,749,300	96,223,919
Africa	20,235,146	8,794,000	177,947,697
World	26,342,330	11,084,500	291,992,646

Source: (FAO, 2019a)

1.1.3 Nutritional constituents of cassava

The bulk of the cassava root consists of moisture, which contributes about 60 - 65 % to the weight of the freshly harvested root, making transportation and handling inefficient. Cassava is rich in calorific content, providing about 250 kcal of energy in the root per ha daily yield, thereby ranking it higher in daily calories per ha daily yield than some major grains crops (J.A. Montagnac, Davis, & Tanumihardjo, 2009). The carbohydrates in cassava account for 80 – 90 % of the root's fresh weight, and consist predominantly, of starch and small quantities of sugars. It is also relatively richer in calories than potato, but not richer in calories than sorghum, wheat, and rice on percentage basis (g/100g). However, cassava is severely lacking in proteins (0.4 – 1.5 %) and lipids (0.1 – 0.3 %) on fresh wt. basis, which makes it an excellent source for starch extraction. The sulphur-containing amino acids (methionine, cysteine, tryptophan) are deficient in cassava, but it is relatively rich in acidic and some basic amino acids (Gil & Buitrago, 2002) such as aspartic acid, glutamic acid and arginine. The fibre content of cassava varies with age and variety and can contain up to 1.5 % fibre. The minerals and vitamins composition in cassava is also not as impressive as in legumes, cereals, fruits and other vegetables (Gil & Buitrago, 2002), but recently developed colored cassava varieties have a comparable pro-vitamin A composition.

Cassava is one of the plant biomass with high amounts of the toxic cyanogenic glucosides in all of its physiological parts. Among these glucosides are linamarin, which accounts for about 95 % of potential toxicity, and lotaustralin, which accounts for the remaining 5 % (Julie A. Montagnac, Davis, & Tanumihardjo, 2009b). Under suitable conditions, the intermediate breakdown products from linamarin are aceto-cyanohydrin and hydrogen cyanide, which are toxic above recommended limits.

Comprehensive literature on the nutritional composition of cassava has been reviewed in a number of publications (Ayetigbo, Latif, Abass, & Müller, 2018; J.A. Montagnac et al., 2009).

1.1.4 Cassava varieties database

Originally, the yellow-fleshed cassava existed in the South American Amazon regions of Brazil and Columbia (Chavez et al., 2005; Iglesias, Mayer, Chavez, & Calle, 1997), before they were selectively bred to their current state and introduced to Africa through research exchange between CGIAR (Consultative Group on International Agricultural Research) institutes. The *cassavabase* has been developed as a database for the systematic recall of genomic and agronomic data on cassava (Fernandez-Pozo et al., 2015) for CGIAR institutions, of which the International Institute of Tropical Agriculture (IITA) is a participant that contributes to the data repository. The database reveals the unique traits assayed for several varieties of cassava. The yellow-fleshed cassava variety IITA-TMS-IBA 011368 is of particular interest in this study due to the traits it possesses, some of which are shown in Figure 1-4 and Table 1-2. The variety is an accession derived from the crossing of parent stocks of IITA-TMS-IBA 940263 (male) and IITA-TMS-IBA 940561 (female). The accession has been used for various studies on the incidence and severity of anthracnose disease, mosaic disease and bacterial blight, probably due to its resistance to these agronomic challenges.

1.1.5 Food uses of cassava

Cassava is processed traditionally into food by boiling, frying, roasting and fermenting. It is essential to process cassava before consumption to reduce cyanogenic toxicity (Julie A. Montagnac et al., 2009b). The most common products made from cassava are flour and starch. The flour is commonly used for baking bread and other confectioneries as shown in Table 1-3.

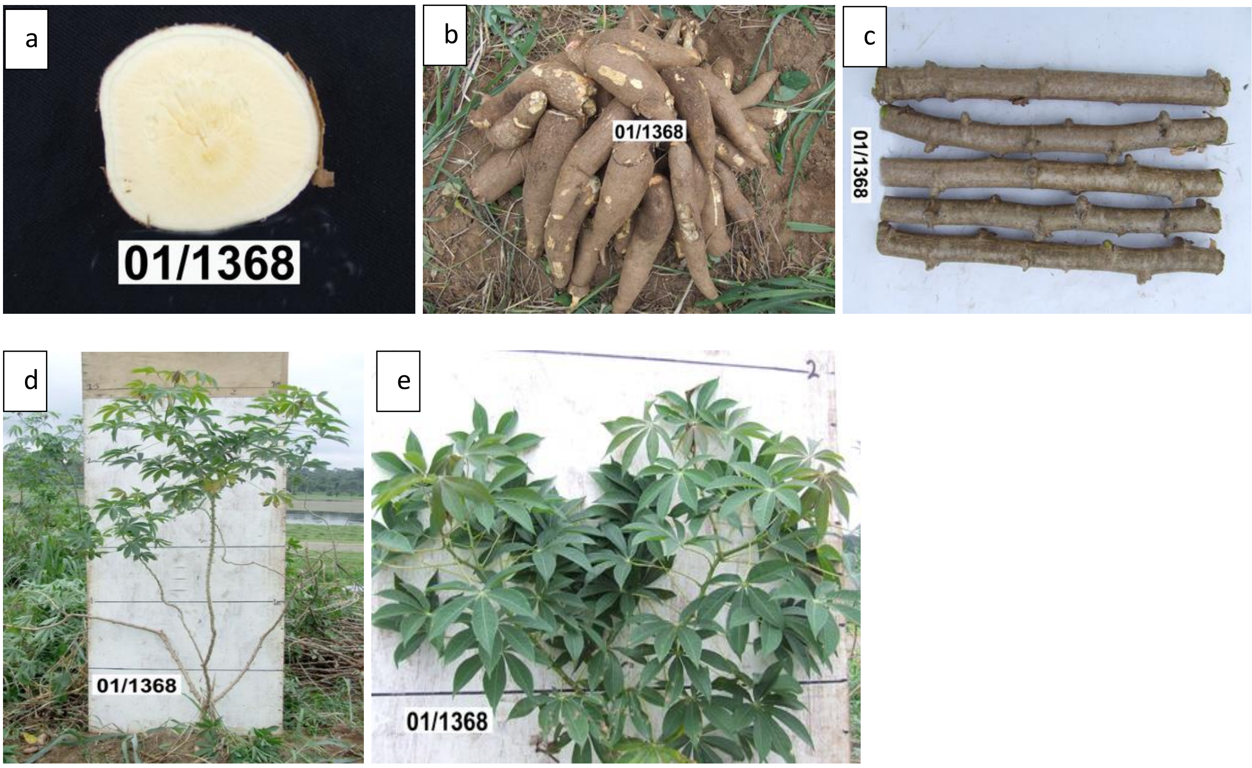

Figure 1-4: Cross-sectional view of root (a), mound of roots (b), stem cuttings (c), above-the-ground plant parts (d) and leaves (e) of accession IITA-TMS-IBA-011368

Table 1-2: Assayed traits of interest of accession IITA-TMS-IBA-011368 (yellow-fleshed cassava)

Trait	Description	Value
Root number counting	A count of the total number of storage roots harvested per plot	57.2 ± 38.6
Fresh storage root weight per plot	Total fresh weight of storage roots harvested per plot	20.7 ± 14.4 kg
Fresh root yield	Fresh weight of harvested roots	18.0 ± 9.3 tons/ha
Dry yield	Dry weight of harvested roots derived by multiplying fresh storage root yield by dry matter content	5.0 ± 2.7 tons/ha
Root surface color visual rating	Visual rating of storage root surface color	2.0 ± 1.2[a]
Fibre content estimation	Part of tuber root that cannot be digested by humans	1.1 ± 0.4 %
Starch content	Percentage of complex carbohydrate found in cassava storage root	17.7 ± 5.9 % [b]
Total carotenoid content	Total extracted carotenoids in cassava storage root as estimated by spectrophotometer	7.0 ± 1.5 µg/g [b]
Hydrogen cyanide (HCN) potential enzymatic method	Indicator of the potential production of HCN in cassava storage roots	6.0 ± 0.8 mg/100g [b, c]
Post-harvest physiological deterioration	Internal root discoloration or vascular streaking that renders cassava roots unfit for human or animal consumption	0.9 ± 0.0[d]
Taste of boiled root	Qualitative taste of boiled root	1.5 ± 0.6[e]

Hydrogen cyanide potential picrate method	Visual qualitative estimate of storage root cyanide content by picrate test	4.7 ± 1.6[f]
Dry matter content	Percentage measured root dry weight per 100g of the root tubers	26.0 ± 5.6 %
Beta-carotene content	Analytical concentration of the β-carotene extracted from root samples and estimated by High Performance Liquid Chromatography	6.1 ± 0.8 µg/g [b]
Ease of peeling root cortex	Visual qualitative rating of the ease of peeling root periderm	2.6 ± 0.8 [g]
Total carotenoids retention percentage	Percentage of total carotenoids content in a prepared food product compared to the carotenoids content in the raw food	7.0 ± 1.8 %
Total carotenoids by chart	Assessment of the level of yellowness in cassava storage root pulp using the total carotenoids chart	3.7 ± 1.2[h]
Root flesh color	Visual rating of root pulp color	2.0 ± 0.2[i]
Post-harvest physiological deterioration variable	Physiological deterioration variable at month 7	1.1 ± 1.3[j]

Source: Fernandez-Pozo et al. (2015). a (rating 1: white or cream, 2: light brown, 3: dark brown); b (fresh weight basis); c (rating <5 mg/100g: low, 5 – 10 mg/100g: medium, 10 mg/100g: high); d (determined by cutting a number of root samples into 7 slices and scoring each slice on a scale of 0 to 10); e (rating 1: sweet, 2: bland, 3: bitter); f (rating from 1: not detectable to 9: very high); g (rating from 3: easy to 7: difficult); h (rating 1: white, 2: light cream, 3: cream, 4: light yellow, 5: yellow, 6: deep yellow, 7: orange, 8: pink), i (1: white, 2: cream, 3: yellow as evaluated by the International Centre for Tropical Agriculture CIAT), j (post- harvest physiological deterioration on scale 1 to 10)

Cassava starch is now used as a substitute for maize starch in preparing salad dishes, soup thickener, sauces and canned foods (Abass, Awoyale, Sanni, & Shittu, 2017). Government policy in Nigeria encourages the statutory complementation of cassava flour with wheat meal in food production in order to promote the local use of cassava, reduce import, and retain foreign exchange (Odum, 2015). The presidential special initiative (PSI) policy in Ghana also focus on the cassava starch value chain to replace imported starch (Nweke, 2004). However, Thailand has gained prominence as the highest exporter of dried cassava chips to Europe and China (Angelucci, 2013).

Several other common traditional products are made from cassava in Africa, Asia and S. America, such as *gari, fufu* and *lafun* in Nigeria, *attieke in* Cote D'Ivoire, *tapioca* in America, *agbalima* in

Ghana, *Polvilho Azedo* (sour starch) in Brazil, *makopa* in Tanzania, *tapai* and *getuk* in Indonesia, and *shimal tarul* in India (Abass et al., 2017; Gomes, Mendes Da Silva, & Ricardo, 2005).

Table 1-3: Cassava food products and levels of inclusion of cassava flour in the food products

Cassava product	User/Industry	Level of inclusion of high quality cassava flour (HQCF) in product (%)
Bread	Bakery	5 - 25
Biscuits	Confectionery	10 – 50
Noodles	Pasta	10
Cake	Confectionery	5 - 100
Maize Semovita	Food mill	18
Chips	Confectionery, Feed mill	Not specified
Pies	Catering	10 - 100
Cookies	Confectionery	10 - 100
Chinchin	Catering, confectionery	25 - 100
Flakes	Confectionery	Not specified

Source: Adapted from Ukwuru & Egbonu (2013)

1.2 Drying

1.2.1 Principle of drying

One of the main objectives of food processing is the conversion of perishable food materials into shelf-stable products, and drying is one way to achieve this. The purposes of drying are the extension of shelf-life by preventing microbial growth and spoilage, quality improvement by minimizing color and nutrient deterioration, and ease of handling by reducing product weight, packaging and storage requirements (Erbay & Icier, 2010; Sokhansanj & Jayas, 1995). During drying, two simultaneous processes occur, including flow of energy from the drying environment to the material and transfer of mass (moisture and volatiles) from within the material to the drying environment (McMinn & Magee, 1999).

In most literature, drying and dehydration (dewatering) has been used interchangeably, and often to the confusion of the scientific audience. A distinction between both processes has been described by Keey (1972) and Mujumdar (1997) to include the different requirements for thermal energy, changes in phase, and state of final product. Usually, drying involves heat and mass transfer which leads to evaporation or sublimation where water and volatiles are removed as vapour from solids, liquid or gaseous materials by a heat exchange source such as hot air or gas, or hot surface in direct or indirect contact. Dehydration, on the other hand may involve partial or almost total removal of water and volatiles mostly from solids and semi-solids by a liquid or solid agent, with the mass transfer not necessarily achieved by heat exchange in direct contact with subject material. Drying often requires higher energy expenditure and activation energy than dehydration. The products obtained by drying could be solid, liquid or gaseous, while dehydrated products can be solid or semi-solid.

Depending on the means of heat and mass transfer, different types of drying methods have been developed (Figure 1-5), with various principles of operation by which drying is achieved.

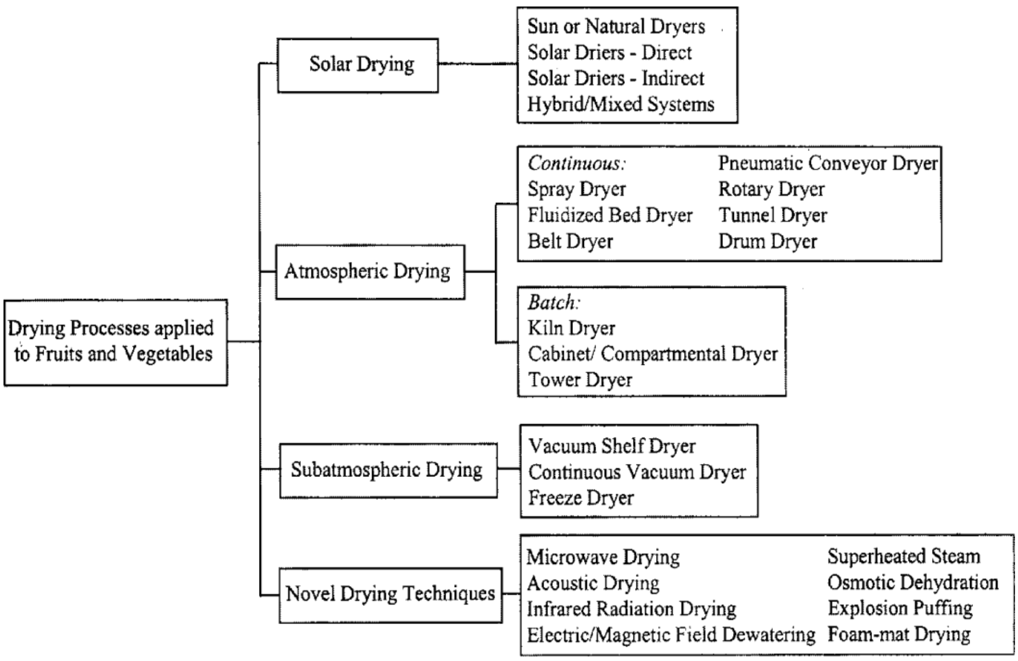

Figure 1-5: The classes of drying techniques and types of dryers (Jayaraman & Das Gupta, 1995).

The mechanisms for moisture transfer during drying include diffusion flux due to the concentration gradient, capillary action, surface diffusion from the solid matrix due to adsorbed liquid, water vapour diffusion due to partial pressure gradient, flow due to shrinkage, evaporation-condensation, liquid transport due to gravity, and water vapour flow due to total pressure gradient (Fortes & Okos, 1980). The most popular mechanisms discussed in scientific publications are diffusion and capillary action. The diffusion theory based on Fick's quantitative adaptation of the Fourier's mathematical series for heat conduction was considered by Crank (Crank, 1975), who proffered mathematical solutions based on certain assumptions. These solutions now form the basis for which most mathematical representation of diffusion during drying are expressed for materials of varying geometry.

Generally, most agricultural food materials dry in the falling rate periods (Afolabi, Tunde-Akintunde, & Adeyanju, 2015; Doymaz, 2012; Naderinezhad, Etesami, Najafabady, & Falavarjani, 2016; B. Singh & Gupta, 2007) where a sufficient energy transfer occurs, unlike the constant rate period, which primarily occurs due to high moisture contents, low drying temperature and low drying potential of the air. Two distinct falling rate periods have also been reported especially for foam-mat dried foods (Ratti & Kudra, 2006), and is attributed to microstructural changes that result in changes in the diffusional mechanism during drying. In a review (Erbay & Icier, 2010) it was identified that during the first falling rate, the primary mechanism for moisture transfer is liquid diffusion, while in the second falling rate, it is the vapour diffusion. A study has also reported an accelerating drying rate followed immediately by a falling rate for Chinese Jujube fruit (Yi, Wu, Zhang, Li, & Luo, 2012).

The kinetics of drying has developed over several decades and has been explained mathematically through a range of models. However, no single unifying theoretical model exists to describe the drying behaviour of all food materials. Erbay & Icier (2010) classified drying models into distributed models and lumped parameter models. Distributed models are those that take into account both the mass and the energy transfer and pressure differential between the interior and exterior boundaries of materials and have a better prediction accuracy to estimate mass and heat flux differences between these boundaries. In contrast, the lumped parameters models do not consider energy flux differences, but assume a uniform energy flux between drying medium and material subjected to drying, and therefore often require a smaller geometry/dimension as a single layer,

Based on the lumped parameters models, a series of theoretical, semi-theoretical and empirical models have been developed based on Fick's second law and Newton's law of cooling or their derivatives. The most common among the semi theoretical models based on Fick's law include the Henderson and Pabis model, logarithmic model, Midilli model, two-term model and their modified forms. For those based on Newton's law, Lewis model and Page model and their modified forms are well known. Empirical models, which are less prominent, include the Thompson model, Wang and Sing model, and Kaleemullah model, among others. Regardless of which model is considered, statistical criteria are often used to select the best model. Validation of selected models is required to determine the suitability of the model for the particular drying conditions.

In some review publications (Erbay & Icier, 2010; Onwude, Hashim, Janius, Nawi, & Abdan, 2016), most drying models considered have constants whose coefficients have been used to derive a range of models that can be used to predict drying kinetics data within the range of drying conditions considered. For instance, in the review, potato slices were reported to be dried at different temperatures, dimensions, and air velocity, and was simulated by 13 models of which the Midilli model was the most appropriate. The model's constants were expressed in quadratic terms of the drying variables.

1.2.2 Drying kinetics of cassava

Due to the high moisture content of cassava (about 60 %), which is primarily responsible for the rapid post-harvest physiological deterioration, it is evident that cassava requires a means to reduce its moisture content. Drying kinetics of cassava are influenced by drying temperature, relative humidity, geometry, varietal differences, air velocity, pre-treatments and drying methods. Certain preliminary operations are employed to enhance drying or to contribute to the preservation of quality of cassava. Such operations may include chipping, peeling, slicing, soaking, blanching, osmotic dehydration and sulphiting, and they may have some influence on the properties of the final dried cassava products.

Sun drying is a common method for drying cassava in the tropics due to its ease of use, favourable climatic conditions of long light-hour, and a low capital requirement. However, product quality (colour, thermo-labile and photo-labile nutrients, microbial load) is usually severely deteriorated due to exposure to contaminants, long hours of ultraviolet radiation and slow drying rate (Erbay & Icier, 2010). Tunde-Akintunde (2010) suggested solar drying as an alternative to sun drying in order to enhance the drying rate and product quality. The design of solar dryers, therefore, required an understanding of the drying kinetics of cassava. In the work, rectangular (3 cm x 3 cm) cassava cuboids were dried in the sun or solar drier after being subjected to soaking, soaking before blanching, and blanching before soaking. Four drying models (Henderson and Pabis, Newton, Page, Logarithmic) were used to fit the moisture ratio (MR) data, while diffusivity was calculated from the linear fit of transformed solution to Fick's diffusion equation. Results showed that blanching before and after the soaking pre-treatments improved the drying efficiency more than soaking alone for both drying methods. However, the drying rate occurred only in the falling rate period for sundried cassava, while constant rate and falling rate periods occurred for solar dried cassava. Page model had the best fit to the MR kinetics data. All the pre-treatments increased the moisture diffusivity, especially for the solar dried cassava. These findings were similar to a previous report made by the authors Tunde-Akintunde & Afon (2010), where cassava chips were dried at 60 ^{o}C at 1.5 m/s after undergoing the same pre-treatments.

In understanding the drying mechanism and kinetics for cassava pulp, seven thin-layer drying models were considered in drying of cassava pulp residue with 80 % initial moisture content at different temperatures (50 – 70 ^{o}C) to resolve the negative environmental impact of the effluent

(Charmongkolpradit & Luampon, 2017). The Midilli model described the moisture ratio (MR) better than other models. Drying time decreased with the increase in temperatures. Suitable empirical equations were derived by regression to predict the Midilli model parameters and the MR at a given temperature and time.

The drying kinetics measured by diffusion coefficient (D_{eff}) and activation energy (E_a) for cassava slices subjected to infrared (0 - 200 W) during convective drying at 85 – 95 ^oC were reported by Fernando, Low, & Ahmad (2011). The D_{eff} increased with temperature and infrared radiation intensity, but E_a decreased with increasing infrared intensity. Cassava had a higher E_a, D_{eff} and Arrhenius constant than other food materials like banana and pumpkin at similar drying conditions, thereby signifying greater ease of moisture diffusion and drying.

In order to produce cassava in a form that is safe and acceptable for export, Ajala, Aboiye, Popoola, & Adeyanju (2012) dried cassava chips with dimensions of 5 x 2 x 0.4 cm at 60 – 80 ^oC in a laboratory tunnel dryer, where the chips dried only in the falling rate period, after being subjected to about 30.3 kJ/mol activation energy. The drying pattern could be adequately simulated by the logarithmic model among the six models considered. Diffusion was shown to be temperature-dependent due to corresponding increases in drying temperature.

1.2.3 Foam-mat drying (FMD)

Food foam is a two-phase system including a dispersed phase and a continuous phase, which is basically produced through incorporating gases (mostly air) into liquid or semi-liquid foods (Kadam, Patil, & Kaushik, 2010; Muthukumaran, Ratti, & Raghavan, 2008). Generally, FMD involves whipping the liquid food to form a stable foam with a large surface area. The foam is subsequently subjected to diverse methods of removing moisture by drying at mild temperatures to yield free-flowing powders. However, some food materials will require the addition of a foaming agent and stabilizer to form stable foams that are subsequently subjected to drying. Foam-mat drying is an effective drying technique that has recently gained more attention because it is not susceptible to some of the major problems associated with traditional dehydration or drying methods, which may include poor rehydration characteristics of dried products, unfavourable loss of sensory appeal, long drying time, handling problems due to stickiness, poor flow or viscosity, and severe nutrient loss (Kadam et al., 2010; Mazza, 1983). This drying technique is considered an economic alternative to drum drying, vacuum drying, spray drying, freeze-drying and other drying techniques used for various foods in the production of food powders.

In foam mat drying, the porous structure of the foams, the increased surface area, and the enhanced heat transfer rate increase the drying rate and provide a higher nutritional and organoleptic quality (Lewicki, 2006). The highly porous structure usually leads to a shorter drying time and better reconstitution properties. Therefore, it is desirable for foams to consist of several small air bubbles, in a homogeneous arrangement.

Generally, several drying methods can be used to dry foams, such as spray drying, air oven drying, microwave drying, and continuous belt tray drying. The most common way of foaming is by whipping in mixers, blenders or special devices. Alternatively, air or gas sparging into liquid foods can be used to produce the foams, but this method sometimes lead to stratification, as less mechanical shear and stress is applied, which may result in incompletely dispersed and inhomogeneous air or gas incorporation (Kadam et al., 2010). A less efficient and uncommon way of foaming is by shaking, but information on this method is rare.

In spite of the advantages FMD offers, certain disadvantages have been observed. The risk of case hardening may occur if foams are not sufficiently stable during drying. Besides, the throughput of FMD compared to many other drying techniques is sometimes lower since the foams need to be spread in thin layers to achieve efficient drying. The low-density foams increase the dryer load frequency, which may be compensated for by shorter drying times (Kadam et al., 2010). Finally, foam mat dried powders may require addition of anti-agglomeration materials due to hydrophilicity and hygroscopicity of some foaming agents, thereby, increasing production costs.

1.2.3.1 Factors influencing foaming of food materials

Some variables influencing the foaming properties of foods include foaming method, concentration and type of foaming agent and stabilizer, whipping time, temperature, total solids content, and nature of food material (Kadam et al., 2010; Sangamithra, Venkatachalam, John, & Kuppuswamy, 2015).

As discussed earlier, the three common methods of foaming are whipping, sparging/bubbling and shaking, and the efficiency of air incorporation increases in the order of presentation under similar foaming conditions (Kadam et al., 2010). Most food foaming processes recorded in scientific literature are by whipping, while sparging and shaking are rare.

Hydrocolloids are important in the formation and maintenance of emulsions, which are, simply, a oil-water interfaces. Hydrocolloids also serve as thickener and gelling agent in the aqueous emulsion by altering rheology in the interface. Among the most widely used polysaccharides in foods are gums, modified starches, modified cellulose, pectin and galactomannans (Eric Dickinson, 2009). It is necessary to subdivide coarse, non-uniform and large emulsion droplets into fine, uniform, and smaller droplets by mechanical agitation such as whipping (E. Dickinson, 1994). The whipping creates a turbulent, convective mass transport, where large molecular species like starch rapidly adsorb emulsifiers at the interface.

High-molecular weight polysaccharides such as gums, pectins, alginates, algae extracts, agar, and surface-active hydrocolloids such as sodium carboxy-methylcellulose have been used in foaming, and could improve the foam stability by increasing the interfacial visco-elasticity of the lamellae (Muthukumaran et al., 2008). Proteins, however, are primarily foaming agents, for instance, albumins. The concentration of the stabilizer should be optimized for maximum drying speed and efficiency. Foam is unstable at concentrations below the critical level of stabilizer application, and a high dose of stabilizer prevents air entrapment during whipping or mechanical mixing (Bikerman, 1973; Ratti & Kudra, 2006).

The extent of the stability of a food foam can be evaluated from the amount of liquid drained from the foam. Drainage is a result of thinning of the lamellae in the foam structure, which in turn leads to a separation of the liquid phase from the interface which consequently leads to film collapse (Muthukumaran et al., 2008). Under-whipping or over-whipping based on the concentration of the foaming agent, the stabilizer, or whipping time can result in a higher drainage of foams depending on the nature of the product. Some reports on foaming of cowpea, yams, cooking banana and plantains (K. O. Falade, Adeyanju, & Uzo-Peters, 2003; Kolawole O. Falade & Okocha, 2012b; Kolawole O. Falade & Onyeoziri, 2012a) showed that longer whipping times and higher concentrations of foaming agent produced more stable foams with lower density when egg albumin is used. However, when glycerol monostearate (GMS) is used, shorter whipping times are usually required. Optimal whipping of cassava pulp into foam in the production of cassava foam powder also revealed low whipping times are better for foam expansion, foam density and foam stability (Ayetigbo, Latif, Abass, & Müller, 2019). This is because the relatively low-molecular GMS could not withstand sustained mechanical shear and stress, compared to proteins, which have the ability to fold, change conformations, increase viscosity, and provide sufficient surface activity in adsorbing more air bubbles within the foam structure. Foam collapse during aging is also due to gravity and the increase in foam bubble size as a result of merging of small bubbles, a process known as *Ostwald ripening*. A good criteria for evaluating acceptable foam stability is when the foam is uniform and does not collapse or drain significant amounts of fluid after 60 min of production (Ratti & Kudra, 2006).

The nature of the food material subjected to foaming is important in understanding its behaviour during foaming. For instance, viscosity of the product can affect stable foam formation. A highly viscous material would result in the reduction of air incorporation during whipping (Karim & Wai, 1999), but a very low-viscous material will often produce weak unstable foams with high liquid drainage. Food materials that are rich in starch such as yam, potato, banana and plantain, do not often readily form stable foams unaided (Kolawole O. Falade & Okocha, 2012b; Kolawole O. Falade &

Onyeoziri, 2012a), while okra readily produced foam due to its protein content and suitable viscous, mucilaginous nature (Kolawole O. Falade & Omojola, 2010). The effect of total solids composition was evident in the differences between the foam density of cooking banana and plantains in a report (Kolawole O. Falade & Okocha, 2012b). Under similar foaming conditions, foams of cooking banana had a lower density than plantains due to their higher starch content and total solids content.

Temperature played a role in influencing the nature of sweet potato foam produced in the study of Ismaila, Sogunle, & Adebayo (2016). The sweet potato paste was whipped at 10 – 30 °C using glycerol monostearate (GMS) and egg albumin at different levels of concentration (5 - 15 %) for various times (3 – 21 min). The foam density decreased with the decrease in temperature when egg albumin was used as foaming agent, but foam density decreased with increasing temperatures for GMS-induced foaming. This influenced the choice of GMS as the preferred foaming agent over egg albumin.

1.2.4 Foam mat drying of tubers, roots, starchy crops and other food materials

There are numerous studies on FMD of tuber and root crops and other starchy food materials, a few of which are presented in Table 1-4, showing the process conditions and notable findings.

A brief review of some studies on FMD of root, tuber crops and other starchy materials is presented here to illustrate the practical application of FMD in foods. The FMD of roots and tubers is recently gaining interest, because FMD was previously considered only ideal for fruit juices, egg, and other liquid foods. However, this has been proven otherwise by several reports on FMD of roots, tubers and starchy materials, some of which are discussed below.

The nature of drying kinetics for foamed tubers or root crops depend on a number of factors such as temperature, foam thickness, type of foaming agent or stabilizer, nature of material, and drying method. Among these factors, temperature is often the more important one. A number of studies have demonstrated these findings.

Table 1-4: Influence of process conditions on properties of some foam mat dried root and tuber crops, and other starchy crops

Crop	Process conditions	Other process conditions	Optimal process conditions	Effect on properties	Use	Reference
Beetroot	Foaming agent: egg albumen, fish gelatine	Concentration of foaming agents: 5 g/100g, 10 g/100g, drying temperature: 50 ºC, foam thickness: 3 mm, drying time: 6 h	-	Fish gelatine had better foaming power. Drying increased redness. Foaming agent concentration increases FE and FS but reduced FD	Natural food colorant	Ng & Sulaiman (2018)
Radish	Foaming agent: *Tween 80*, filler: maltodextrin	Concentration of foaming agent: 0.7 % v/v, concentration of filler: 6 – 10 % w/w, drying temperature: 50 – 70 ºC, foam thickness: 2 mm	Drying temperature: 58.5 ºC, maltodextrin concentration: 7.3 %, to produce a yield of 8.7 % and total phenol content of 7.9 %	Antioxidants content decreased with temperature and maltodextrin concentration. Quadratic response model equations predict antioxidants and yield accurately	Ready-to-cook radish powder with high antioxidant power	Kusuma, Kumalaningsih, & Pranowo (2019)
Lesser yam	Foaming agent: egg white, filler: dextrin, maltodextrin, NaCMC	Concentration of foaming agent: 2 - 10 %, drying temperature: 60 ºC, drying time: 6 hr, whipping time: 5 min, freeze and thaw cycle at -20 ºC and 8 º C respectively	0.5 % dextrin as filler, 2 % egg white concentration, precipitation temperature of -20 ºC to yield inulin of 85.8 % purity	Increase in foaming agent concentration resulted in lower yield of inulin and higher WAC of inulin. FMD improved inulin solubility and reduced particle size	Production of inulin powder	Harmayani, Winarti, & Nurismanto (2011)
White sweet potato	Foaming agent: egg white, filler: NaCMC	Concentration of foaming agent: 2 - 10 %, blanching for 0 - 1 min, drying temperature: 60 ºC, drying time: 3 h	2 % egg white, to yield 22.5 % inulin with molecular weight of 282.2 g/mol for blanched sample	Increase in foaming agent concentration resulted in lower yield, moisture content, and MW of inulin, and higher solubility and WAC of inulin especially in blanched formulation	Production of inulin powder	Yudhistira, Abigail, Siswanti, & Prabawa (2020)
Yam	Foaming agent: GMS, drying methods: cabinet drying, foam mat drying, Varieties: *Abuja*, *Efuru*	Pre-treatment by cooking for 5 min, cabinet drying: 80 – 100 ºC, 1.5 m/s. Foam mat drying: using GMS of concentration 0.005 - 0.02 % w/w, whipping time: 3 – 18 min, drying temperature: 70 ºC	Concentration of GMS: 0.02 %, whipping time: 9 min	Foam density decreased with GMS concentration and whipping time. Foam mat drying reduced drying time and browning index, but increased L*. Foam dried and fresh yams had better sensory	Instant yam flour	Kolawole O. Falade & Onyeoziri (2012a)

				appeal than cabinet dried yams when made into instant pounded yam		
Yacon	Foaming agent: egg albumin	Concentration of foaming agent: 200 g/L, concentration of juice and concentrate: 8, 24 º Brix, drying temperature: 50 – 70 ºC, foam thickness: 5 – 15 mm, whipping time: 20 min	Drying temperature 70 ºC, foam thickness 5 mm, air velocity 4 m/s	Drying condition had no effect on solubility, density, porosity and microstructure, but reduced a_w, and hygroscopicity	Yacon powder as ingredient for food preparation	T.S. Franco, Perusselo, Ellendersen, & Masson (2016)
Carrot	Foaming agent: *Tween 80*, filler: maltodextrin	Concentration of foaming agent: 0.01 – 0.3 % v/v, drying temperature: 40 – 70 ºC	Foaming agent concentration: 0.2 % v/v, drying temperature: 50 ºC to produce carrot powder of β-carotene content between 10.36 – 10.55 mg/kg	Foaming agent concentration beyond 0.2 % v/v and drying temperature above 50 ºC led to lower β-carotene content	Carrot powder rich in β-carotene	Fardiyah, Rumhayati, & Khotimah (2018)
Cowpea	Foaming agent: GMS, egg albumen	Paste concentration: 22 - 28 % TS, foaming agents concentration: 2.5 – 15 % w/w, whipping time: 3 -21 min, whipping temperature: 15 – 35 ºC, drying temperature: 60 ºC	Minimum FD at whipping time of 9 and 21 min for GMS and egg albumen, respectively	FD decreased with increase in foaming agent concentration and decrease in TS. GMS foams were more stable	*akara*	Falade, Adeyanju, & Uzo-Peters (2003)
Ripe banana	Foaming agents: GMS, soy protein, *dream whip*, gelatine	Concentration: up to 10 g/100g, puree density: 0.93 g/mL, whipping time: 0 - 12 min, foam thickness: 5 – 20 mm, drying temperature: 45 – 90 ºC, air speed: 0.62 – 1.03 m/s	Soy protein 10 g/100g, 12 min whipping, foam thickness 10 mm, drying temperature 60 ºC, air speed 0.82 m/s	Soy protein had better foaming power. Drying was governed by capillary action than diffusion and occurred at falling rate only. Air velocity had insignificant effect on drying rate	Fruit powder ingredient	Sankat & Castaigne (2004)

FE – foam expansion, FS – foam stability, FD – foam density, GMS – glycerol monostearate, TS – total solids, NaCMC – sodium carboxymethylcellulose, FMD – foam mat drying, WAC – water absorption capacity, MW – molecular weight, L* - luminousity, a_w – water activity

Talita Szlapak Franco, Perussello, Ellendersen, & Masson (2017) studied the drying behaviour of yacon juice foamed by egg albumin and an industrial emulsifier and dried at different temperatures (50 – 70 ºC) and foam thicknesses (0.5 – 1.5 cm). The moisture ratio profiles were fitted by nine thin-layer drying models. The logarithmic model giving the best fit. Coefficients of the logarithmic model parameter related to the drying constant (k) and the effective diffusivity increased with temperature, but effective diffusivity also increased with foam thickness. The foams dried only in the falling rate period, indicating that diffusion was the primary mechanism for moisture transfer. Response surface models and graphs revealed a decrease in drying time as temperature increased and foam thickness decreased.

In a previous research, the same authors (T.S. Franco, Perusselo, Ellendersen, & Masson, 2016) produced yacon juice powder from the tuberous root of yacon by whipping the yacon juice (YJ) and juice concentrate (CYJ) with the aid of egg albumin as foaming agent. The juice was dried at different temperatures (50 – 70 ºC) and foam thicknesses (0.5 – 1.5 cm) and the effect of these drying variables on the physicochemical properties and microstructure of powders was studied. A decrease in moisture content and water activity of the resulting foam powders was observed with increasing temperature and decreasing foam thickness. There was, however, no changes in the proximate composition and solubility of the foam powders as the drying variables changed. Notably, the CYJ powders had a slightly lower density and protein content and higher porosity and total carbohydrates content compared to the YJ powders due to a higher viscosity and total soluble solids, which resulted in a lower incorporation of egg albumin. Response surface model equations adequately predicted the moisture content, a_w and water absorption index of the foam powders. Also, the temperature, foam thickness and the interaction between both variables significantly influenced the a_w of the YJ foam powder; while only temperature had significant impact on the properties for CYJ.

Cultivar differences (*Abuja* and *Efuru*) and drying method (cabinet drying and foam-mat drying) played a role in distinguishing the physicochemical and pasting properties and sensory attributes of two yam cultivars in the work of Falade & Onyeoziri (2012a). The foam-mat drying was conducted as an alternative drying method to cabinet drying in producing instant yam flour in order to circumvent the disadvantages of cabinet drying such as shrinkage, colour degradation, long drying time, poor rehydration, poor texture and flavour, and significant nutrient loss. The results showed that foam-mat-dried yam foams dried in a shorter period than cabinet-dried yams and had a lighter colour (L*) and lower browning index and thus, better colour characteristics. Foam mat drying into flour also improved the peak, trough and final viscosities of both yam cultivars above that of cabinet-dried yam flour. The *Efuru* cultivar had a higher pasting temperature than the *Abuja* cultivar. Generally, pounded yam made from the foam-mat dried instant yam flour of both varieties was similar in colour and taste scores to that traditionally made from fresh yams.

Physical properties and stability of yacon foams prepared from yacon juice and concentrate for drying was influenced by the nature and concentration of the foaming agents (ovalbumin and commercial emulsifier) and whipping time according to the report of Talita Szlapak Franco, Ellendersen, Fattori, Granato, & Masson (2015). Foam density decreased significantly with an increased concentration of foaming agent and whipping time, while foam overrun and air volume fraction increased significantly. The commercial emulsifier produced greater expansion and stability of foams than ovalbumin at similar concentration levels and whipping time due to the greater ability to diffuse within the foam matrix and their relatively lower molecular weight. Micrographs of the foams revealed a high number of small sized bubbles with small diameters, which gradually lose stability over the resting time. The bubbles lose their round shapes, forming polygonal edges as the resting time increased.

Often, optimization of foaming and drying are the objectives for the foam mat drying of tuber crops. One of such studies was conducted for potato by Chakraborty, Banerjee, & Mazumder (2014) who optimised foaming of potato using variables such as drying time (5, 6, and 7 h), drying temperature (50, 55, and 60 ^{o}C) and concentration of the foaming agent glycerol monostearate, GMS (1, 2, and 3 %). The GMS resulted in the highest foam expansion and foam stability when potato puree was whipped with a GMS concentration of 2 % for 10 min. The response variables considered were final moisture content, coefficient of reconstitution, browning index, and percentage of gelatinized starch of the dried potato foam powder. Optimal conditions were obtained at a drying temperature of 60 ^{o}C using 2 % GMS dried for 135 min, which resulted in a final moisture content of 1.89 %, coefficient of reconstitution of 0.914, browning index of 0.013, and percentage gelatinized starch of 70 %. Generally, an increase in drying temperature and time resulted in lower final moisture content and an increased browning index. The foamed potato puree had a better browning index than non-foamed puree.

Sweet potato paste whipped at 10 – 30 ^{o}C using GMS and egg albumin at different levels of concentration of 5, 7.5, 10, 12.5, and 15 % for 3 – 21 min revealed that temperature and type of foaming agent had an effect on the foam density (Ismaila et al., 2016). Foam density decreased with a decrease in temperature when egg albumin was used as foaming agent, while foam density decreased with increasing temperature for GMs-induced sweet potato foams. Egg albumin-induced foams were also less stable than GMs-induced foams. The GMs-induced foams reached the lowest density at 15 % concentration, and was the preferred foaming agent.

Among the other starchy materials that have been processed by FMD are cooking banana and plantain (Kolawole O. Falade & Okocha, 2012b). The starchy crops were foamed and dried at different temperatures (60 - 80 ^{o}C) using GMS at concentrations ranging from 0.005 – 0.02 % and whipping times between 3 - 18 min. Lower foam densities were obtained when higher GMS concentration were whipped for a longer time, until about 18 min when the foam density starts to increase again. The cooking banana foams had lower densities compared to the plantain foams due to their higher total and soluble solids and starch contents. Its powder also had higher water absorption capacity than plantain foam powder. In addition, lower drying temperatures and GMS concentration resulted in longer drying times. Sensory properties of the fresh plantain and cooking banana were significantly better than those of the pastes reconstituted from the foam powders. The research showed that the variety plays a role in the different foaming and drying behaviours of the materials, and the critical concentration of foaming agent is to be considered if a foam of optimal density is to be obtained.

The drainage of foams is a measure of foam stability, and is closely related to the physical and chemical properties of the foaming agent. This was demonstrated by Carp, Bartholomai, & Pilosof (1997) who studied the stability of foams developed by whipping different concentrations (5 - 80 g/kg) of native and denatured soy protein isolate and monitoring the drainage pattern using an empirical model. The drainage profile was sigmoidal and decreased as the concentration of the protein isolates decreased. The denatured soy protein had a higher stability and lower rate of drainage over time than the native soy protein. Generally, the rate of drainage increased rapidly in about 20 min and decreased slowly afterwards until no more changes were observed. In addition, the empirical model parameters related to the sigmoidal character of the drainage profile, and the time required for half of the volume of maximum drainage to occur, were increased with protein concentration. These parameters were also higher for the denatured soy protein isolate than the native soy protein isolate.

Azizpour, Mohebbi, Khodaparast, & Varidi (2014) optimized the foam mat formation and drying of shrimps. They arrived at a conclusion that a xanthan gum concentration of 0.19 % w/w, a water-shrimp ratio of 4.5:1 w/w, and a whipping time of 5.89 min gave foam density of 0.44 g/cm^3 and a drainage volume of 1.58 mL. The drying time reduced with increasing drying temperature, and occurred mostly in the constant rate period.

It has been shown that foam mat drying can be used for a variety of food materials to achieve various purposes, which may be for sensorial reasons, quality preservation, energy efficiency or functionality.

1.3 Problem statement

The future of cassava as a leading food security and commercial crop in Nigeria, Africa and the rest of the world, is bright. With concerted research efforts, new varieties with improved yield, nutrient content, disease resistance, and other key agronomic characteristics, are increasingly developed. However, cassava is a very vulnerable crop due to its susceptibility to rapid post-harvest physiological deterioration, PPD (Ayetigbo et al., 2019). Although, recent efforts to elongate the shelf-life of freshly harvested cassava by wax-coating could delay the PPD symptoms by 14 days (Abass et al., 2017), there is still the need for long-term shelf-stability. Therefore, drying cassava in different states (chip, dice, mash, granule, strip, pulp, foam) using various drying techniques has become necessary. Many processing techniques developed to process cassava into edible products, such as fermentation, retting, soaking, grating, pressing, frying, drying, roasting, pounding, cooking, boiling, etc., sometimes result in severe nutrient loss, material loss, negative environmental impact, unsafe cyanogenic glucosides levels, unacceptable sensorial appeal, and poor functionality. A growing interest in coloured-flesh (yellow, orange, cream, red, pink, purple) cassava has presented challenges of retention of the pro-vitamin A nutrients (total carotenoids, in general) in these special breeds throughout the processing chain. In addition, the presence of cyanogenic glucosides in cassava have presented some challenges to its utilization as safe food. Most of the processing (boiling, baking, frying, roasting, steaming) and drying methods (oven drying and sun drying) when used individually to process cassava into edible foods and flour, have not satisfactorily reduced its cyanogenic potential to acceptable levels (Julie A. Montagnac et al., 2009b), except when used in a combined manner. Many white-fleshed varieties have a relatively higher cyanogenic glucosides content than most yellow-fleshed varieties (Gu, Yao, Li, & Chen, 2013), and the cyanogens are usually only satisfactorily reduced by fermentation after soaking, grating or retting, which takes considerable time, labour and equipment. Particularly, a common practice in developing countries, which involves sun drying the bulk cassava chips, often results in contaminated, poor coloured products, with heavy reliance on favourable climate disposition. Besides, other drying methods like oven drying, flash drying, freeze-drying, solar drying, etc., are not affordable for small-scale cassava processors. Hence, a simple, affordable drying method, which can satisfactorily reduce cyanogenic toxicity to acceptable levels, while retaining functionality and labile nutrients is required. Foam-mat drying was presented to resolve most of these challenges.

Many white-fleshed varieties are popularly cultivated in Nigeria and the rest of the world, but the emergence, cultivation, and acceptance of yellow-fleshed cassava and its products is still comparatively lower, in spite of its comparative advantages in nutrition (J.A. Montagnac et al., 2009) and post-harvest storability (Chavez et al., 2000; Talsma, 2014). Hence, an understanding of the comparison of various properties of white and yellow cassava varieties before and after processing is important in recommending for sustained development, production, utilization and consumption of the yellow-fleshed cassava.

In a number of developing countries where cassava plays great economic and food security roles, government policies aim at research to increase pathways for cassava utilization to drive local use and foreign exchange generation (Odum, 2015). In many cases though, cassava utilization has been restricted to a few ranges of traditionally produced cassava products usually consumed locally in the country. In light of this, foaming cassava into a foam and drying into foam powder could be introduced as a technique to process cassava into other forms that are safe, edible, shelf-stable, functional, and nutritious. Such foams or foam powders have, for instance, the potential to be included as ingredients in the production of cream-based foods like mayonnaise, sauces and ice cream.

Based on the aforementioned, the author has not found any study on foam mat drying and the comparison of the properties of foam and foam-mat dried products of white-fleshed cassava and, especially, for the recent breeds of yellow-fleshed cassava varieties developed by the International Institute of Tropical Agriculture (IITA) of the Consultative Group on International Agricultural Research (CGIAR).

1.4 Objectives and scope of research

The general objective of this study was to investigate the foam mat drying technique as a simple alternative drying technique for the processing of cassava into other forms (foam, foam powder), which are safe, have a high retention of nutrients and better functionality, which may contribute to increase the utilization value of cassava. In addition, a classic comparison of the properties of the white-fleshed and yellow-fleshed cassava varieties was made in order to determine how the varieties differ when subjected to foam mat drying.

The specific objectives were:

1. Reviewing the general properties of cassava and cassava products from the perspective of comparison between white-fleshed and yellow-fleshed cassava varieties, understanding how this affects production, processing, and utilization of the varieties, and the argument for preference of sustainability in production and adoption of yellow-fleshed cassava varieties,
2. Optimization of the process variables for foaming of a white-fleshed cassava variety and a yellow-fleshed cassava variety, the effect of the process variables on the properties of the cassava foams, and a comparison of the properties of the cassava pulp, foam and foam powder,
3. Understanding the effect of varying the drying conditions (temperature and foam thickness) on selected physicochemical properties of cassava foam from a white-fleshed cassava variety and a yellow-fleshed cassava variety during drying, and

4. Understanding and comparing the drying kinetics of foams of the white-fleshed cassava variety and the yellow-fleshed cassava variety, and estimation of the drying kinetic parameters.

In order to achieve these objectives, the scope of this cumulative dissertation was divided into three parts.

Part I focuses on a review of the comparison of properties of root, flour and starch of white-fleshed and yellow-fleshed cassava variants and the effect of processing on their properties with a view to recommending sustainable strategies for the increased consideration of yellow-fleshed cassava variants in cultivation, processing and food production. The chapter lays a foundation for the basis on which the comparisons between both types of variants was made.

Part II focuses on the preparation, optimization and characterization of foam produced from white-fleshed and yellow-fleshed cassava varieties in comparison to each other. Here, foaming was introduced as a process for the production of cassava foam and foam powder, which are uncommon forms not usually considered in the processing and utilization of cassava. The foaming process was optimized by response surface method (RSM) based on response criteria of maximum foam expansion and minimum foam density following a standard experimental design of process variables such as the concentration of foaming agent, concentration of stabilizer, and whipping time. Some properties of the cassava pulp, optimal foam and foam powder were also compared. The properties considered include colour, total carotenoids content, total cyanogenic potential, foam morphology and microstructure.

Part III focuses on studying the effect of varying the drying conditions, such as temperature and foam thickness, on the drying behaviour of the previous optimally produced white and yellow cassava foams. The drying kinetics were also studied to determine the drying pattern of the foams. The effect of the drying variables on some selected physicochemical properties of the foam powders, such as total carotenoids content, total cyanogenic glucosides content, colour, and microstructure were studied.

In conclusion, a general discussion and outlook on future prospects on cassava varieties with respect to foam mat drying of cassava was made.

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2 Part I: Comparing characteristics of root, flour and starch of biofortified yellow-flesh and white-flesh cassava variants, and sustainability considerations: A Review

2.1 Abstract

Cassava is a significant food security and industrial crop, contributing as food, feed and industrial biomass in Africa, Asia and South America. Breeding efforts have led to the development of cassava variants having desirable traits such as increased root, flour, and starch yield, reduced toxicity, reduced pest/disease susceptibility and improved nutrient contents. Prominent among those breeding efforts is the development of colored-flesh cassava variants, especially biofortified yellow-fleshed ones, with increased pro-vitamin A carotenoids, compared to the white-flesh variants. The concept of sustainability in adoption of biofortified yellow-flesh cassava and its products cannot be fully grasped without some detailed information on its properties and how these variants compare to those of the white-flesh cassava. Flour and starch are highly profitable food products derived from cassava. Cassava roots can be visually distinguished based on flesh color and other physical properties, just as their flours and starches can be differentiated by their macro- and micro-properties. The few subtle differences that exist between cassava variants are identified and exploited by consumers and industry. Although white-flesh variants are still widely cultivated, value addition offered by biofortified yellow-flesh variants may strengthen acceptance and widespread cultivation among farmers, and, possibly, cultivation of biofortified yellow-flesh variants may outpace that of white-flesh variants in the future. This review compares properties of cassava root, flour, and starch from white-flesh and biofortified yellow-flesh variants. It also states the factors affecting the chemical, functional, and physicochemical properties; relationships between the physicochemical and

Ayetigbo, O., Latif, S., Abass, A., & Müller, J. (2018). Comparing characteristics of root, flour and starch of biofortified yellow-flesh and white-flesh cassava variants, and sustainability considerations: A review. *Sustainability (Switzerland)*, *10*(9), 3089. https://doi.org/10.3390/su10093089

functional properties; effects of processing on the nutritional properties; and practical considerations for sustaining adoption of the biofortified yellow-flesh cassava.

Keywords: Yellow cassava; sustainability; cassava variants; cassava processing; carotenoids retention; amylose

2.2 Introduction

Cassava is a staple food crop for more than half a billion people in the tropical and subtropical regions of the world and mainly used as food, feed and industrial raw material (J. H. Bradbury & Holloway, 1988; Mcdowell & Oduro, 2017; J.A. Montagnac et al., 2009; Vimala, Thushara, & Nambisan, 2010). It is the sixth most important commercially cultivated food crop after wheat, maize, potato, rice and barley (J. H. Bradbury & Holloway, 1988). Cassava is a highly resilient crop that can withstand stress from drought and dry poor soils while still giving acceptable yields (J. H. Bradbury & Holloway, 1988). In addition, cassava is easy to cultivate and its roots can stay reserved in the soil for several months (J. H. Bradbury & Holloway, 1988) when the farmer's storage space is limited, thereby creating opportunity for extended harvest and sustained availability. It therefore fits description as a *survival* crop that can potentially secure food supply (J.A. Montagnac et al., 2009) and sustain livelihoods of large populations in difficult times.

In the regions where cassava is cultivated, the flesh color is traditionally white (Vimala et al., 2010). This is conventionally important to produce "white" starch or high quality flour. However, other colored-flesh cassava variants (yellow, orange, cream, and red) have emerged to challenge this supposition. In this article, the term "variant" generally refers to phenotypes, genotypes, progenies, accessions, varieties, clones, or cultivars—as the case may be in the referred literature—while yellow-flesh cassava and biofortified yellow-flesh cassava all refer to same thing. Flesh color and culinary quality have therefore become vital in the selection of cassava for food (Vimala et al., 2010). White-flesh (and other dull colored) variants have negligible carotenoid content compared to yellow-flesh variants (J. H. Bradbury & Holloway, 1988; Gegios et al., 2010; Mcdowell & Oduro, 2017; J.A. Montagnac et al., 2009). Variants with deeper color intensity have a higher carotene content (Chavez et al., 2000). Visual differences also exist between root and flour of white-flesh and yellow-flesh variants, but not for the starch.

Sub-Saharan Africa, Asia, and South America are the largest cassava producers in the world. Yellow-flesh cassava, and other biofortified cassava have considerable potential in alleviating food insecurity in developing countries (J.A. Montagnac et al., 2009). Currently, issues remain about widespread acceptance, commercial cultivation, and consumption of the yellow-flesh cassava variants despite their immediate nutritional advantage over white-flesh cassava variants. Some of the challenges have arisen from poor understanding of nutritional benefits of the colored-flesh cassava, misinformation about the nature of development of the variants as genetically modified crops, unwillingness of farmers to change cultivation pattern, and weak governmental commitment to propagation and dissemination for public awareness. These challenges could be stumbling blocks in the sustenance of cultivating yellow-flesh and other colored-flesh cassava. This is particularly unexpected since crops such as maize, potato and cocoyam have recorded relatively huge successes in this regard in the past.

Cassava generally has location-specific properties which have been discussed in the literature. At locations in Southern China, variants that are now commonly cultivated for starch include five white-flesh variants and two yellow-flesh variants (Table 2-1) (Gu et al., 2013). Indonesia also has different variants cultivated for food (Anggraini, Sudarmonowati, Hartati, Suurs, & Visser, 2009). Among those are yellow-flesh (Mentega) and white-flesh (Adira 2 and Darul Hidayah) variants (Table 2-1). A notable difference between these Indonesian variants is that all yellow-flesh variants are sweet,

Table 2-1: Studies conducted on various white-flesh and yellow-flesh cassava variants in different locations.

Location	Institution	Flesh color	Variant(s)	Use	Properties of interest	Reference
Asia						
India	CTCRI	White	*T.P white, T.P brown, I-4, Raman kappa*	Food	Good cooking quality	(Vimala, Nambisan, Thushara, & Unnikrishnan, 2009)
		Yellow	*Zoen kunnu, Chirakkarode, Narayana kappa; I-2, -3, -5, -6; Sree Visakham, NTA, Ambakkadan, Kaliyan, Kandhari padarppan; Narukku I,II,III; Kalikalan*		Good cooking quality, moderate or high carotenoids content	
Indonesia	LIPI	White	*Adira 2 and 4, Darul Hidayah, Gatot Kaca, Menti, Perelek,Aceh Utara, Manihot, Ketan,Maneot, Gebang*	Food, feed, starch, Flour, pellets	Sweet, bitter	(Anggraini et al., 2009)
		Yellow	*Adira 1, Tim-tim 29, Mangkler, Tim-tim 40, Mentega, Mentega Aceh Besar*	food, starch	Sweet	
South China	CATAS	White	*SC 5, SC 6, SC 7, SC 8, and SC 205*	Starch, biofuel	low/high MC *,high SC *, low/high HCN	(Gu et al., 2013)
		Yellow	SC 9, SC 10		high DM *, low/high SC *, low/high HCN	
America						
USA	USDA-ARS-PWA	White	Unspecified cultivar (from Las Montanas supermarket)	Food	negligible carotenoids content	(La Frano, Woodhouse, Burnett, & Burri, 2013)
		Yellow	*GM905-69* (from CIAT)		High carotenoids content retainable in blood plasma	
Africa						
Nigeria	IITA	White	*TME1, 30572, 91/02324*	Flour	White clones	(B. Maziya-Dixon, Adebowale, Onabanjo, & Dixon, 2005)
		Yellow	*01/1115, 01/1224, 01/1235, 01/1273, 01/1277, 01/1331, 01/1335, 01/1368, 01/1371, 01/1412, 01/1413, 01/1442, 01/1610, 01/1646, 01/1649, 01/1662, 01/1663, 90/01554, 94/0006, 94/0330, 95/0379, 98/2132, 00/0028, 00/0093, 01/1172, 01/1181, 01/1206, 01/1231, 01/1296, 01/1380, 01/1404, 01/1417, 01/1423, 01/1551, 01/1560, 01/1635, 01/1659, 99/2987, 99/7578, Z97/0474*		Clones of varying β-carotene content	
Nigeria	NRCRI	White	*AR-37-108, TMS 30572, CR-36-5,02/0007, CR-12-45, NR03/0155, NR02/0018, AR 1-82, 03/0174*	Gari, flour	High starch, dry matter	(Ukenye, Ukpabi, Chijoke, Egesi, & Njoku, 2013)
		Yellow	*UMUCASS 36, 37,38,* and *98/2132*		High moisture, amylose carotenoids,	
Nigeria	NRCRI	White, Yellow	*UMUCASS 36, 37, 38,* and *TMS 30572*	Fufu, flour, mash	Fermented mash and dough formation and acceptability	(Omodamiro et al., 2012)
Nigeria	NRCRI	White	*TMS 30572*	Flour, starch, bread, cake, chinchin, strips, salad cream	High starch content	(Aniedu & Omodamiro, 2012)
		Yellow	NR 07/0427, 07/0432, 07/0326, 07/0506, 07/0497, 07/0499		High starch and carotenoids	

Note: * Location and/or genotype dependent; CATAS, Chinese Academy of Tropical Agricultural Sciences; LIPI, Indonesian Institute of Sciences; IITA, International Institute of Tropical Agriculture; CIAT, International Center for Tropical Agriculture; CTCRI, Central Tuber Crops Research Institute; USDA-ARS-PWA, Western Human Nutrition Research Center; NRCRI, National Root Crops Research Institute; DM, dry matter; MC, water content; SC, starch content, dry basis; HCN, hydrocyanide content.

while white-flesh ones are either bitter or sweet. The bitter taste may not only be due to the high content of toxic cyanogenic glucosides (HCN > 100 mg/kg) in the variants, but also due to high levels of antioxidants. Hence, the yellow-flesh variant is preferred for local food preparation in Indonesia (Anggraini et al., 2009). In a bid to sustain production of improved cassava variants in Nigeria, six yellow-flesh variants were released under the IITA-HarvestPlus Project between 2011 and 2014 (IITA, 2014; Oparinde et al., 2016). The first set of released variants had a β-carotene content of 6–8 µg/g on fresh weight basis, while the second set of variants introduced had an average β-carotene content of about 10 µg/g on fresh weight basis. Several clones of yellow-flesh variants have been under investigation to select the most suitable traits for release. A total carotenoid content of almost 25 µg/g has been attained in South American variants (Ceballos et al., 2013; Sanchez et al., 2012). Sustained efforts are ongoing to develop variants with up to 15 µg/g of β-carotene (Saltzman et al., 2013). The acceptability of yellow-flesh variants is promising among farmers and consumers, as they are more stable after harvest than their white-flesh counterparts (Chavez et al., 2005). The increasing marketability of yellow-fleshed varieties, e.g. Narayanakappa in India (Vimala et al., 2010; Vimala, Thushara, Nambisan, & Sreekumar, 2011) and NR 07/0326 in Nigeria (Aniedu & Omodamiro, 2012), is documented due to the culinary value and the quality of flour and baked goods that they can yield. From a nutritional point of view, yellow-flesh variants have been used to partially meet the recommended vitamin A requirements of cassava-consuming populations. For example, in Kenya (Talsma, 2014), where every year 23,500 children die due to a deficiency of micronutrients, and where many school-aged children suffer from sub-clinical vitamin A deficiency (UNICEF, 2005), yellow-flesh cassava was used to combat these deficiencies. Adding biofortified yellow-flesh cassava to the lunch of the schoolchildren successfully improved nutrient adequacy, but additional nutritional supplement was recommended. In addition, majority of the respondents in the organoleptics aspect of the study preferred the taste, color, and texture of yellow-flesh cassava to the white-flesh one (Talsma, 2014).

Cassava flour is a valuable product obtained from cassava roots after processing. Generally, to produce the flour, cassava root is peeled, washed, chipped, milled, pressed to expel most of the toxic liquor, dried, fine-milled, and sieved. It is relatively cheap to produce traditionally. Industry-grade high quality cassava flour, however, requires improved processing inputs, which may add to the costs. Due to its special properties such as its clear appearance, low off-flavor tendency and ideal viscosity, it is regarded as a vital ingredient in the food industry (B. Maziya-Dixon et al., 2005).

Cassava starch is a highly suitable material for food and industrial use. It is edible, non-toxic, and functionally important in the food and non-food sectors of industry. Briefly, cassava starch is produced in sequence by peeling, chipping, wet milling, sieving, sedimenting, decanting, drying and pulverizing. Cassava has a high proportion (65 – 80 %) of starch (Alves, 2002; Bokanga, 2000), which is low in contaminants compared to other botanical starches (Ellis et al., 1998; S. N. Moorthy, 2002). Cassava starch embodies positive characteristics such as high paste clarity, relatively good stability to retrogradation, low protein clog/complex, swelling capacity, and good texture (Ellis et al., 1998), which makes it suitable for use in many foods. For instance, better quality bread has been made when cassava starch is included in baking (Defloor, Leijskens, Bokanga, & Delcour, 1995). Therefore, it is highly desirable to select certain variants of cassava as industrial starch source, depending on their inherent characteristics (Gu et al., 2013).

It is worth mentioning that, while cassava flour consists mostly of starch, the presence of relatively higher fiber, protein, minerals and vitamins contents in the flour compared to the starch could confer certain differences in their properties.

Several review articles have been written on the properties of cassava root starches (in native and modified forms) especially from white-flesh variants (Hoover, 2001; S. N. Moorthy, 2002; Zhu, 2015). In comparison, there has been little focus on the properties of root, flour, and starch of yellow-flesh cassava variants. It is therefore necessary to compile more information on yellow-flesh (and other colored-flesh) variants, since there is an increasing interest in the value-added, biofortified cassava variants and products derived from them. Due to issues with relatively restricted acceptance, cultivation and consumption of yellow-flesh cassava, it is pertinent to study if they are comparable to, or offer any nutritional, functional, or physicochemical advantages over the white-flesh cassava variants in a bid to argue for continued sustenance of efforts to improve its level of acceptance and adoption by the agro-allied industry and the public at large. A positive outcome could encourage public-private investments in breeding and adoption programs in Sub-Saharan Africa. Therefore, the comparison of properties of cassava root, flour, and starch is discussed from a number of literature sources, based on differing flesh colors. For instance, nutritional and chemical properties such as protein, carotenoids, minerals, starch and amylose contents are discussed. Physicochemical and functional properties such as water and oil absorption capacity, swelling power, solubility, and pasting characteristics are also discussed. Factors that influence the differences in properties and effects of processing on the variants are considered. In addition, some peculiar challenges and possible solutions in adoption of the biofortified yellow cassava in Africa are discussed with regard to issues of sustainability. Recommendations based on the review findings are made.

2.3 Methodology

This work uses an extensive review of several scientific, technical and economic literature on analysis of variants of white-flesh and biofortified yellow-flesh cassava focused on the properties of the cassava variants and how they compare to one another. Most of the studies considered were very recent (2000–2018), with very few older studies published decades ago (1959–1999). Authors sourced information from original research articles, review articles, proceedings of conferences, books, working papers and own research. No personal communication sources were consulted, and very few online sites were consulted. Data reported were based on direct values published in the literature and deductions from illustrations. While literature is fairly available on sustainability and the adoption of many improved white-flesh cassava variants with regards to disease resistance, yield, and other agronomic attributes, very few studies have reported the subject of sustainability and adoption of biofortified yellow-flesh cassava with focus on post-harvest quality. Even fewer have focused on detailed comparison of the several technical properties of white-flesh and yellow-flesh cassava variants in locations around the world with a view to arguing for its sustained cultivation, use and adoption in Sub-Saharan Africa.

2.4 Chemical properties

The literature classifies cassava root as a high calorie food (J.A. Montagnac et al., 2009; Okigbo, 1980) with a high percentage of carbohydrates (80 – 90% dry basis) consisting almost entirely of starch (Gil & Buitrago, 2002). Nonetheless, cassava root is relatively poor in other nutrients such as proteins, lipids, and vitamins (Talsma, 2014). Cassava roots generally have a high moisture content, which can differ with variants. A reliable comparison of the moisture contents between variants is possible with dry basis measurements. Most literature reports higher values of moisture contents in yellow-flesh variants. Moisture content of the respective root, flour and starch of yellow-flesh cassava variants is reported to be higher (Aniedu & Omodamiro, 2012), marginally higher (B. Maziya-Dixon et al., 2005) or significantly higher (Onitilo, Sanni, Daniel, Maziya-Dixon, & Dixon, 2007) than for those of white-fleshed variants (Table 2-2). Likewise, Ukenye et al. (2013) reported a higher dry matter content for white-flesh variants compared to yellow-flesh variants, and dry matter of starch extracted from white-flesh variants (89.04 – 96.41 %) was significantly higher than that from yellow-flesh variants (88.47 %) (Onitilo, Sanni, Daniel, et al., 2007). An association between the concentration of carotenoids and the moisture content of cassava and its products may be possible considering that, in numerous publications, the average moisture content of cassava roots,

Table 2-2: Proximate composition of cassava root, flour and starch from white-flesh and yellow-flesh variants.

Location	Flesh color	Variant(s)	MC (%)	Protein (%)	Lipids (%)	Fiber	Ash (%)	NFE	Reference
Root									
South China	White	5 [a]	57–72	-	-	-	-	-	(Gu et al., 2013)
	Yellow	2 [a]	56.4–68.5	-	-	-	-	-	
USA	White	2 [b]	-	-	-	-	-	-	(La Frano et al., 2013)
	Yellow/cream-orange	2 [b]	59.1 [α]	-	-	-	-	-	
Nigeria	White	9 [c]	57.46–75.91	2.07–7.92	0.02–3.66	0.62–4.92	0.33–1.1	89.09–95.69	(Ukenye et al., 2013)
	Yellow	4 [c]	66.19–73.49	2.75–8.10	0.29–3.2	1.07–2.14	0.55–1.04	89.50–91.52	
	White	1 [d]	71.27	-	-	-	-	-	(Aniedu & Omodamiro, 2012)
Nigeria	Yellow	6 [d]	72.05–75.26	-	-	-	-	-	
India	White	4 [e]	-	2.0–2.9	-	-	-	-	(Vimala et al., 2009)
	Yellow, orange	43 [e]	58.5–81.7	1.5–3.1	-	-	-	-	
Flour									
Nigeria	White	3 [f]	10.90–11.85	0.81–1.26	-	-	0.74–1.43	-	(B. Maziya-Dixon et al., 2005)
	Yellow	40 [f]	10.78–12.72	0.56–0.96	-	-	0.77–1.43	-	
Nigeria	White	1 [d]	-	-	-	1.63	1.15	-	(Aniedu & Omodamiro, 2012)
	Yellow	6 [d]	-	-	-	0.62–1.74	0.93–1.85	-	
Starch									
South China	White	5 [a]	-	-	-	-	-	-	(Gu et al., 2013)
	Yellow	2 [a]	-	-	-	-	-		
Indonesia	White	15 [g]	-	-	-	-	-	-	(Anggraini et al., 2009)
	Yellow	2 [g]							
Nigeria	White	39 [h]	3.59–10.96	0.23–0.7	-	-	0.03–0.49	-	(Onitilo, Sanni, Daniel, et al., 2007)
	Yellow	1 [h]	11.53	0.23	-	-	0.16	-	

Note: MC, moisture content (wet basis); NFE, Nitrogen-free extract or Total carbohydrate; α from separate lots after transport, storage, freezing, and thawing; a, eight locations, three replicates, completely randomized; b, two genotypes, two lots, one processing method, randomized tests; c, 16 cultivars, proximate analyses on dry matter basis; d, seven varieties, seven processed products; e, 43 yellow-orange flesh local clones and accessions, 8 cream-flesh clones, 4 white-flesh local clones, 10th month harvest; f, two sets, four replicates, completely randomized, three drying methods; g, 11 months at harvest, selected from 71 local and improved genotypes; h, 36 CMD-resistant and 4 non CMD-resistant varieties flour and starch usually ranks in the color sequence: yellow = orange > cream > white (Aniedu & Omodamiro, 2012; La Frano et al., 2013; B. Maziya-Dixon et al., 2005; Onitilo, Sanni, Daniel, et al., 2007; Ukenye et al., 2013; Vimala et al., 2009). Despite the relatively higher amount of moisture in yellow-flesh cassava roots, they tend to store better after harvest than their white-flesh counterparts, perhaps due to the additional anti-oxidative effect of carotenoids present (Chavez et al., 2000). This beneficial property could be appreciated by farmers, thus encouraging sustainable post-harvest practices and processing. A safe moisture limit for starch storage on the international market is 13 % (ISI, 1970; Radley, 1976b, 1976a).

The poor nutrients density of cassava (Buitrago, 1990; S. N. Moorthy, Rickard, & Blanshard, 2002; S. N. Moorthy, Wenham, & Blanshard, 1996) is exemplified in its low protein content. Compared to other roots and tubers, cassava roots have a low protein content of about 1–3 % on dry basis (Buitrago, 1990), and are particularly poor in sulfur-rich amino acids. Acidic and basic amino acids such as glutamic, aspartic and arginine are, however, relatively plentiful in cassava roots (Gil & Buitrago, 2002). Because of this, cassava diet from the roots has to be supplemented by other protein sources. Nonetheless, Montagnac et al. (2009) reported a number of attempts to improve protein in cassava by biofortification and post-harvest processing, with some recorded successes. Protein content (Table 2-2) was significantly higher in the flour of white-flesh cassava variants than in the flour of yellow-flesh variants (B. Maziya-Dixon et al., 2005). In cassava roots reported by Ukenye et al. (2013), the protein content was not significantly different between variants. Protein may be lost during processing of cassava root into flour and starch. Hence, protein content in cassava could be variant-dependent.

The fiber content of cassava roots depends on the variant and age at harvest (J.A. Montagnac et al., 2009). A relatively higher fiber content of 0.62 – 4.92 % has been found in roots of white-flesh cassava variants than in yellow-flesh and cream-flesh variants (Ukenye et al., 2013). Likewise, crude fiber in cassava flour is generally higher in white-flesh variants than yellow-flesh ones (Aniedu & Omodamiro, 2012). The difference in fiber content contributes to the higher dry matter in white-flesh variants than yellow-flesh variants. The isolation procedure undergone during starch extrication rids cassava starch of most fiber. Residual fiber influences texture and in vitro digestibility of cassava starch and flour. Cassava starch is characteristically low in fiber (0.10 – 0.15 %) and lipids (0.11 – 0.22 %) (S. N. Moorthy et al., 2002, 1996). About half the lipids in cassava roots are non-polar, or in glycolipid forms (especially galactose diglycerides), but fatty acids such as oleates and palmitates are more commonly found (Gil & Buitrago, 2002; Hudson & Ogunsua, 1974). Lipids may be involved in the retention of the lipid-soluble carotenoids in yellow-flesh cassava.

Cassava is not particularly rich in all mineral nutrients; hence, diets based on cassava alone may not fulfill adequate mineral nutritional requirement in humans. Chavez et al. (2000) analyzed 20 variants of cassava collected from several core clones and quantified the major minerals present. Average content of zinc, iron, calcium, magnesium, sodium, potassium and sulfur (dry basis) were 6.4 mg/kg, 9.6 mg/kg, 590 mg/kg, 1153 mg/kg, 66.4 mg/kg, 8903 mg/kg, and 273 mg/kg, respectively. Other minerals were only found in negligible quantities. Total phosphorus content in cassava is as low as 70–120 mg/kg of root (Rickard, Asaoka, & Blanshard, 1991). An average phosphorus content of 1284 mg/kg has been reported for cassava roots (Chavez et al., 2000), and the phosphate content did not vary by flesh color. Phosphate in starches of seven yellow-flesh and white-flesh Indonesian variants were similar, and had negligible amounts (23.5–25.3 nmol/mg) of phosphorus (Anggraini et al., 2009), attached mostly at C-3 and C-6 positions on anhydro-glucose units. In other tuber crops, especially potato, the phosphate content is relatively high, and influences a number of physicochemical and functional properties (S. N. Moorthy, 2002). However, the use of cassava in industrial food and non-food use is almost unrivalled. Due to its comparably superior solubility and paste clarity, low gelatinization temperature and low retrogradation tendency (S. N.

Moorthy, 2002), the industrial use of cassava in food applications, textile processing and in confectioneries endears it to the industry. In addition, cassava flour and starch are more popular, cheaper, and more available in commercial quantities than those of potato across regions of Sub-Saharan Africa.

Other micronutrients of more recent significance and interest in cassava are pro-vitamin A carotenoids and vitamin C. Vitamin C, which is important for mineral absorption in the gut, is found in relatively higher amounts than carotenoids in fresh cassava. For instance, among more than 500 cassava root lines evaluated by Chavez et al. (2000), vitamin C averaged 9.5 mg/100 g in fresh cassava although it is much more susceptible to losses during processing than carotenes. Minimal processing of cassava by methods susceptible to oxidation is recommended, if some vitamin C is to be retained. However, much of the processing techniques used for converting cassava to edible, safe food cannot guarantee its retention. Carotenoids are important for healthy body metabolism and disease prevention. Of the carotenoids found in yellow-flesh cassava roots, β-carotenes are present in higher concentrations than other carotenoids involved in the biosynthesis of vitamin A (Wolf, 1982). They are important micronutrients in global health issues, particularly in developing countries (Noel, 2001; Underwood, 2000; WHO, 1995). Many studies have measured carotenoids in cassava (Table 2-3) with significant differences existing between the variants. The Indian yellow-flesh variant Narayanakappa had lower total carotenoids and β-carotene (3.1 µg/g, and 2.3 µg/g, respectively) contents than three other orange-flesh variants (Vimala et al., 2010). The higher color intensity of orange-fleshed variants could indicate higher concentrations in carotenoids than the yellow-flesh cassava. The concentrations differed by variant when some processing techniques were employed (Vimala et al., 2011). Total carotenoids of roots of three yellow-flesh cassava variants from Nigeria ranged between 2.6–7.3 µg/g (average 4.9 µg/g), and varied significantly depending on the variant (Busie Maziya-Dixon, Awoyale, & Dixon, 2015). These values are close to those reported

Table 2-3: Chemical composition of cassava root, flour and starch from white-flesh and yellow-flesh variants

Location	Flesh color	Variant(s)	Starch content (dw) (%)	Sugars (%)	Amylose (%)	Carotenoids μg/g (fw)	β-carotene μg/g (fw)	HCN (mg/kg)	Reference
Root									
South China	White	5 [a]	63–83.2		-			47.4–304.7	(Gu et al., 2013)
	Yellow	2 [a]	55.1–76.5		-	-	-	68–265	
USA	White	2 [d]	-	-	-	-	0.99	5.27	(La Frano et al., 2013)
	Yellow/Cream-orange	2 [d]	-	-	-	-	8, 21.1 [α]	280, 5.51 [α]	
Nigeria	White	9 [e]	13.47–30.97 *	-	9.79–22.88 [μ]	0.51–2.29	-	-	(Ukenye et al., 2013)
	Yellow	4 [e]	14.29–20.00 *	-	13.31–24.48 [μ]	3.31–4.79	-	-	
Nigeria	White	1 [g]	29.13 *	-	-	~ 0.53	-	-	(Aniedu & Omodamiro, 2012)
	Yellow	6 [g]	11.69–29.16 *	-	-	~ 1.2–3.88	-	-	
India	White	4 [h]	-	-	-	-	-	-	(Vimala et al., 2009)
	Yellow, orange	43 [h]	-	-	-	2.0–13.6	0.7–11.1	-	
Flour									
Nigeria	White	3 [c]	70.48–82.42	2.25–3.79	18.18–20.29 [μ]	-	-	-	(B. Maziya-Dixon et al., 2005)
	Yellow	40 [c]	67.08–81.18	1.71–5.66	15.71–22.25 [μ]	-	-	-	
Nigeria	White	1 [g]	61.05 *	-	-	~ 0.15	-	-	(Aniedu & Omodamiro, 2012)
	Yellow	6 [g]	23.18–53.56 *	-	-	~ 0.6–0.88	-	-	
Starch									
South China	White	5 [a]	-	-	13.5–22.5	-	-	-	(Gu et al., 2013)
	Yellow	2 [a]	-	-	15–25	-	-	-	
Indonesia	White	15 [b]			16.8–21.3 [Ω]	-	-	-	(Anggraini et al., 2009)
	Yellow	2 [b]			17.4–20.2 [Ω]	-	-	-	
Nigeria	White	39 [f]	60.34–86.79	0.51–3.56	15.24–30.20 [μ]	-	-	-	(Onitilo, Sanni, Daniel, et al., 2007)
	Yellow	1 [f]	69.90	0.97	28.61 [μ]	-	-	-	

Note: fw, fresh weight; dw, dry weight; *, starch by wet sedimentation; α, from separate lots after transport, storage, freezing, and thawing; **Ω**, amylose by enzymatic method; μ, amylose by iodine-binding spectrophotometry; a, eight locations, three replicates, completely randomized; b, 11 months at harvest, selected from 71 local and improved genotypes; c, two sets, four replicates, completely randomized, three drying methods; d, two genotypes, two lots, one processing method, randomized tests; e, 16 cultivars, proximate analyses on dry matter basis; f, 36 CMD-resistant and 4 non CMD-resistant varieties; g, seven varieties, seven processed products; h, 43 yellow-orange flesh local clones and accessions, 8 cream-flesh clones, 4 white-flesh local clones, 10th month harvest.

(6.26–7.76 µg/g) for other variants of yellow-flesh cassava by Omodamiro et al. (2012), but considerably higher than that of white-flesh variants (0.35 µg/g). Again, root and flour from six yellow-flesh cassava variants were about three to six folds richer in carotenoids than from white-flesh variants (Aniedu & Omodamiro, 2012). Thus, the value addition offered by yellow-flesh cassava over white-flesh cassava as a vector for biofortification cannot be overemphasized. Ceballos et al. (2012) determined total carotenoid content of six variants of yellow-flesh cassava from Colombia as 8.32 – 16.40 µg/g (wb), which consists of 70% all-trans β-carotene and 5% each of the isomers 9-cis and 13-cis β-carotene. The proximal parts of the roots had a higher concentration of total carotenoids, β-carotenes, and higher dry matter than central and distal parts, signifying inhomogeneous distribution of carotenoids in cassava, and could be informative in preferred choice of parts for consumption. Visual inspection of cassava root color intensity could be used as a casual, non-empirical indicator for carotenoid concentration as conducted by Ukenye et al. (2013), where color intensity and carotenoid content ranked: yellow-flesh > cream-flesh > white-flesh. On a dry basis, total carotenoids and β carotene contents quantified for three cassava roots (Chavez et al., 2007) were 9.06 – 21.95 µg/g and 7.16 – 13.50 µg/g, respectively, with HPLC chromatograms revealing the presence of isomeric forms of carotene: 13-cis-β- carotene and 9-cis-β-carotene in relatively lower quantities. A similar study was conducted by Oliveira, Lucia de Carvalho, Nutti, Jose de Carvalho, & Fukuda (2010) for 12 bitter yellow-flesh cassava roots, where total carotenoids and β-carotene (isomeric forms: all-E-β carotene, 13-Z-β carotene and 9-Z-β carotene) ranged between 1.97 – 16.33 µg/g and 1.37 – 7.66 µg/g, respectively, while the total carotenoid content for flour of five other bitter yellow-flesh variants was 3.65 – 18.92 µg/g. Thus, carotenoids in cassava can be unstable during processing, and converted to other more stable forms. Two genes have been thought to be implicated in defining concentration of carotenes found in several cassava variants, one coding for transportation of products of precursors, and the other for accumulation (Chavez et al., 2000; Gregorio, 2002). These genes could be manipulated for breeding purposes in developing cassava of increasingly higher carotenoids content. Carotenoid concentrationin cassava can be considered a qualitative trait, determined by a few genes, and not readily repressed or promoted due to effects of the environment (Ssemakula, Dixon, & Maziya-Dixon, 2007). The study (Ssemakula et al., 2007), which describes the individual and interactive effects of genotype (G), year of cultivation (Y), and location (L) on the fresh yield and total carotenoid quality of 24 yellow-flesh and 3 white-flesh variants in Nigeria, showed that G had the strongest impact on total carotenoids, while the location was the decisive factor for high fresh weight yields. Each factor had a significant effect on both qualities, but Y and interaction effect G-L-Y were only partially significant. Interaction effects Y-L and G-L were strongly significant, but G-Y was not significant. Interacting principal component analysis (IPCA) was helpful in selecting the genotypes and locations with best strengths and minimal compromise for the targeted qualities.

Amylose and amylopectin play crucial compositional and functional roles in cassava starch, influencing properties such as crystallinity, gelatinization, retrogradation, gelling, and pasting. Cassava starch with low amylose has higher crystallinity corresponding to a reduced amorphous band (Tukomane, Leerapongnun, Shobsngob, & Varavinit, 2007), and high-amylose starch retrogrades relatively easily (Rodríguez-Sandoval, Fernández-Quintero, Cuvelier, Relkin, & Bello-Pérez, 2008). Amylopectin molecular structure, as determined by degree of branching, molecular weight, and chain length can be influenced by the activity of starch branching enzymes of different polymorphic forms (Han et al., 2004). When determined from the roots directly, amylose content of yellow-flesh cultivars was similar to that of white-flesh variants (Ukenye et al., 2013). A contrasting observation was made for other roots/tubers, such as sweet potatoes (Nabubuya, Namutebi, Byaruhanga, Narvhus, & Wicklund, 2012) and yam bean (*Pachyrhizus tuberosus*) tuber, where amylose content in yellow-flesh variants was significantly higher than in white-flesh variants

(Ascheri, Zamudio, Carvalho, Arevalo, & Fontoura, 2014). Significant difference ($P < 0.01$) was found between amylose of cassava flour of 40 yellow-flesh (15.71 – 22.25 %) variants and three white-flesh (18.18 – 20.29 %) variants from Nigeria (B. Maziya-Dixon et al., 2005), when studied for effect of drying method and variety. The difference in amylose may have partly contributed to the higher paste peak viscosity of flours from most yellow-flesh variants compared to white-fleshed ones in the study. Amylopectin plays a more significant role, however, in the pasting properties of cassava (Juliano et al., 1987). Amylose content of cassava starch varies widely between 14 – 24 % (Rickard et al., 1991), but starches of waxy (amylopectin-rich) variants may contain as low as 0 – 3.4 % amylose (Ceballos et al., 2007). Amylose of starches of seven variants from Southern China ranged from 13.5 – 24.65 %, varying significantly with location, environment, and variant (Gu et al., 2013). Among these variants, the yellow-flesh ones had similar amylose content to white-flesh ones (Table 2-3). A similar trend was found in other works (Awoyale, Sanni, Shittu, & Adegunwa, 2015; Ikegwu, Nwobasi, Odoh, & Oledinma, 2009; Onitilo, Sanni, Daniel, et al., 2007), where similar methods were used for amylose determination. Again, amylose in starches of 17 Indonesian variants was similar regardless of flesh color, ranging 17.1 – 21.3 % (Anggraini et al., 2009). No difference was found between the amylose content in starches of yellow-flesh variants (17.4 – 20.2 %) and white-flesh variants (16.8 – 21.3 %). Any variations in values of amylose content reported could be due to different methods of determination employed.

Starch content of cassava can be determined chemically or enzymatically, but starch yield is the amount of starch physically recoverable from cassava root. Total starch content (Table 2-3) of flour from 40 yellow-flesh cassava variants (67.08 – 81.18 %) was similar to that of flour of three white-flesh variants (70.48 – 82.42 %) from Nigeria, when studied for effect of drying method and variety (B. Maziya-Dixon et al., 2005). Starch yield from four yellow-flesh cassava variants was lower than starch yield from white and cream-flesh variants, with total carbohydrates following the same trend

(Ukenye et al., 2013). Again, starch extracted from six roots and flours of recently released yellow-flesh variants was lower on the average in comparison to that from white-flesh variants (Aniedu & Omodamiro, 2012). These reports indicate that the starch content of white-flesh cassava variants is significantly higher than that of yellow-flesh variants, although genotypic differences (B. Maziya-Dixon et al., 2005) and age can also cause differences in starch contents between these variants. This might reveal that there is possibly a reduced activity of granule bound starch synthase (GBBS), soluble starch synthase (SSS) and starch branching enzymes (SBE) for starch synthesis (Kossmann & Lloyd, 2000) in yellow-flesh variants.

Sugars such as sucrose, glucose, fructose and maltose have been quantified in cassava roots (Tewe, 2004). Overall, about 17 % sucrose has been found in sweet variants of cassava roots (Okigbo, 1980). Anggraini et al. (2009) found all yellow-flesh variants studied were sweet, while white-flesh variants were either bitter or sweet depending on the variant. The amount of compounds responsible for the bitterness, such as tannins and cyanogens, was significantly lower in yellow-flesh roots than in white-flesh roots (Gu et al., 2013) and may influence taste. In contrast, similar or even higher amounts of sugars have been found in some white-flesh variants compared to yellow-flesh variants (Onitilo, Sanni, Daniel, et al., 2007). In fact, Oliveira et al. (2010) has reported 17 known bitter yellow-flesh cassava variants cultivated in Brazil. Total sugars were found to be significantly higher among flours of yellow-flesh cassava variants (Table 2-3) than flours of white-flesh cassava variants in the study by Maziya-Dixon et al. (2005). Hence, this might be the plausible reason for mild to sweet taste among most yellow-flesh variants. These findings imply that the differences in variants and cultivation conditions could be strong factors influencing sugar composition in cassava.

The ash content is an important component of cassava, and is an indication of the mineral richness and non-volatiles content of cassava (J.A. Montagnac et al., 2009). Total non-incinerable matter (ash) of cassava was reported to be similar between both white-flesh and yellow-flesh variants

(Ukenye et al., 2013). Ash content reported for cassava flour and starch made from white cassava were within similar range as for yellow-flesh variants (Aniedu & Omodamiro, 2012; B. Maziya-Dixon et al., 2005; Onitilo, Sanni, Daniel, et al., 2007). Among these cassava materials, starch had the lowest ash content. Cassava leaves, however, have a significantly higher ash content than the roots (J.A. Montagnac et al., 2009). Processing of cassava has been reported to significantly reduce ash content of the roots, with a similar trend for minerals (J.A. Montagnac et al., 2009). Hence, severe processing techniques such as those involving application of high temperature and chemicals and excessive fermentation, washing and milling treatments could significantly reduce ash in cassava-dominated diets.

2.5 Physicochemical and functional properties

Cassava roots have different physiological and functional parts in various colors (Figure 2-1). Peel colors of light, and dark brown; cortex colors of pink, yellow, purple, light brown, cream, and white; flesh colors of yellow, white, and red; and root shapes of conical, cylindrical and irregular have been reported (Anggraini et al., 2009; Fukuda, Guevara, Kawuki, & Ferguson, 2010; Gu et al., 2013; N. M. A. Nassar, 2007). Water content, starch content, dry matter, cyanogen content, and tannins of roots vary with genotype, location and environmental conditions (Gu et al., 2013), and can influence physicochemical and functional properties of cassava. Due to relatively lower dry matter of cassava variants with higher β-carotene contents such as the yellow-flesh cassava (S. N. Moorthy, Jos, Nair, & Sreekumari, 1990), improving the dry matter content in yellow-flesh cassava roots is important to cassava breeders in reducing processing losses of pro-vitamin A (Ceballos et al., 2012). Reducing processing losses could enhance the sustainable adoption of yellow cassava by farmers and food processors. Reducing cassava processing losses primarily depends on root yield. Generally, root yield is considered as a polygenic trait (Cach et al., 2006; Easwari & Sheela, 1998), resulting from a number of genes expressed based on the environment in which the roots are cultivated.

(a)

(b)

(c)

(d)

Figure 2-1**:** Visual differences in: (a) cassava root size and shape; (b) cassava cortex color; (c) flesh color; and (d) peel color. Source: Anggraini et al. (2009). * Permissions for Figure 2-1(a, b) granted by Prof. (Dr.) Richard Visser; Figure 2-1(c, d) from own source.

Physicochemical and functional properties of cassava include morphology of its starch, water and oil absorption, surface color, density, swelling power and solubility, gel freeze–thaw stability, paste clarity, least gelation concentration, and pasting.

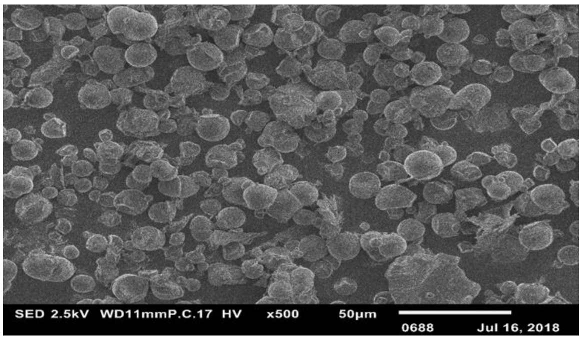
2.5.1 Morphology and crystallinity of starch

Morphology of cassava starch plays an important role in its functionality. Morphological characteristics of cassava starch are shown in Table 2-4. Light and compound microscopy, as well as electron microscopy, has been used to study morphological properties of isolated cassava starch (Nuwamanya, Baguma, Emmambux, Taylor, & Patrick, 2010). Authors have also investigated morphology of starch in cassava flour (Figure 2-2). Starch granules of seven Southern China variants grown in eight different locations had essentially similar shapes and sizes among the white and yellow-flesh variants, such as round, oval, and truncated shapes as well as a wide range of dimension (5 – 40 µm) (Gu et al., 2013). All the granules were of unimodal distribution, with sizes from 10 to 15 µm more frequently occurring than others. Granules with sizes above 30 µm were the fewest. Hence, small and medium-sized granules form the bulk class of granule types found in cassava starches. In the work of Anggraini et al. (2009), the average starch granule size of a yellow-flesh variant was similar to that of white-flesh variants. In other studies on starches, bimodal distribution was reported (Eke et al., 2009; Onitilo, Sanni, Daniel, et al., 2007) for 39 white-flesh cassava variants and 40 variants of white and yellow-flesh cassava, consisting entirely of medium sized granules with sizes ranging 12.5–22.50 µm and 12.5–24.17 µm, respectively. Tri-modal distribution has also been reported for nine Ugandan white-flesh cassava starches (Nuwamanya, Baguma, Emmambux, Taylor, et al., 2010), with medium-sized granules occurring more frequently. Therefore, whenever starch granule size is of paramount interest in industrial applications (such as in paper, textile, and pharmaceutical industries) both types of variants could be used. X-ray diffraction studies of cassava starches revealed A-type crystallinity of about 35%

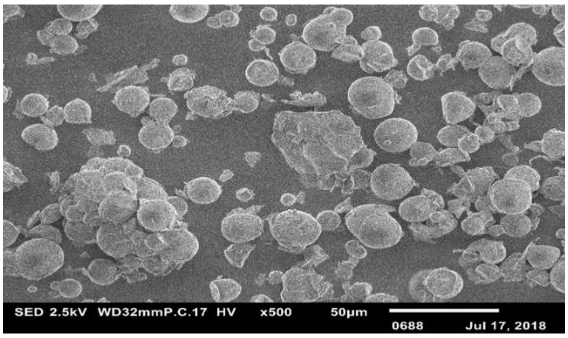
Table 2-4: Morphology and crystallinity of starch of white-flesh and yellow-flesh cassava variants.

Location	Flesh color	Variant(s)	Shapes	MGS (μm)	GSI (μm)	GMS (μm)	MS (μm)	S, M, L (%)	Reference
South China	White	5 [a]	Round, oval, truncated	-	5–40	10–15	-	33,63,3 *	(Gu et al., 2013)
	Yellow	2 [a]	Round, oval, truncated	-	5–40	10–15	-	33,63,3 *	
Indonesia	White	6 [b]	-	7.3–9.5	-	ca. 3.2–4.1	7.8–10.8	-	(Anggraini et al., 2009)
	Yellow	1 [b]	-	8.0	-	3.5	8.5	-	
Nigeria	White,	40 [c]	Kettledrum, round with indentation on one side	-	12.50–24.17	15.83, 16.67 *	-	0,100,0 *	(Onitilo, Sanni, Daniel, et al., 2007)
	Yellow	1 [c]	Round	20	-	-	-	-	

Note: MGS, mean granule size; GSI, granule size interval; GMS, granule modal size(s); MS, median size; S,M,L (%), percentage of small, medium, and large granules (separated respectively by comma) classified according to Singh, McCarthy, & Singh (2006) and Lindeboom, Chang, & Tyler (2004); *, estimated from graph/table; a, cultivars in eight locations, three replicates, completely randomized; b, 11 months at harvest, selected from 71 local and improved genotypes; c, 36 CMD-resistant and 4 non CMD-resistant varieties.



(a)



(b)

Figure 2-2: Remission scanning electron micrographs of starch granules showing shape and size of granules, and cell wall fragments in: (a) white cassava flour; and (b) yellow cassava flour. Source: authors' own source

(Defloor, Dehing, & Delcour, 1998; Nuwamanya, Baguma, Emmambux, & Patrick, 2010). Crystalline pattern of cassava starch has been reviewed by Zhu (2015). Cassava starches with higher crystallinity tend to have a higher peak viscosity, pasting temperature, and gelatinization temperature (Defloor et al., 1998), as they may require more energy to melt starch crystallites of their granules, a factor mainly determined by the nature of amylopectin present (Rodríguez-Sandoval et al., 2008; Tukomane et al., 2007). Since the literature is sparse on crystallinity of cassava starches from yellow-flesh variants, this is an area requiring more research to compare with starches of white-flesh variants.

2.5.2 Surface color

Color is an important organoleptic quality attribute, which is considered in the acceptance of crop products (Vámos-Vigyázó & Haard, 1981). Generally, yellow-flesh cassava looks more attractive than white-flesh cassava. Apart from β-carotene, other carotenoids, such as lutein, contribute to the overall color of colored-flesh cassava, as seen in red-flesh Brazilian variants (N. Nassar, Vizzotto, Da Silva, Schwartz, & Pires-Junior, 2005). Cassava flour made from cassava root retains the color of the root flesh. A reason could be that carotenoids are color-active compounds that are lipid-soluble and the color retention in flour could be due to the complex with mucilage and latex (S. N. Moorthy, 2002) as well as starch–lipid, fiber–lipid, and protein–lipid interactions. Hence, cassava flour retains a more intense color, while cassava starch made from cassava root is relatively purer in state, and has less intense color. Few studies report the color of cassava root, flour, or starch and how they relate to other properties. The Commission Internationale de l'Eclairage (CIE) L*, a*, b* color system was employed to measure tri-stimulus surface color of starch from several white-flesh and yellow-flesh variants of cassava. The L*, a* and b* values are measure of extent of lightness, redness-greenness and yellowness-blueness of the surface color of a material (Eke et al., 2009). L* values between 83.97 and 93.17 were recorded for several white-flesh and yellow-flesh cassava starches (Onitilo, Sanni, Daniel, et al., 2007). These values were close to those reported by Eke et al. (2009) for similar variants, with average L* values of 87.66 – 93.73 for two consecutive seasons. Ladeira, Souza, & Pena (2013) reported L* values of 72.43 – 81.19, a* values of -0.9 to -1.63, and b* values of 14.08 – 16.29 for three cream-fleshed Brazilian cassava roots. Similarly, L* values of 83.65 – 87.22, a* values of -0.24 to 0.33, and b* values of 3.57 – 5.02 were reported for starches of these three cassava roots. These values are quite different from L* values of 93.93 – 97.92, a* values of 0.12 – 0.23, and b* values of 0.78 – 1.30 for cassava starch, and L* values of 93.85 – 95.80, a* values of -0.32 to -0.97, and b* values of 6.07–10.22 for cassava flour of five

Ghanaian white-flesh variants (Oduro-Yeboah, Johnson, Sakyi-Dawson, & Budu, 2010). Thus, starches from cassava have higher L* values and lower b* values compared to the corresponding roots and flour, regardless of the flesh color of the variants they have been isolated from. The assumption that starches from colored-flesh cassava variants are probably colored could not be supported because the starches are much lighter and have much lower extent of yellowness than the roots and flours. Moorthy (2002) reported the color of isolated cassava starch as white, unlike from some other tuber crops. For instance, yellow color in yellow-flesh yam starch has been reported (Kolawole O. Falade & Ayetigbo, 2015). A more complete color grading from measurements of other color parameters (a*, b*, H*, ΔC, E and %W) is not reported in most works. The relationship between color and physicochemical properties is not explored in detail. Onitilo et al. (2007) found that a strong significant relationship exists between color and swelling power, solubility, and water absorption capacity of cassava starches, but no reason was given for this. An explanation could be some of the subtle physicochemical characteristics that differentiate white-flesh and yellow-flesh variants from one another as well as genetics and cultivation conditions (location, environment, climate/season, weeding, fertilizing, precipitation, etc.).

2.5.3 Density and flow properties

Loose bulk density (LBD) of high-quality cassava flour from six yellow-flesh variants was similar to that from white-fleshed ones, but packed bulk density (PBD) was higher on the average for flour of white-flesh variants (1.42 g/mL) (Aniedu & Omodamiro, 2012). Packed bulk density (0.695 – 0.703 g/mL) did not differ significantly between cassava starch extracted from three yellow-flesh variants (Awoyale et al., 2015), but was lower than that reported by (Agunbiade & Ighodaro, 2010) for white-flesh variants. A strong positive relationship was found between PBD and peak time for pasting of the starches. It could be reasoned that starches of high PBD have a low void volume, high surface area to volume ratio, and could be arrayed tightly, making disintegration of inter-granular integrity more difficult, thus, requiring a relatively longer time to reach peak viscosity. Longer peak time translates to extra production costs for the food industry, but could also be an advantage functionally, because starches resistant to rapid peak time can be useful in preserving structural integrity of foods. Granular integrity is an important element in the ability of starchy foods to absorb water (Rickard et al., 1991). Significant negative correlation has been found between PBD and water absorption of yam starches (Kolawole O. Falade & Ayetigbo, 2015).

Starches of white-flesh and yellow-flesh variants of cassava have a similar dispersibility and reconstitution index, and may require only little agitation energy for reconstitution. Addition of surfactants can greatly influence dispersibility. Awoyale et al. (2015) reported 80–86 % dispersibility for yellow-flesh cassava variants, similar to those of white-flesh variants as reported by Onitilo et al. (2007).

2.5.4 Water and oil absorption

Water absorption and oil absorption capacity entail ability of components of cassava to bind water and oil at hydrophilic and hydrophobic sites, respectively. Water and oil absorption are relevant because some major differences between white and yellow cassava variants that cassava breeders find intriguing are the relatively higher dry matter and starch in white-flesh cassava than yellow-flesh cassava (Ceballos et al., 2012; S. N. Moorthy et al., 1990), which influence water and oil absorption. Hence, the ability of the dry matter, starch, and other components to bind with water or oil films is important in studying how these interactions influence properties of cassava flour from a macroscopic point of view. Starch and other components can also form emulsions with oil and water films. In food use, oil absorption capacity of cassava starch and flour contribute to ensuring stable and uniform pastes and emulsions are formed in production of local confections and baked goods, and as anti-sticking material during cooking of pasta or frying of fishes as commonly practices in rural areas in some West African countries. In non-food use, these properties are important in formation of emulsion in paints, in textile sizing and shaping for local fashion or ceremonial wears, in soluble adhesives or gums and in release of active ingredients of drugs in vivo. This contribution to the local industry is important in sustaining livelihoods as it has created jobs for many unskilled and unemployed youths. On average, starches of three yellow-flesh variants of cassava absorbed 79.56 % of their weight of water, indicating good water absorption capacity (Awoyale et al., 2015). Significant differences among the variants indicated differences in granular interaction with water molecules. The WAC reported by Ikegwu et al. (2009) for starches of 13 white-flesh variants ranged between 59.75 – 68.02 %, but Onitilo et al. (2007) reported WAC of 86.83 – 127.54 % for 39 white-flesh cassava variants. This implies that WAC of both variant types are variant-dependent. Cassava starch has a fairly high oil absorption capacity as reported by Ikegwu et al. (2009) and Omodamiro, Iwe, & Ukpabi (2007). Little, however, is reported on the oil absorption for flour and starch of white-flesh, and yellow-flesh cassava.

2.5.5 Swelling power (SP) and solubility

Starch and flour swell when their molecular components absorb and bind water by hydrogen bonds. The swelling power of cassava starch is functionally beneficial in use as thickener in the food industry, and its solubility, in use as degradable excipients in drug delivery systems. Thickening is required in soups, gravies, baby foods, and breakfast gruels. In a study of Indonesian cassava variants (Anggraini et al., 2009), starch suspension of a yellow-flesh variant at 84 °C, swelled above thrice its volume at 64 °C; similar to starch from white-flesh cassava variants, which also swelled about two to three times its initial volume at these temperatures (Table 2-5). The cassava starches swell increasingly with temperature across all variants, and had higher swelling performance than corn starch (4 – 18 mL/g), but lower than potato starch (42 – 168 mL/g). Hence, cassava starch or flour is well suited as food thickener. Starches of higher mean granule size are deemed to have higher SP (Asaoka, Blanshard, & Rickard, 1991, 1992), but the contrary was argued for potato and

Table 2-5: Physicochemical and functional properties of starch from white-flesh and yellow-flesh cassava variants.

Location	Flesh color	Variant(s)	PC (%)	FTS (%)	SP or SI [Ω]	SOL [Ω] (%)	WAC (%)	LGC (%)	Dispersibility (%)	Reference
South China	White	5 [a]	23.2–39.6 [*]	39.6–96.7	-	-	-	-	-	(Gu et al., 2013)
	Yellow	2 [a]	23.5–30 [*]	46–95	-	-	-	-		
Indonesia	White	7 [b]	63.1 [α]	-	16–32 mL/g, 40–60 mL/g (64 and 84 °C)	-	-	-	-	(Anggraini et al., 2009)
	Yellow	1 [b]	67.6 [α]	-	18 mL/g, 56 mL/g (64 and 84 °C)	-	-	-	-	
Nigeria	White	39 [c]	-	-	9.04–16.9% (80 °C)	1.03–47.07 (80 °C)	86.83–127.54	2–4.67	82–89.5	(Onitilo, Sanni, Daniel, et al., 2007)
	Yellow	1 [c]	-	-	11.53 % (80 °C)	13.46 (80 °C)	92.34	2.67	84	

Note: PC, paste clarity; FTS, freeze thaw stability; SP, swelling power; SI, swelling index; SOL, solubility; WAC, water absorption capacity; OAC, oil absorption capacity; LGC, least concentration for gel formation; *, location dependent; α, average estimated from charts; **Ω**, swelling power (at respective temperatures in parenthesis separated by comma); a, eight locations, three replicates, completely randomized; b, 11 months at harvest, selected from 71 local and improved genotypes; c, 36 CMD-resistant and 4 non CMD-resistant varieties sweet potato starches (Chen, Schols, & Voragen, 2003; J. Singh, Kaur, & McCarthy, 2009; N. Singh & Kaur, 2004). Three improved yellow-flesh cassava variants from Nigeria had starches whose mean SP (7.46 %) and solubility (1.67 %) were low at 60 °C (Awoyale et al., 2015), signifying low interface between the starch chains in amorphous and crystalline regions. Swelling power is affected by factors such as intrinsic inter-granule binding forces, granule morphology, and amylose–amylopectin ratio (Hoover, 2001; Narpinder Singh, Kaur, Sandhu, & Guraya, 2004). Comparison of swelling power between white-flesh and yellow-flesh variants essentially depends on the genetic character of the variant studied. For instance, while white-flesh variants had higher swelling power (Kay, 1987; Onitilo, Sanni, Daniel, et al., 2007) and solubility (Eke et al., 2007; Onitilo, Sanni, Daniel, et al., 2007) than some yellow-fleshed ones, other starches of white-flesh variants with lower SP have been reported (Anggraini et al., 2009). The amylose of starch introduces a dilution effect and restricts the capability for swelling (Leach, Mccowen, & Schoch, 1959). Yellow-flesh cassava variants have been found to have similar amylose, but lower dry matter content, as discussed earlier, which could be the reason for their comparably lower swelling power. Modification of starch by chemical and physical means could significantly alter swelling and solubility properties. Little is mentioned in the literature on SP and solubility of cassava flour from white-flesh and yellow-flesh variants, but similar trend is expected as with cassava starch.

2.5.6 Paste clarity (PC)

Paste clarity of cassava is important in products requiring translucence or gloss, such as gumdrops, jellies, and paints. Cassava starch generally has a high paste clarity (Table 2-5). Paste clarity of starches of seven variants from Southern China ranged between 23.2 – 39.6 % (Gu et al., 2013). Starch paste clarity of a yellow-flesh variant (SC 10) was not different to paste clarity of starches of white-flesh variants, but one yellow-flesh variant (SC 9) showed comparably lower clarity. For Indonesian variants (Anggraini et al., 2009), starch paste clarity of a yellow-flesh variant (Mentega) was considerably higher than that of two white-flesh variants (Gatot Kaca and Ketan).

Hence, differences in paste clarity of cassava starch may not be argued from the flesh color perspective. All the cassava starch pastes became twice as turbid after six days of storage. Clarity of tuber and root starches is higher than clarity in cereal starches and the clarity of cassava starch paste ranks next only to potato starch (Achille, Georges, & Alphonse, 2007). Because of this, and its inexpensiveness, cassava starch has a long history of industrial use as glazing agent and thickener in the production of textiles and soup sauces respectively. Resultant swelling due to amylopectin leads to a viscous gel of high clarity. Polymer concentration and molecular weight have been correlated with turbidity (or clarity) of the starch (Miles, Morris, & Ring, 1985).

2.5.7 Least concentration for gel formation (LGC)

Low concentration of starch is usually required for gel formation. Therefore, LGC refers to the least amount of starch required to form a stable gel. This property is relevant to the breakfast meal and confections food industry, and in pharmaceutic excipients. Starch concentration of 2.67 % was required to form a stable gel for yellow-flesh variants, and concentrations of 2 – 4.67 % were required for starches of white-flesh variants (Onitilo, Sanni, Daniel, et al., 2007). Awoyale et al. (2015) also revealed that LGC of 4.01 – 4.06 was required for gel formation in three biofortified yellow-flesh cassava starches. Hence, yellow-flesh and white-flesh variants are quite similar in LGC. Instead, variations in amylose–amylopectin ratio, crystallinity of starch, degree of branching, and molecular weight ratio play larger roles in influencing LGC.

2.5.8 Freeze–thaw gel stability

When starches gelatinize by heating in water suspension, they lose their ordered crystalline structure and on cooling, reordering occurs, but not to the precise initial crystalline state (Hoover, 2001). Subjecting starch gel to cycles of periodic heating and cooling often results in deterioration of hydrogen bonding with water. There is a loss of hydrogen linkages resulting in readily exuded water molecules. The freeze–thaw stability of starch gels from seven southern Chinese cassava variants during storage was 39.6 – 96.7 % (Gu et al., 2013). Freeze–thaw (FT) characteristics of starch of yellow-flesh tubers among these variants varied significantly from those of the white-fleshed ones, a result connected to the starch amylose–amylopectin compositions. Freeze–thaw property was affected by location and environment, in addition to genotypic differences, although, in most locations, the yellow-flesh ones had lower FT values, and thus were less susceptible to effects of freeze–thaw cycles. The cassava starches all had poor freeze–thaw properties. For this reason, the use of cassava starch in foods requiring cold storage is restricted, unless the starch is modified. Little literature is available on FT properties of starch or flour from colored-flesh variants.

2.5.9 Textural properties

Textural properties measure strain–stress relationships of a material when a defined magnitude of force is exerted to test material strength. For starch gels, such properties include elasticity, cohesiveness, hardness, and adhesiveness. Elasticity is a measure of extent to which starch gel can be extended before disintegration, and is representative of extent of chemical bond stretching and bending among its constituents. Cohesiveness and adhesiveness are measures of intra-molecular bond strength and resistance to disintegration within the gel. Hardness of starch gel is a measure of amount of compressional force that the homogeneous starch gel can withstand before mechanical disintegration. Starch gel (5.3 % *w/v*) from white-flesh and yellow-flesh variants had closely related values of elasticity (0.52 – 0.54), cohesiveness (0.57 – 0.81), adhesiveness (1.27 – 2.27 mJ), and gel hardness (4.7 – 7.6 N) (Anggraini et al., 2009). The cassava starches formed more adhesive, but softer gel than potato and cereal starches. Adhesive property of cassava starch gel is useful in paper and cardboard manufacturing, while its elastic nature could find relevance in confectioneries, such as soft-centered jellies, gums, and baked goods. Textural properties of starch gels are connected to amylose–amylopectin interactions; intricate networking of both constituent polymers could improve gel strength.

2.5.10 Pasting properties

Pasting properties of cassava is important in studying the behavior of cassava starch or flour suspension during regulated heating, holding and cooling temperature regimes. Some pasting properties of cassava can differ significantly among variants, location, and cultivation conditions. Other pasting properties are similar between the cassava variants, and this advantage can be helpful in considering the use of yellow-flesh cassava starch or flour as substitute for white-flesh cassava starch or flour in food, and thereby enhance acceptance by industry in a bid to encourage sustained production by farmers who are less informed of the similarities. Comparing pasting properties of cassava starch or flour in the literature is complicated due to different paste concentration, method of determination, variant analyzed, and temperature regime used. Therefore, varying outcomes of paste viscosity comparisons occur, and are context-specific. Some pasting properties differ significantly between flour or starch from yellow-flesh and white-flesh variants (Table 2-6). For instance, most starch pasting properties were significantly higher for starches of yellow-flesh cassava (Awoyale et al., 2015) than for those of white-flesh cassava at similar or even higher paste concentration of white-flesh cassava starch (Eke et al., 2009; Ikegwu et al., 2009) using similar method.

Pasting temperature (PT) of starch or flour is the temperature at which a sudden rise in viscosity is first noted with concurrent swelling. A positive relationship exists between PT, water-binding capacity and gelatinization temperature. High PT relates to a restricted swelling ability (Emiola & Delarosa, 1981; Numfor, Walter, & Schwartz, 1996). Cassava flour from 40 various yellow-flesh variants, however, did not vary significantly in PT to flour from three white-flesh variants (B. Maziya-Dixon et al., 2005). Pasting temperature of starch from seven cassava variants grown in Southern China ranged between 61.7 – 69.1 °C (Gu et al., 2013). The starch pasting temperature of

Table 2-6: Pasting properties of flour and starch from white-flesh and yellow-flesh cassava variants

Location	Flesh color	Variants	PV (RVU)	TV (RVU)	BV (RVU)	FV (RVU)	SV (RVU)	PT (° C)	Peak time (min.)	Reference
Flour										
Nigeria	White	3 [b]	280.11–352.93	90.40–121.56	159.58–211.43	127.34–173.31	20.60–54.50	64.23–64.73	3.62–3.86	(B. Maziya-Dixon et al., 2005)
	Yellow	40 [b]	271.85–471.29	13.24–174.61	177.57–257.71	27.28–240.01	14.04–73.07	64.06–65.21	3.51–3.87	
Starch										
South China	White	5 [a]	187–303 BU	-	-	-	-	61.7–68.5	-	(Gu et al., 2013)
	Yellow	2 [a]	210–297 BU	-	-	-	-	63–69.1	-	

Note: PV, peak; TV, trough; BV, breakdown; FV, final; SV, setback; PT, pasting temperature; BU, Brabender unit; RVU, Rapid viscosity unit; a, eight locations, three replicates, completely randomized; b, two sets, four replicates, completely randomized, three drying methods, 10% *w/v* viscosity paste concentration.

the yellow-flesh ones was similar to that for white-flesh variants. Pasting temperature varied significantly with location and environmental conditions (Gu et al., 2013). Pasting temperature of starch of three yellow-flesh variants (Awoyale et al., 2015) averaged 76.76 °C, quite higher than the temperature for various white-flesh variants in other works (Ikegwu et al., 2009; Nuwamanya, Baguma, Emmambux, Taylor, et al., 2010; Onitilo, Sanni, Daniel, et al., 2007; Onitilo, Sanni, Oyewole, & Maziya-Dixon, 2007). The differences in amylose content may have influenced this outcome. Amylose acts as a diluent during pasting, and has been cited as being positively related with PT (Zhu, 2015). Presence of non-starch components may insulate, bind, or occlude starch from thermal effects. Low PT of cassava starch has economic advantages in saving energy costs, as less thermal energy will be expended for pasting compared to more temperature-resilient starches from potato (S. N. Moorthy, 2002), rice (Cameron, Wang, & Moldenhauer, 2007) and yam (Shanavas, 2013). Cassava starches readily lose their structural integrity when heated in solution.

Peak viscosity (PV) is an important rheological property of starchy foods, and reflects the behavior of flour and starch paste under varying shear, temperature and time. Differences in PV of cassava variants have been found in the literature. Of seven cassava variants in Southern China, peak viscosity of the starch of yellow-flesh variants varied widely to that of starches of white-flesh variants (Gu et al., 2013) depending on location and variant type. For cassava flour of 43 yellow-flesh and white-flesh variants (B. Maziya-Dixon et al., 2005), PV was similar between both variant types. Peak viscosity reported for yellow-flesh cassava starch (Awoyale et al., 2015) was higher than for starches of white-flesh cassava studied by Nuwamanya et al. (2010), Eke et al. (2009) and Ikegwu et al. (2009). Paste concentration and season of harvest may have influenced this outcome, apart from amylose content. An exception is the average PV of starch from three yellow-flesh variants from Nigeria reported as 382.14 RVU (rapid viscosity unit) (Awoyale et al., 2015), which was similar to PV of starches of white-flesh variants reported by Onitilo et al. (2007) based on similar paste concentration and method of determination.

Other tuber/root crops, for instance, *Pachyhizus tuberosus*, exhibited a similar trend, as there was no significant difference in PV when comparisons were made between yellow-flesh variants and white-flesh ones (Ascheri et al., 2014). The corresponding time required for viscosity to peak (peak time) was not different across variants of different flesh color (B. Maziya-Dixon et al., 2005; Onitilo, Sanni, Daniel, et al., 2007). Mean peak time of starch from three yellow-flesh cassava variants was 4.6 min (Awoyale et al., 2015).

Trough viscosity (TV) and breakdown viscosity (BV) are measures of resistance and disintegration of flour or starch, respectively, when exposed to temperature changes during pasting. The TV and BV of flours of white-flesh and yellow-flesh variants were within similar range, as reported by Maziya-Dixon et al. (B. Maziya-Dixon et al., 2005). For starch, a mean BV of 138.69 RVU was recorded for three yellow-flesh variants (Awoyale et al., 2015), higher than for all white-flesh variants studied by Ikegwu et al. (2009), but lower than for starches of several white-flesh variants studied by Onitilo et al. (2007) and Eke et al. (2009). High breakdown viscosity is a disadvantage in many food applications because it results in unevenly distributed viscosity (Defloor, Leijskens, Bokanga, & Delcour, 1994).

Setback viscosity (SV) can be considered a measure of tendency for flour or starch to retrograde, due to realignment of amylose molecules. Setback viscosity was within similar range between flours of yellow-flesh and white-flesh variants (B. Maziya-Dixon et al., 2005). The same was not found for starches of several white-flesh variants (Eke et al., 2009; Ikegwu et al., 2009; Onitilo, Sanni, Daniel, et al., 2007) which have generally lower SV than starches of yellow-flesh variants (Awoyale et al., 2015), with few exceptions.

The FV is characteristic for the final product quality of starch-based foods. FV was within similar range between flours of white-flesh and yellow-flesh variants (B. Maziya-Dixon et al., 2005). Final viscosity of starch of three yellow-flesh variants (Awoyale et al., 2015) surpassed those of the white-flesh variants reported so far. Again, variant-specificity influenced the differences in FV for variants studied in both works.

2.5.11 Gelatinization and retrogradation

Pure starch crystallites should melt over a narrow range of gelatinization temperatures. Starch of low gelatinization temperature is cost-effective in industrial food production as it limits energy expense. For starch of 17 Indonesian variants analyzed for their gelatinization properties (Anggraini et al., 2009), enthalpy (ΔH) of gelatinization of starch from yellow-flesh variants (11.5 J/g) was similar to, or lower than, that of white-flesh variants (Table 2-7). Gelatinization onset at 63.5 – 66.1 °C was similar for all variants studied, regardless of flesh color, and was higher than gelatinization onset of wheat (60.2 °C) and potato (61.8 °C) starches in the same study. Gelatinization temperature of cassava starches may, however, be influenced by season of cultivation, location and cultivar (Asaoka et al., 1991; Defloor et al., 1998), due to environmental factors and gene-associated factors contributing to the starch structure and composition. Although cassava flour consists mostly of starch, gelatinization temperatures (onset, peak and conclusion) reported for cassava flour was higher than for cassava starch in some studies by Defloor et al. (1994) and Hoover (2001), due to the presence of non-starch components in cassava flour. Gelatinization characteristics could be used to determine purity or adulteration of starch in the industry. The degree of association between starch crystallites, and crystalline–amorphous interactions may also explain differences in gelatinization temperatures of starch or flour (Defloor et al., 1998).

An index of retrogradation of seven Southern Chinese cassava starches varied between 52.3 – 100 % (Gu et al., 2013), indicative of high retrogradation tendencies. Retrogradation among starches of both white-flesh and yellow-flesh cassava was not different. Variant differences did not have a significant influence on retrogradation of cassava starches compared to the location and environment

Table 2-7: Thermal properties of starch from white and colored-flesh cassava variants

Location	Flesh color	Variant(s)	Location	T_o (°C)	T_p (°C)	ΔH (J/g)	Reference
Indonesia	White	*Adira 4, Darul Idayah, Gatot Kaca, Roti, Perelek, Gading merah* [a]	Indonesia	63.5 - 65.6	68.0 – 69.5	11.1–14.3	(Anggraini et al., 2009)
	Yellow	*Mentega* [a]	Indonesia	64.6	69.4	11.5	

Note: [a] 11 months at harvest, selected from 71 local and improved genotypes.

of cultivation in the study. Retrogradation is a disadvantage in use of cassava starch since the starch loses its water holding capacity, becomes irreversibly crystalline, unyielding, and undergoes syneresis.

2.6 Relationships (correlation or regression) between physicochemical and functional properties of cassava

A few studies demonstrate the relationships between physicochemical and functional properties of cassava. Flesh color has been positively correlated with total carotenoids in some works (Chavez et al., 2007; Iglesias et al., 1997). Low dry matter has also been associated with carotenoid contents of cassava variants (Jos, Nair, Moorthy, & Nair, 1990; S. N. Moorthy et al., 1990). A common theory that postharvest physiological deterioration (PPD) and shelf storability may be influenced by pro-vitamin A content of yellow cassava roots due to the anti-oxidative nature of the compounds may be true. Postharvest physiological deterioration of cassava includes vascular streaking, tissue softening, rotting, and discoloration resulting from biochemical changes. A report by Chavez et al. (2000) correlated PPD of 30 cassava variants with vitamins after six days in storage and revealed there was significant evidence to support this hypothesis, but conclusions could not be drawn since there was a low correlation. It was further established that >0.5 mg/kg carotene ensured that PPD did not result in reduction of carotene nutrients exceeding 30 %. Toxicity, as measured by cyanogenic content, varied significantly in different parts of the cassava plant. Concentration of cyanogenic compounds in the root, stem, and leaf of cassava are independent of one another because total cyanogens in those parts are influenced by age at maturity or harvest, precipitation/rainfall, genetics, fertilization, soil type, location, etc. (Aloys & Ming, 2006; Bokanga, 1994; Bokanga, Ekanayake, Dixon, & Porto, 1994; IITA, 1993).

Water absorption capacity of three yellow-flesh variants had a significant negative correlation with breakdown viscosity of the starches. A significant negative linear regression coefficient has been observed between starch granule damage and gelatinization properties of cassava starch, such as enthalpy and onset of gelatinization, especially when grown under less water stress (Defloor et al., 1998).

A study on 79 cassava variants in China revealed no relationship between amylose, peak viscosity and clarity of the starches (Gu, Li, Li, & Li, 2009), but a report by Charles, Chang, Ko, Sriroth, & Huang (2004) found correlations between these properties. The amount of rainfall cassava received during cultivation was negatively correlated to starch yield and dry matter (Gu et al., 2013), while starch content significantly correlated positively with dry matter (0.54, $p < 0.01$). In the same work, freeze–thaw stability correlated positively to retrogradation (0.355, $p < 0.05$), indicating that cassava starches that are stable to freeze–thaw cycles may not readily retrograde. Starch granule volume, and surface area correlated positively with viscosity (0.350, 0.336, $p < 0.05$).

Pasting properties of cassava as well as other tuber crops have been found to negatively correlate with protein content (Moorthy, 2002). Since amylose content is a major composition of cassava starch, there was a positive correlation with pasting temperature and peak time ($r = 0.45$). Higher proportions of amylose in the starch require longer periods to leach out of the granule matrix before complete solubilization and swelling occurs (Moorthy, 2002; Nuwamanya, Baguma, Emmambux, Taylor, et al., 2010). Starch–fiber interaction may have a negative effect on peak viscosity ($r = -0.544$) and swelling power ($r = -0.805$), but a positive correlation with pasting temperature ($r = 0.422$) (Moorthy, 2002; Nuwamanya, Baguma, Emmambux, Taylor, et al., 2010). Swelling of cassava starch is negatively correlated with pasting temperature ($r = -0.629$), but positively correlated with peak viscosity, $r = 0.588$ (Nuwamanya, Baguma, Emmambux, Taylor, et al., 2010).

2.7 Effects of processing on nutrients in white-flesh and biofortified yellow-flesh cassava roots and flour

Cassava is safe for consumption only after undergoing appropriate processing, which may include one or a combination of some treatments such as boiling, frying, fermenting, drying, baking, or size-reduction, all of which contribute to reducing cyanogenic glucosides (Ernesto et al., 2002). However, the downside of these processing operations is often a resultant reduction of nutrients, or conversion to other forms than the original nutrients. For instance, production of flour and other foods from cassava often leads to a loss of vital micronutrients, some of which are discussed below.

In a study of 28 clonal variants selected by Chavez et al. (2000) from a large genetic pool of cassava, boiling of the roots led to an average reduction of carotene by 34 %. In addition, flour produced after oven drying and sun drying lost an average of 44 % and 73 % carotene, respectively. In India, Narayanakappa, a yellow-fleshed cassava, and three other colored-flesh variants, all of high-carotene content, were processed by boiling, frying, sun drying and oven drying (Vimala et al., 2010, 2011), and the effect on the concentration of total carotenoids and β-carotene were studied. Destruction of total carotenoids and beta carotene was found to be in the order: sun drying (44 – 67 % and 43 – 79 %) > frying (20 – 51 % and 16 – 56 %) > boiling (16 – 52 % and 19 – 49 %) > oven drying (16 – 45 % and 5 – 36 %) (Vimala et al., 2011). Boiling intensified the color of the cassava chips, possibly due to starch gelatinization, however, the profound release of carotenoids from cassava matrices could also be a reason (La Frano et al., 2013). Frying depleted carotenoids, which are known to be fat-soluble. Diminished retention was highest for variant *Acc-3*, which had the highest amounts of carotenoids and β-carotene. Rapid deterioration of carotenoids during exposure to light and heat can be attributed to their sensitivity towards oxidation and isomerization. Similar results have been reported in other studies (Chavez et al., 2000; Nascimento, Fernandes, & Kimura, 2008; Oliviera et al., 2008; Omodamiro et al., 2012). Retention of carotenoids after processing is essential in adopting yellow-flesh cassava as a means of combating vitamin A deficiency in affected populations.

Other forms of processing affect retention of carotenoids in cassava. Grated cassava mash, fermented cassava mash, and fermented-cooked cassava dough (fufu) retained 97.68 – 98.48 %, 94.68 – 96.66 %, and 86.42 – 90.24 % of original total carotenoids in yellow-flesh cassava (6.26 –

7.76 µg/g), respectively (Omodamiro et al., 2012). Drying the product from the "odorless" non-fermented method resulted in a significant loss of carotenoids, the severity being higher with sun drying than oven drying. Generally, the acceptability of *fufu* by sensory panelists, in terms of color, was best with the traditional method (Omodamiro et al., 2012), because the method enhanced carotenoids retention better than sun drying and oven drying methods.

Evaluation of retained micronutrients, such as zinc, iron and total carotenoids, was made after three yellow-flesh cassava variants TMS 01/1371, 01/1235, and 94/0006 were processed traditionally by four methods: boiling, fermenting (raw fufu), fermenting and cooking (cooked fufu) and fermenting and roasting (gari) (Busie Maziya-Dixon et al., 2015). Boiling led to losses of about 4 – 52 % of carotenoids, 3.6 – 20.6 % of iron, and 2.7 – 21.7 % of zinc. Fermentation significantly increased the average carotenoid content of the cassava roots from 4.9 µg/g to 8.64 µg/g according to wet basis measurements. A possible reason could be that, as major compositions of cassava (carbohydrates, moisture, and fiber) reduce by hydrolysis during fermentation, the proportion of other minor compositions such as carotenoids will apparently increase. Dry basis measurements could have given a more accurate trend of what transpired during processing (Ortiz et al., 2011). Fermentation also significantly reduced the average iron and zinc content from 7.47 mg/kg to 7.13 mg/kg, and 8.95 mg/kg to 5.58 mg/kg, respectively. Fermentation leaches minerals due to the acidic nature of fermentate (fufu), and oxidative activities of microbes that use these micronutrients for development and growth. Boiling fermented cassava paste to achieve a doughy consistency further led to a reduction in the average carotenoid (3.64 µg/g) and zinc content (6.23 mg/kg), thus retaining less carotenoids (21.5 %) and zinc (34.1 %) than the uncooked paste. Only 32.5 % iron was retained. The high temperature employed may have resulted in the rapid oxidation, isomerization, and destruction of vitamin A precursors (Boon, McClements, Weiss, & Decker, 2010; Rodriguez-Amaya, 1997; Smolin & Grosvenor, 2003), and leaching of the minerals. Again, fermenting and subsequent roasting (gari) was reported to increase average carotenoids and iron of three yellow-flesh variants from 4.9 µg/g to 10.6 µg/g, and from 7.5 mg/kg to 8.2 mg/kg, respectively. This is due to the dry nature of gari, and the fresh weight basis by which the determinations were made. Hence, the increase in the carotenoids and iron content was not an increase in actual amounts. There was an average retention of about 45 % and 22 % of carotenoids and iron, respectively, while 90 % of zinc was lost. Heating, increase in surface area, and agitation (Agarwal, Shen, Agarwal, & Rao, 2003; Clinton, 2009; Dewanto, Wu, Adom, & Liu, 2002; Schierle et al., 1997; Stahl & Sies, 1992, 1996; Xianquan, Shi, Kakuda, & Yueming, 2005) during gari production may have increased carotenoids available for quantification. Chopping (to increase surface area) and brief heating of colored-flesh cassava roots was adjudged to have contributed to the bioavailability of carotenoids and vitamin A by disrupting cell wall and protein–carotenoids complexes (La Frano et al., 2013).

High performance liquid chromatograms (Ceballos et al., 2012) revealed that boiling can reduce total carotenoids and all-trans-β-carotenes of yellow-flesh cassava from 32.6 µg/g to 27.2 µg/g and 22.7 µg/g to 15.3 µg/g, respectively, on dry weight basis. The reduction of all-trans β-carotenes has been characterized as isomerization to 13-cis and 15-cis-β-carotene in boiled cassava (Ceballos et al., 2012; Thakkar, Huo, Maziya-Dixon, & Failla, 2009). Dry matter also reduced from 34.4 % to 29.7 % after boiling for 30 min. However, high retention (86.6 %) of total carotenoids was observed in the work (Ceballos et al., 2012), and it was postulated that high dry matter in yellow-flesh variants might enhance retention of carotenoids in general.

Individual and interaction effects (Chavez et al., 2007) of variants and processing methods showed significant differences in the retention of β-carotene among yellow-flesh cassava variants. This is an important criterion in the selection of variants to be adopted for vitamin A bio-fortification. A ranking of the processing methods vis-à-vis β-carotene retention was: oven drying (71.9 %) > shadow drying (59.2 %) > boiling (55.7 %) > sun drying (37.9 %) > gari production (34.1 %). Storage of cassava up to four weeks in any form (flour, chip or root) after sun drying and oven drying resulted in reducing the retained β-carotene by slightly above 50 %, depending on the severity of size-reduction (flour > chip > root). Vacuum storage reduced residual β-carotene, possibly due to the permeability of packaging used, and not as a result of the vacuum created. Generally, a reduction of oxygen species in an environment could deter oxidation of carotenoids.

Processing of five bitter yellow-flesh variants of cassava from Brazil (Oliveira et al., 2010) to flour reduced total carotenoids by an average of 50 %, with further reduction of 33–99 % during storage for up to 19 days. By the fourth week in storage, total carotenoids of the variants had completely diminished.

Processing could, in addition, lead to a reduction of cassava toxicity. Breeding to reduce toxicity is an ongoing sustained effort by scientists and breeders in research institutes in Africa and Asia. La Frano et al. (2013) determined toxic cyanogenic contents of white-flesh (5.27 ppm) and yellow-flesh (5.51 – 280 ppm) cassava variants for safety reasons, and found a complete absence after they were processed by boiling into porridge, while 99 % and 96 % of β-carotene was retained, respectively. Generally, white-flesh cassava variants have a negligible β-carotene content, losing less than 1 % during boiling (La Frano et al., 2013), but variants with a high initial carotene content lose it much more readily during processing (Chavez et al., 2000, 2007). Furthermore, in the work of Diallo et al. (2014), three cassava variants in Senegal were processed into four products—chips, flour, gari, and attieke—and their cyanide concentration (wb) was evaluated for the extent of detoxification. The chips retained 15.1 – 51.6 % of cyanogenic toxicity, but gari, flour and attieke retained as low as 0 – 1.8 %, 0 – 2.8 %, and 1.1 – 5.4 % cyanogens, respectively. These levels were below the allowed toxicity recommendation (<10 ppm) of the Codex Alimentarius Commission (FAO, 1991) for cassava flour, and are thus regarded safe for consumption.

In Nigeria, value-addition has been achieved in using yellow-flesh variants in producing gari instead of the traditional practice of adding red palm oil to the white cassava granules to improve the vitamin A content of the food. Not only are production costs reduced, but a healthy form of fortification is also acquired by the yellow-flesh variants with yields close to the white-flesh ones.

From a culinary and health/nutrition perspective, adding palm oil may not be acceptable in gari due to phase separation in water-based processes as well as for cholesterol-related issues.

Vitamin C retention is very low in processed cassava roots and flour. Only 36.6 %, 6.2 %, and 0.005 % of vitamin C was retained after boiling, oven-drying and sun drying, respectively (Chavez et al., 2000). Pregnant women, lactating mothers and children (Black et al., 2008) need the vital minerals (iron and zinc) and pro-vitamin A to prevent anemia, diarrhea, stunted growth, and defective eyesight. Evidence from trials with American women (La Frano et al., 2013) and Kenyan children (Talsma, 2014) has shown that feeding biofortified cassava is more efficient in the bioavailability of pro-vitamin A compounds than white-flesh cassava. Some new yellow-flesh cassava roots in Nigeria could potentially supply about 25 % of the daily vitamin A requirement if consumed in sufficient amounts (Aniedu & Omodamiro, 2012). Hence, processes retaining much of these micronutrients are beneficial, especially when losses are unavoidable (Ceballos et al., 2012). An indirect, but efficient way to reduce nutrient losses in cassava during processing could be to significantly improve the nutrient content of the raw, unprocessed crop. Efforts to achieve this by biofortification in increasing the protein, minerals, starch and β-carotene concentrations in cassava, has been reported (J.A. Montagnac et al., 2009). This has been the focus of majority of cassava breeders in research institutes in Africa and Asia. Post-harvest technique, such as solid-state fermentation has also been used to increase protein in cassava (Iyayi & Losel, 2001). In addition, minimal processing sufficient to make cassava edible and safe should be encouraged. Excessive fermentation, drying, boiling, cooking, retting, and frying cause major losses in nutrients (J.A. Montagnac et al., 2009), and should be avoided.

2.8 Practical considerations for sustainability in adoption of biofortified yellow-flesh cassava

To argue for the sustained cultivation of biofortified yellow cassava and the production, utilization and consumption of its products, it is important to have detailed information on properties of the biofortified variant in comparison to the conventional white-flesh cassava. The arguments focus on the advantages offered by the biofortified variants, such as substitutability, nutrition, safety for consumption, storage life and relative ease of harvest and post-harvest handling. Many of the data discussed in this work show that biofortified yellow-flesh cassava can be a suitable, and arguably better, substitute compared to the conventional white-flesh cassava. The argument can be made based on the considerations discussed below, which has evidently, and can potentially, make biofortified yellow-flesh cassava more sustainable in many aspects than white-flesh cassava.

First, biofortified yellow-flesh cassava root, flour and starch has many similar physicochemical and functional properties as found for those of white-flesh cassava, and can, therefore, serve as a substitute in any products derived from white-flesh cassava root, flour and starch. This flexibility in utilization is not possible for white-flesh cassava when pro-vitamin A nutrition is of concern, making this additional advantage of nutrition a case for sustained utilization and consumption of biofortified yellow cassava as food. This was already demonstrated by Talsma (2014) in a school children feeding program in Kenya. In addition, the development of biofortified yellow-flesh cassava has evidently explored possibilities of creating value-added cassava variants without genetic modification which is still contended as ethically unacceptable. Biofortification is considered sustainable because it requires a one-time investment only, which further allows farmers flexibility in cultivation. This curbs complete dependence of farmers on manufacturers for cultivation materials supply, as is usually associated with genetically modified crops. Such flexibility is enhanced by the value addition offered by yellow-flesh cassava regarding amount of vitamin nutrient per hectare cultivated. The biofortified cassava can reach subsistent poor farmers and people in remote areas where supplementation programs, which are usually more expensive and unaffordable, scarcely reach (Saltzman et al., 2013).

Second, most biofortified yellow-flesh cassava variants are sweet tasting, containing mild-to-moderate toxic cyanogenic glucosides compared to the majority of white-flesh variants (Gu et al., 2013). Lower concentrations of the toxic compound can guarantee sustainable production plans by reducing time and labor for detoxification during processing, ultimately leading to production of safer foods. In addition, lower toxicity levels could reduce toxic residues in soil and environment of rural communities and urban centers of Africa where large quantities are regularly processed. This issue is of considerable concern to proponents of environmental sustainability since the run-off from these processing centers often result in pollution and contamination of nearby water bodies and the disruption of natural ecosystem of plants and animals.

Third, post-harvest storage of biofortified yellow-flesh cassava is more sustainable, due to its robust and longer shelf-stability (Chavez et al., 2000; Talsma, 2014) compared to white-flesh cassava. This implies it can secure longer availability periods, while the farmer awaits or is engaged in a new planting cycle. Ongoing unpublished research by the authors has observed that properly waxed yellow-flesh cassava roots have much longer storage life and acceptable quality at 3 – 5 months in refrigeration at 3 °C, than waxed white-flesh cassava roots which developed unacceptable quality after 3 – 5 weeks under similar conditions.

Fourth, harvesting and post-harvest handling of some variants of biofortified yellow-flesh cassava has been reported to be less tedious than for white-flesh cassava. Farmers' response to surveys reveal they were easier to harvest and peel (Gonzalez, Perez, Cardoso, Andrade, & Johnson, 2011) than conventional white-flesh cassava. This advantage could reduce labor and energy costs, making manual or commercial harvesting and peeling more sustainable.

This work therefore explored comparison of the properties of both variants of cassava for the purpose of assisting farmers, processors and other interest groups in making informed choices on variants with sustainable properties. It may be surmised that, in the near future, the popularity of yellow-flesh cassava may outpace that of the conventional white-flesh cassava (Ilona, Bouis, Palenberg, Moursi, & Oparinde, 2017) if some measures are taken strategically. Such measures should include a more committed and robust coordination of national governments programs, research groups, and other cassava stakeholders in ensuring rapid and widespread re-orientation, adoption and dissemination of the biofortified yellow cassava and its products to the public. In addition, encouraging market-based approach in cassava value chain to attract private investors (Ilona et al., 2017; Oparinde et al., 2016) can be helpful.

While the adoption of biofortified orange-flesh sweet potato in Sub-Saharan Africa has achieved remarkable success in countries including South Africa, Mozambique, and Uganda, such cannot be said yet of the biofortified yellow cassava. Originally, pro-vitamins-rich cassava existed in the Amazon regions of South America. They were subsequently bred (Chavez et al., 2005; Iglesias et al., 1997) and introduced to African countries including Nigeria and Kenya through research cooperation of the International Center for Tropical Agriculture (CIAT), Colombia and the International Institute of Tropical Agriculture, Nigeria. More successes seem to have been achieved in South America regarding the yield, nutrients density (Chavez et al., 2000; Ilona et al., 2017) and public acceptance of biofortified yellow cassava variants than in Sub-Saharan Africa. For instance, in northeast Brazil, a survey of 760 farmers reveal 28 % of farmers already preferred yellow cassava variants, with about 70 % of them been familiar with the yellow varieties (Gonzalez et al., 2011). About 15 % of the farmers cultivated the variants as early as the first year of release of the variants. Nevertheless, few successes in acceptance of biofortified yellow cassava in production of gari and fufu, for instance, has been reported in Oyo and Akwa Ibom regions of Nigeria (Ilona et al., 2017)]. One major gap that continues to hamper the adoption of the biofortified variants is the weakened state of the extension service in the agricultural sector of some African countries, for instance, Nigeria (Oparinde et al., 2016).

2.9 Conclusion and recommendation

Overall, the physical properties of starch from white-flesh and yellow-flesh variants of cassava are largely similar. Morphology, thermal, crystallinity, color, and flow properties are also similar. Color differences between root and flour of white-flesh and yellow-flesh cassava are significant. However, some chemical, pasting and physicochemical properties vary significantly between the white-flesh and yellow-flesh cassava variants. Amylose content, starch content, dry matter, carotenoids, β-carotene, peak viscosity, setback viscosity and final viscosity reported in several works show variant-specific differences in these properties. Genetics play the biggest role in determining differences in characteristics between white-flesh and yellow-flesh cassava and their products. Modification of cassava flour, and its effects and benefits have not been exhaustively researched. Colored-flesh variants increasingly have the potential of matching prevalence of white-flesh variants in the future if propagation and dissemination of research results is sustained. In retrospect, the authors recommend yellow-flesh cassava for commercialized cultivation because the yellow-flesh cassava variants have largely similar properties as white-flesh cassava variants, are nutritionally valuable in some respects, and store better after harvest than white-flesh cassava. Therefore, breeding efforts to bridge the gaps in properties observed in both types of variants could hold the key to nutritional and functional uses of yellow-flesh cassava just as much as white-flesh cassava. In Sub-Saharan Africa, the challenges with adoption of the biofortified yellow-flesh cassava by farmers and the public is particularly exacerbated by conservative attitude of farmers, unwillingness to try new methods or crops, poor understanding of the advantages it offers compared to the white-flesh cassava, misinformation on the origin of biofortified variants as genetically modified, and poor commitment of the governments to consistently develop agricultural policies and extensions that will drive acceptance of the biofortified variants. Some measures suggested to resolve these challenges are serious commitment of national and regional governments in promoting the biofortified variants, nationwide dissemination of success stories of adoption, upscale of knowledge on the variant to the farmers and the public and subsidies-for-adoption programs. In addition, research bodies in Sub-Saharan Africa need to adopt workable blueprints already achieving better successes in South America and Asia with regards to development of improved biofortified variants of higher yield and nutrients density to make their cultivation more sustainable.

2.10 Author contributions

Conceptualization, O.A., S.L., and J.M.; Resources, O.A.; Data Curation, O.A.; Writing—Original Draft Preparation, O.A.; Writing—Review and Editing, S.L., A.A., and J.M; Visualization, J.M.; Supervision, S.L., A.A., and J.M; Project Administration, J.M., A.A; and Funding Acquisition, S.L., A.A., and J.M.

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2.13 Conflict of interests

The authors of this work declare no conflict of interests in preparation and publication of this article. The article is an original work, and does not infringe the intellectual property rights of any other person or entity, hence, cannot be construed as plagiarizing any other published work.

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3 Part II: Preparation, optimization and characterization of foam from white-flesh and yellow-flesh cassava (*Manihot esculenta*) for powder production

3.1 Abstract

Cassava foam, another form in which cassava may potentially be used as food, was produced from the pulp of yellow-flesh and white-flesh cassava varieties by whipping with foaming agent (20 %w/w glycerol monostearate colloid, GMS) and stabilizer (sodium carboxymethyl cellulose, NaCMC). Cassava foaming was optimized for concentration of foaming agent, stabilizer and whipping time. Using Box-Behnken experimental design, two responses were measured: foam expansion (FE, %) and foam density (FD, g/mL). White-flesh cassava pulp required 14.97 % GMS, 0.51 % NaCMC and 2.07 min to give a foam of 52.63 % expansion and density of 0.75 g/mL. Yellow-flesh cassava pulp required 14.29 % GMS, 0.6 % NaCMC and 2 min to yield a foam of 48.25 % expansion and density of 0.76 g/mL. Predicted optimal FE and FD were 54.9 % and 0.73 g/mL for white-flesh cassava foam, and 49.86 % and 0.73 g/mL for yellow-flesh cassava foam, respectively, and are close to validated values. The optimal foams were quite stable after 4 h at 25 ± 2 °C, with low volume collapse of 1.79 % and 1.26 % for white and yellow cassava foams, respectively. The optimal cassava foams were dried into foam powder. There was significant difference in color values (L*, a*, b*, C*, E*, H*, % W, $\Delta E^{*}_{yellow-white}$) and total carotenoids content of pulp, optimal foam, and powder of both varieties. Microstructure analysis of the optimal foams revealed round air bubbles and positive skewed distribution of bubble sizes. Foaming and drying significantly reduced total cyanogenic potential in cassava, and may be considered as processing operations capable of reducing cyanogenic potential in cassava considerably.

Keywords: Glycerol monostearate; Cassava foam; Response surface method; Foam-mat drying; Carotenoids; Cyanogenic potential

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3.2 Introduction

Cassava root is susceptible to rapid post-harvest physiological deterioration. Hence, reducing its postharvest loss and expanding its utilization would be in harmony with the evolving policies to expand its food and non-food uses in some developing countries, such as Nigeria and Ghana. Cassava foam is another form in which cassava can be utilized in food, apart from the traditional food and feed uses of cassava in the form of flour, starch, granules, chips or pellets. In literature, roots, tubers or starchy crops, such as yacon (Talita Szlapak Franco et al., 2015), yam (Kolawole O. Falade & Onyeoziri, 2012a) and banana (Sankat & Castaigne, 2004) have been processed by foaming. The use of cassava starch with other constituents (like fiber, proteins, oil) for formation of biodegradable foam for packaging of foods has been reported (Kaisangsri, Kerdchoechuen, & Laohakunjit, 2012, 2014; Salgado, Schmidt, Molina, & Mauri, 2008), but not much has been reported on direct use of cassava foam in making edible foods or food ingredients.

Food foams are two-phase systems involving homogeneously dispersed gas in continuous liquid phase (Vernon-Carter, Espinosa-Paredes, Beristain, & Romero-Tehuitzil, 2001). Foam mat drying is increasingly being considered recently by food scientists due to the inherent advantages it provides (Franco, Perussello, Ellendersen, & Masson, 2017; Qadri, Srivastava, & Yousuf, 2019; Qadri & Srivastava, 2017). Of the many factors influencing food foam properties, the characteristics of foaming agent, whipping time and nature of incorporated gas and liquid phase play greater roles (Karim & Wai, 1999). Fatty acids with glyceryl moieties, such as glycerol monostearate, have ability to assist foam formation in foods by reducing surface tension (Campbell & Mougeot, 1999) and forming hydrophobic-hydrophilic interactions within foam films. Methyl cellulose derivatives, such as sodium carboxymethyl cellulose (NaCMC), however, have stabilizing power to maintain foam films just like in emulsions. Both hydrocolloids have been used in food foam applications to assist in foam development and stability prior to drying, thus restricting foam collapse and non-uniform drying (Karim & Wai, 1999). Whipping cassava into foams may present a non-conventional form in which cassava can be used directly in edible foam-based or cream-based foods without starch extraction, which requires additional energy, labor and environmental impact from residues. Drying of food foams can result in instant powders with high shelf stability, low water activity, high functionality, high reconstitution power and lower storage volume and mass. The powders may have quite different properties from the traditional flour commodity (Kolawole O. Falade & Onyeoziri, 2012a; Karim & Wai, 1999; Raharitsifa, Genovese, & Ratti, 2006). Moreso, traditional drying method of bulk cassava chips by sun drying or oven drying usually result in less attractive color development (Kolawole O. Falade & Onyeoziri, 2012a) and probably more rapid loss of carotenoids compared to foam drying which may offer better retention of carotenoids in yellow cassava during drying due to protection of the carotenoids in the foam matrix. Foaming prior to drying may also contribute significantly to reduction of cyanogenic glucosides in cassava since it requires a finer comminution or size reduction to rupture cell matrix and create larger surface area for intricate contact between linamarine and linamarase. This detoxification is usually not efficient when cassava is sun-dried or oven-dried as bulk material.

Recently, yellow-flesh varieties of cassava were bred and disseminated to farmers by research institutes of the Consultative Group on International Agricultural Research (CGIAR) to combat vitamin A deficiency in developing countries of Africa, Latin America and Asia. The yellow cassava variety has been found to have significantly higher total carotenoids content but lower starch content and dry matter than the more conventional white cassava (Ayetigbo et al., 2018). While the variety could impart nutritional benefits to malnourished populations in Africa, most of the existing cassava processing techniques significantly reduce the nutrients in foods made from biofortified yellow-flesh cassava (Ayetigbo et al., 2018). Making food foams from this nutrient-dense crop and the potential for use in edible foods may offer an opportunity for improving the nutritional status of consumers of cassava. In addition, increasing the scope of utilization pathways of cassava for edible food is being canvassed for by governments of regions where they are commercially cultivated and consumed for economic reasons. For instance, the use of cassava flour in bread making in Nigeria has been executed by the food legislation policy of its government (Odum, 2015).

To the best of our knowledge, information is not readily available on cassava foaming, using food-grade foaming agent and stabilizer, into foam or powder potentially intended for edible food use or as food ingredient, and not as a packaging material. Optimization of the foaming process and characteristics of cassava foam and foam powder is not yet considered in most literature, especially for the yellow-flesh cassava varieties. In addition, the possible influence of foaming and drying on reduction of cyanogenic glucosides in cassava has not been considered in most research. The objectives of this work was to develop cassava foam, optimize the process variables for foaming and validation of the optimal foaming variables by response surface method. The effects of foaming and drying on color, total carotenoids content, microstructure and cyanogenic glucosides potential of cassava pulp, foam and foam powder will also be investigated.

3.3 Materials and Methods

3.3.1 Materials

Waxed white-flesh cassava from Costa Rica was purchased from a supermarket in Stuttgart, Germany. Fresh yellow-flesh cassava (TMS-IBA 011368) was harvested from cassava breeding unit of the International Institute of Tropical Agriculture, IITA, Ibadan, Nigeria. They were waxed and transported to the University of Hohenheim, Stuttgart, in rigid paperboard boxes with several holes for aeration. Both were stored briefly at 3 ^{o}C. The foaming agent used was a 20 % w/w glycerol monostearate, GMS

(MRS Scientific Ltd., Essex, UK) colloid which was prepared fresh as described in literature (Kolawole O. Falade & Onyeoziri, 2012a) by dispersing GMS powder in hot distilled water and immediately blending for 1 min in a mixer (Bajaj Mixer-Grinder, Bajaj Electricals ltd., Mumbai, India) at maximum speed setting to give a cream-white smooth homogenate. Sodium carboxy-methyl cellulose, NaCMC (MRS Scientific Ltd., Essex, UK) was used in its powder form.

3.3.2 Methods

3.3.2.1 Foam preparation

The cassava roots were peeled into potassium metabisulphite ($K_2S_2O_5$) solution (1 g/L) to restrict discoloration, drained, chipped and milled into a fine pulp of about 1.5 ^{o}Brix (ATAGO PR-201 palette, ATAGO co. ltd., Tokyo, Japan), using a blender (WARING commercial®, 8010G, Torrington, Connecticut, USA). Preliminary experiments revealed blending ratio of 1:3 of cassava-flesh to $K_2S_2O_5$ solution, by weight, resulted in pulp that yielded increased foam volume with foaming agent concentration (5-15 %) and stabilizer concentrations (1 %) used. Lower ratios (1:1, 1:2) resulted in too viscous pulps of low foam volume, and higher ratio (1:4) yielded thin pulps of high foam collapse. The concentrations of GMS, concentrations of NaCMC, and whipping time considered were within the range of those reviewed in literature (Sangamithra, Venkatachalam, John, & Kuppuswamy, 2015b). About 200 mL of resulting pulp was weighed in graduated 500 mL measuring cylinder and mass noted. The pulp was transferred into the stainless steel cup of a mixer (Bajaj Mixer-Grinder, Bajaj Electricals ltd., India). Foaming agent was added at three concentration levels (5 %, 10 % and 15 %, corresponding to original GMS concentrations of 1 %, 2 % and 3 %, respectively), and stabilizer NaCMC was added at three concentration levels (0.2 %, 0.4 % and 0.6 %) based on pulp weight. Concentrations were within food additive regulatory limits (Rajkumar, Kailappan, Viswanathan, Raghavan, & Ratti, 2007). The mixture was whipped for 2, 4 and 6 min. The resulting foam was carefully transferred into a wide-mouth graduated 500 mL measuring cylinder and volume and mass noted. Foam properties were calculated as (Rajkumar et al., 2007):

$$\text{Foam expansion, FE (\%)} = \frac{V_f - V_p}{V_p} \cdot 100 \quad (3\text{-}1)$$

$$\text{Foam density, FD (g/mL)} = \frac{m_f}{V_f} \quad (3\text{-}2)$$

$$\text{Foam collapse, FC (\%)} = \frac{V_{f_i} - V_{f_t}}{V_{f_i}} \cdot 100 \quad (3\text{-}3)$$

where V_f (mL) is final volume of foam, V_p (mL) is initial volume of pulp, m_f (g) is mass of foam, V_{fi} (mL) is initial volume of foam and V_{ft} (mL) is volume of foam after 4 h exposure at ambience (25 ± 2 ºC). The choice of determining FC after 4 h was because preliminary experiments have shown that the first four hours of drying the foam is critical to rapid loss of moisture, therefore, if foam is not stable within this period, it could collapse and undergo non-uniform drying. In other works, collapse or drainage of foams have been measured at ambient temperature between 2 - 20 h (Raharitsifa et al., 2006; Rajkumar et al., 2007; Vernon-Carter et al., 2001). Experiments were conducted in triplicates.

3.3.2.2 Optimization of cassava foaming

Foaming experiment was conducted according to a Box-Behnken experiment design with three independent variables: concentration of GMS (5, 10, 15 %), concentration of NaCMC (0.2, 0.4, 0.6 %) and whipping time (2, 4, 6 min). Two responses were considered: FE and FD. Main and interaction effects of independent variables on responses, and 3-dimension response surfaces were developed using Design expert® 6.0.6 (Stat-Ease Inc., Minneapolis, USA). Optimization of foaming was carried out by numeric method based on desirability function, with criteria for selection based on maximum FE and minimum FD. The general quadratic regression equation used to describe each response was based on the main and interaction effects of independent variables and their coefficients (β_i, where i = 0 - 9) as:

$$\text{Response} = \beta_0 + \beta_1 \cdot \text{GMS} + \beta_2 \cdot \text{NaCMC} + \beta_3 \cdot \text{Time} + \beta_4 \cdot \text{GMS}^2 + \beta_5 \cdot \text{NaCMC}^2 + \beta_6 \cdot \text{Time}^2 + \beta_7 \cdot \text{GMS} \cdot \text{NaCMC} + \beta_8 \cdot \text{GMS} \cdot \text{Time} + \beta_9 \cdot \text{NaCMC} \cdot \text{Time} \quad (3\text{-}4)$$

3.3.2.3 Drying of cassava foam to foam powder

Optimal foam was collected and spread uniformly to be dried in pans (dimension 250 mm x 155 mm x 10 mm) at 55 ^{o}C in a thermostatically-controlled air oven (Heraeus, Thermo Scientific, Germany) for about 24 h, when the weight change was no longer apparent. Drying at a mild temperature (55 ^{o}C) was to relatively preserve the starch granules from complete gelatinization, to considerably retain total carotenoids (for yellow cassava) and reserve some activity of linamarase for detoxification during drying. Cassava starch has been found to gelatinize at onset of 60.11 ^{o}C (Nwokocha, Aviara, Senan, & Williams, 2009). Elevated temperatures may also result in rapid thermal destruction of carotenoids (Boon et al., 2010), while linamarase has optimum activity close to 55 ^{o}C (Mkpong, Yan, Chism, & Sayre, 1990). Foam thickness of 10 mm has been used in drying food foams (Ratti & Kudra, 2006). The dry porous foam mat was scraped off from the pan and pulverized gently in a coffee blender (PC-KSW 1021, Proficook Ltd., China) and packed in sealed plastic bags as foam powder.

3.3.2.4 Color evaluation and total carotenoids content (TCC)

Color was determined using a colorimeter (Chromameter CR 410 Konica Minolta, Sensing Inc., Japan) having optical sensor lens at 2^{o} observer, illuminated by D65 light and calibrated with a standard white tile (Y = 93.0, x = 0.3167, y = 0.3338). Eighteen measurements of L^* (lightness-darkness), a^* (redness-greenness) and b^* (yellowness-blueness) color parameters were determined. From the data obtained, chroma (C^*), hue angle (H^*), total color (E^*), total color difference ($\Delta E^*_{\text{yellow-white}}$, between yellow and white cassava pulp, foam, or foam powder with white cassava color as reference) and degree of whiteness, W (%) were calculated according to respective equations 3-5, 3-6, 3-7, 3-8, and 3-9 (Gonnet, 1999; Hunt, 1991).

$$C^* = \left({a^*}^2 + {b^*}^2\right)^{0.5} \tag{3-5}$$

$$H^* = \tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{3-6}$$

$$E^* = \left({L^*}^2 + {a^*}^2 + {b^*}^2\right)^{0.5} \tag{3-7}$$

$$\Delta E^*_{yellow-white} = \left(\left({L^*}_{yellow} - {L^*}_{white}\right)^2 + \left({a^*}_{yellow} - {a^*}_{white}\right)^2 + \left({b^*}_{yellow} - {b^*}_{white}\right)^2\right)^{0.5} \tag{3-8}$$

$$W\ (\%) = 100 - \left[\left(100 - {L^*}^2\right) + \left({a^*}^2 + {b^*}^2\right)\right]^{0.5} \tag{3-9}$$

Total carotenoids content (µg/g) of cassava pulp, foam and powder was determined by method described by (Ceballos et al., 2012) and expressed in dry basis. Briefly, 5g of sample was dispersed in 10 mL of acetone for 10 min and followed by homogenization with 10 mL of petroleum ether for 1 min. The homogenate was centrifuged at 3000 rpm for 10 min at 10 ^oC and the carotenoids-rich organic phase was collected. This extraction-separation process was repeated on the retentate three times with subsequent 5 mL of acetone and 5 mL petroleum ether. Pooled organic extract was washed three times with 10 mL of 0.1 M NaCl solution and centrifuged as earlier. The refined organic phase was pipetted out and adjusted to between 10-15 mL. Total carotenoids (µg/g) was calculated as described by Jaeger DeCarvalho et al. (2012).

3.3.2.5 Microstructure of cassava pulp, foam and foam powder

Microstructure of freshly prepared cassava pulp and optimal cassava foam was captured using a microscope (Carl Zeiss Primovert, Carl Zeiss Microimaging GMBH, Germany) with integrated digital camera (ProgRes CT3). A dedicated software (ProgRes Capture Pro 2.8., JENOPTIC optical systems, Germany) was used to analyze air bubbles size. Multiple measurements (80) were recorded per sample. Microstructure of cassava foam powder was captured using a remission scanning electron microscope (JSM-IT 100, JEOL GmbH, Freising, Germany) after gluing the powder to carbon discs on the end of gold-plated cylinder, and placed on the sample platform. The system was evacuated, and electrons were beamed at accelerating voltage of about 2.5 kV and a probe current of 17 mA. Images were displayed and captured digitally on an interface of a dedicated software (In Touch Scope, version 1.090, JEOL Technics Ltd., Freising, Germany).

3.3.2.6 Estimation of total cyanogenic potential

Cyanogenic glucosides are toxic compounds found in cassava which renders it unsafe to consume without proper processing. An insight into the effect of foaming and drying on reduction of cyanogenic potential of cassava was investigated. A slightly modified picrate paper kit method described by Bradbury, Egan, & Bradbury (1999) was used to determine total cyanogens (assayed as total HCN equivalent, µg/g) in fresh cassava and cassava foam powder. Linamarase was extracted according to description by Haque & Bradbury (2004). Briefly, about 100 mg of dried sample was placed in a plastic vial and 1mL of 0.1M sodium phosphate buffer (pH 6) and 0.1 mL of linamarase extract was added. A yellow picrate paper glued to plastic strip was inserted just above the mixture and the vial was capped tightly. The mixture was incubated at 30 ^{o}C for 24 h. Standard linamarine concentrations and a blank were subjected to similar protocol. Absorbance of 5 mL water-eluate from the picrate papers was measured at 510 nm by a spectrophotometer (Hach Lange DR 6000, Hach Lange GmbH, Berlin, Germany) and total cyanogen content was determined from the calibration curve of linamarine standard.

3.4 Statistical analyses

Data were presented as mean ± standard deviation. Statistical analyses was conducted to separate means by Duncan ad hoc test using SPSS 16.0 (SPSS Inc., Chicago, Illinois, USA). Optimization, effects of variables, and response surface was developed using Design expert 6.0.6. Quality of response surface model was statistically assessed by high values of coefficient of determination (R^2) and adjusted R^2; and low values of root mean square error (RMSE) and mean absolute percentage error (MAPE) as calculated below (Ferrari & Hubinger, 2008; Salim, Garièpy, & Raghavan, 2016) :

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{n}(X_{exp}-X_{pred})^2}{\sum_{i=1}^{n}(X_{exp}-\bar{X}_{exp})^2}\right) \tag{3-10}$$

$$Adjusted\ R^2 = 1 - \left(\frac{(1-R^2)\cdot(n-1)}{n-k-1}\right) \tag{3-11}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_{pred}-X_{exp})^2} \tag{3-12}$$

$$MAPE\,(\%) = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{X_{exp}-X_{pred}}{X_{exp}}\right| \tag{3-13}$$

where X_{exp} is experimental value, X_{pred} is predicted value, n is number of observations and k is number of model variables.

3.5 Results

The total soluble solids of white and yellow cassava pulp was similar (1.5 ± 0.3 ^{o}Brix). The density of white cassava pulp (1.016 ± 0.006 g/mL) and yellow cassava pulp (1.004 ± 0.006 g/mL) were significantly ($P < 0.05$) higher than density of their respective foams. Density of white cassava foam and yellow cassava foam ranged between 0.731 - 0.863 g/mL and 0.728 - 0.830 g/mL, respectively. Foam collapse (FC) ranged between 0.00 - 10.94 % for white cassava foams and between 0.00 - 5.04 % for yellow cassava foams. Within the range of independent variables considered, FE of white cassava foam and yellow cassava foam ranged between 26.0 - 50.0 % and between 23.0 - 48.3 % (Table 3-1), while FD ranged between 0.731 - 0.863 g/mL and 0.728 - 0.830 g/mL, respectively. White cassava pulp required 14.97 % GMS, 0.51 % NaCMC and 2.07 min whipping to yield an optimal foam of 52.63 % expansion and density of 0.75 g/mL. Yellow-flesh cassava pulp required 14.29 % GMS, 0.6 % NaCMC and 2 min whipping to yield an optimal foam of 48.25 % FE and FD of 0.76 g/mL. Generally, increasing GMS concentration from 5 % to 15 % correspondingly resulted in increased FE and reduction in FD, progressively producing lighter, but more foam volume. Increasing NaCMC concentration from 0.2 % to 0.6 % had an opposite effect and produced thicker foams. Increase in whipping time from 2 min to 6 min considerably resulted in decrease in FE and increase in FD.

The quadratic models generated were significant (P = 0.0025 – 0.0072) and had non-significant lack of fit (P = 0.1608). The models had high fit quality (R^2 = 0.9064-0.9321, Adjusted R^2 = 0.786-0.8447, RMSE = 0.0088-1.923, MAPE = 0.850-4.267 %) to estimate cassava foam properties and effect of the variables on foam properties (Table 3-2). Predicted optimal FE and FD (Table 3-3) for both varieties are close to validated values. Optimal white cassava foam has significantly higher expansion than optimal yellow cassava foam, but FD and FC were not significantly different between both optimal foams. The response surfaces (Figure 3-1, Figure 3-2) show profiles of FE and FD, respectively, as influenced by concentrations of GMS, NaCMC and whipping time.

For color, white cassava pulp, optimal foam and foam powder had significantly higher L^* than their yellow counterparts (Table 3-4). The pulp, optimal foam and powder of yellow cassava had significantly higher yellowness (b^*) than those of white cassava, consequent of the higher TCC in them. The intensity of b^* for yellow cassava is in the order: pulp > optimal foam > powder. All hue angles (H^*) are within the yellowness-redness axis, but closer to the yellowness axis. Significant differences were found between H^* of white and yellow cassava pulp and optimal foam. The total color difference ($\Delta E^*_{yellow-white}$) between yellow and white cassava pulp was higher than between the optimal foams, which in turn, was higher than that between the foam powders.

Table 3-1: Effect of concentration of foaming agent (GMS), and stabilizer (NaCMC) and whipping time (Time) on foam expansion (FE) and foam density (FD) of foam from yellow-flesh and white-flesh cassava varieties

GMS (%)	NaCMC (%)	Time (min)	GMS (%)	NaCMC (%)	Time (min)	Cassava varieties			
						White		Yellow	
Values			Codes			FE (%)	FD (g/mL)	FE (%)	FD (g/mL)
10	0.2	2	0	-1	-1	48.83^{ab}±2.02	0.731^{f}±0.009	44.15^{ab}±2.33	0.728^{e}±0.006
10	0.4	4	0	0	0	30.63^{ef}±4.44	0.831^{bc}±0.022	39.67^{bc}±1.26	0.766^{bcd}±0.013
5	0.4	2	-1	0	-1	33.83^{de}±2.02	0.781^{d}±0.009	23.00^{e}±1.32	0.823^{a}±0.017
15	0.4	2	+1	0	-1	50.00^{a}±0.00	0.762^{de}±0.007	47.33^{a}±1.76	0.751^{cde}±0.004
10	0.4	4	0	0	0	30.63^{ef}±4.44	0.831^{bc}±0.022	39.67^{bc}±1.26	0.766^{bcd}±0.013
10	0.6	2	0	+1	-1	45.67^{b}±0.76	0.747^{ef}±0.002	37.50^{bc}±1.50	0.768^{bcd}±0.009
5	0.2	4	-1	-1	0	40.67^{c}±1.76	0.732^{f}±0.009	29.00^{de}±1.00	0.769^{bcd}±0.010
10	0.4	4	0	0	0	30.63^{ef}±4.44	0.831^{bc}±0.022	39.67^{bc}±1.26	0.766^{bcd}±0.013
15	0.2	4	+1	-1	0	35.83^{d}±1.44	0.839^{b}±0.014	33.83^{cd}±8.08	0.826^{a}±0.041
5	0.6	4	-1	+1	0	28.83^{fg}±1.26	0.814^{c}±0.009	23.33^{e}±0.76	0.830^{a}±0.005
15	0.6	4	+1	+1	0	46.67^{ab}±2.89	0.776^{d}±0.010	48.33^{a}±1.04	0.758^{cde}±0.002
10	0.4	4	0	0	0	30.63^{ef}±4.33	0.831^{bc}±0.022	39.67^{bc}±1.26	0.766^{bcd}±0.013
10	0.2	6	0	-1	+1	33.50^{de}±3.04	0.813^{c}±0.018	43.33^{ab}±1.04	0.742^{de}±0.007
5	0.4	6	-1	0	+1	32.67^{def}±1.53	0.783^{d}±0.007	27.17^{e}±2.57	0.803^{ab}±0.014
15	0.4	6	+1	0	+1	35.83^{d}±0.76	0.840^{b}±0.006	40.17^{bc}±8.75	0.803^{ab}±0.049
10	0.6	6	0	+1	+1	26.00^{g}±0.87	0.863^{a}±0.002	37.83^{bc}±1.15	0.780^{bc}±0.004
10	0.4	4	0	0	0	30.63^{ef}±4.44	0.831^{bc}±0.022	39.67^{bc}±1.26	0.766^{bcd}±0.013

Means in column followed by same superscript(s) are not significantly different ($P \geq 0.05$)

Table 3-2: Analysis of variance, model coefficients (β), and model accuracy assessment (R^2, Adj R^2, RMSE, MAPE) for cassava foam expansion (FE) and foam density (FD) based on independent variables: concentration of foaming agent (GMS), stabilizer (NaCMC) and whipping time (Time)

	White-fleshed						Yellow-fleshed					
Source of vriation	SS	DF	MS	F-value	Prob>F	Coefficient (β)	SS	DF	MS	F-value	Prob>F	Coefficient (β)
FE (%)												
Model	842.12	9	93.57	10.07	0.0030*	88.75	862.56	9	95.84	10.67	0.0025*	14.06
GMS	130.68	1	130.68	14.06	0.0072*	-2.94	563.92	1	563.92	62.78	<0.0001*	5.73
NaCMC	17.01	1	17.01	1.83	0.2181	-130.96	1.38	1	1.38	0.15	0.7070	-57.84
Time	316.68	1	316.68	34.08	0.0006*	-6.76	1.52	1	1.52	0.17	0.6931	.50
GMS^2	50.84	1	50.84	5.47	0.0519	0.14	160.03	1	160.03	17.82	0.0039*	-0.25
$NaCMC^2$	63.77	1	63.77	6.86	0.0344*	97.29	0.064	1	0.064	0.0071	0.9351	3.08
$Time^2$	66.53	1	66.53	7.16	0.0317*	0.99	3.53	1	3.53	0.39	0.5509	0.23
GMS · NaCMC	128.44	1	128.44	13.82	0.0075*	5.67	101.67	1	101.67	11.32	0.0120*	5.04
GMS · Time	42.25	1	42.25	4.55	0.0704	-0.33	32.11	1	32.11	3.57	0.1006	-0.28
NaCMC · Time	4.69	1	4.69	0.51	0.5002	-2.71	0.33	1	0.33	0.037	0.8529	0.72
Residual	65.04	7	9.29				62.88	7	8.98			
Lack of Fit	65.04	3	21.68	2.33	0.1608		62.88	3	20.96	2.33	0.1608	
Pure error	0.00	4	0.00				0.00	4	0.00			
	R^2	Adj R^2	RMSE	MAPE (%)			R^2	Adj R^2	RMSE	MAPE (%)		
	0.9283	0.8361	0.0112	4.096			0.9321	0.8447	1.923	4.267		
FD (g/mL)												
Model	0.025	9	0.00277	9.03	0.0042*	0.433	0.013	9	0.00141	7.53	0.0072*	0.793
GMS	0.00147	1	0.00147	4.78	0.0651	0.0248	0.000984	1	0.000984	5.25	0.0557	-0.0247
NaCMC	0.000904	1	0.000904	2.94	0.1299	0.766	0.000619	1	0.000619	3.3	0.1121	0.474
Time	0.00967	1	0.00967	31.48	0.0008*	0.031	0.000398	1	0.000398	2.12	0.1885	-0.00169
GMS^2	0.00154	1	0.00154	5.00	0.0604	-0.00076	0.00521	1	0.00521	27.79	0.0012*	0.00141
$NaCMC^2$	0.00201	1	0.00201	6.56	0.0375*	-0.547	0.000122	1	0.000122	0.65	0.4457	-0.135
$Time^2$	0.00179	1	0.00179	5.82	0.0466*	-0.00515	0.000161	1	0.000161	0.86	0.3853	-0.00154
GMS · NaCMC	0.00522	1	0.00522	16.99	0.0044*	-0.0361	0.00408	1	0.00408	21.76	0.0023*	-0.0319
GMS · Time	0.00146	1	0.00146	4.74	0.0658	0.00191	0.00128	1	0.00128	6.81	0.0350*	0.00179
NaCMC · Time	0.000291	1	0.000291	0.95	0.3628	0.0213	$3.41x10^{-7}$	1	$3.41x10^{-7}$	0.00182	0.9672	-0.000729
Residual	0.00215	7	0.000307				0.00131	7	0.000187			
Lack of Fit	0.00215	3	0.000717	2.33	0.1608		0.00131	3	0.000437	2.33	0.1608	
Pure error	0.000	4	0.000				0.000	4	0.000			
	R^2	Adj R^2	RMSE	MAPE (%)			R^2	Adj R^2	RMSE	MAPE (%)		
	0.9207	0.8188	0.0112	1.049			0.9064	0.7860	0.0088	0.850%		

SS -sum of squares, DF - degree(s) of freedom, MS - mean square. * significant at 5% level ($P < 0.05$).

Table 3-3: Optimal concentration of foaming agent (GMS), stabilizer (NaCMC), whipping time (Time) and predicted and validated values of foam expansion (FE) and foam density (FD) of cassava

Variety	GMS (%)	NaCMC (%)	Time (min)	FE (%)	FD (g/mL)	FE (%)	FD (g/mL)	Foam Collapse (%)
				Predicted		Validated		
White-fleshed	14.97	0.51	2.07	54.9	0.73	$52.63^{a}\pm1.03$	$0.753^{a}\pm0.005$	$1.79^{a}\pm0.41$
Yellow-fleshed	14.29	0.60	2.00	49.9	0.73	$48.25^{b}\pm1.71$	$0.758^{a}\pm0.007$	$1.26^{a}\pm0.42$

Means in column followed by same superscript(s) are not significantly different ($P\geq0.05$)

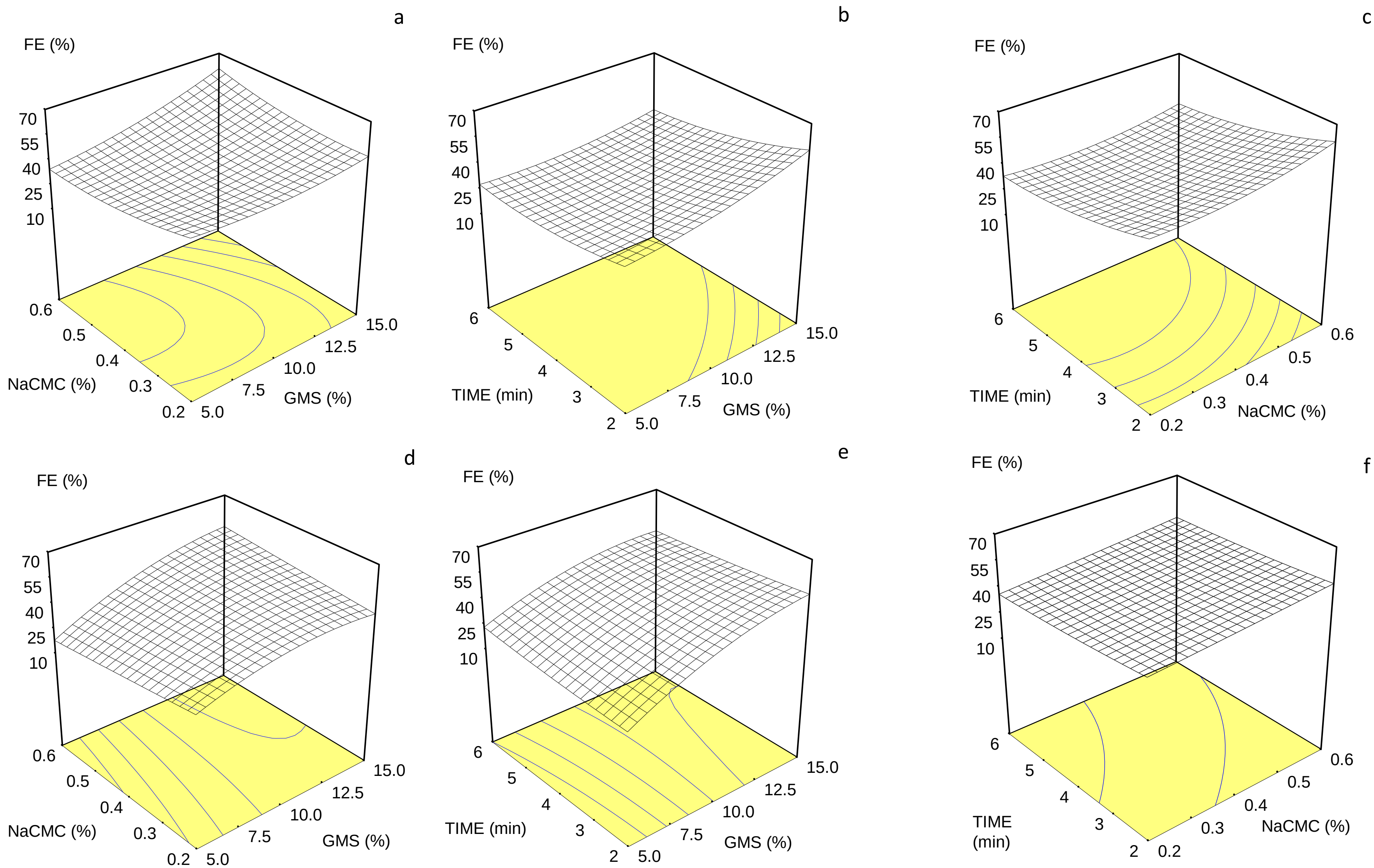


Figure 3-1: Response surface plot of foam expansion (FE) for white cassava (a-c) and yellow cassava (d-f) showing the influence of concentration of foaming agent (GMS) and stabilizer (NaCMC) and whipping time (TIME)

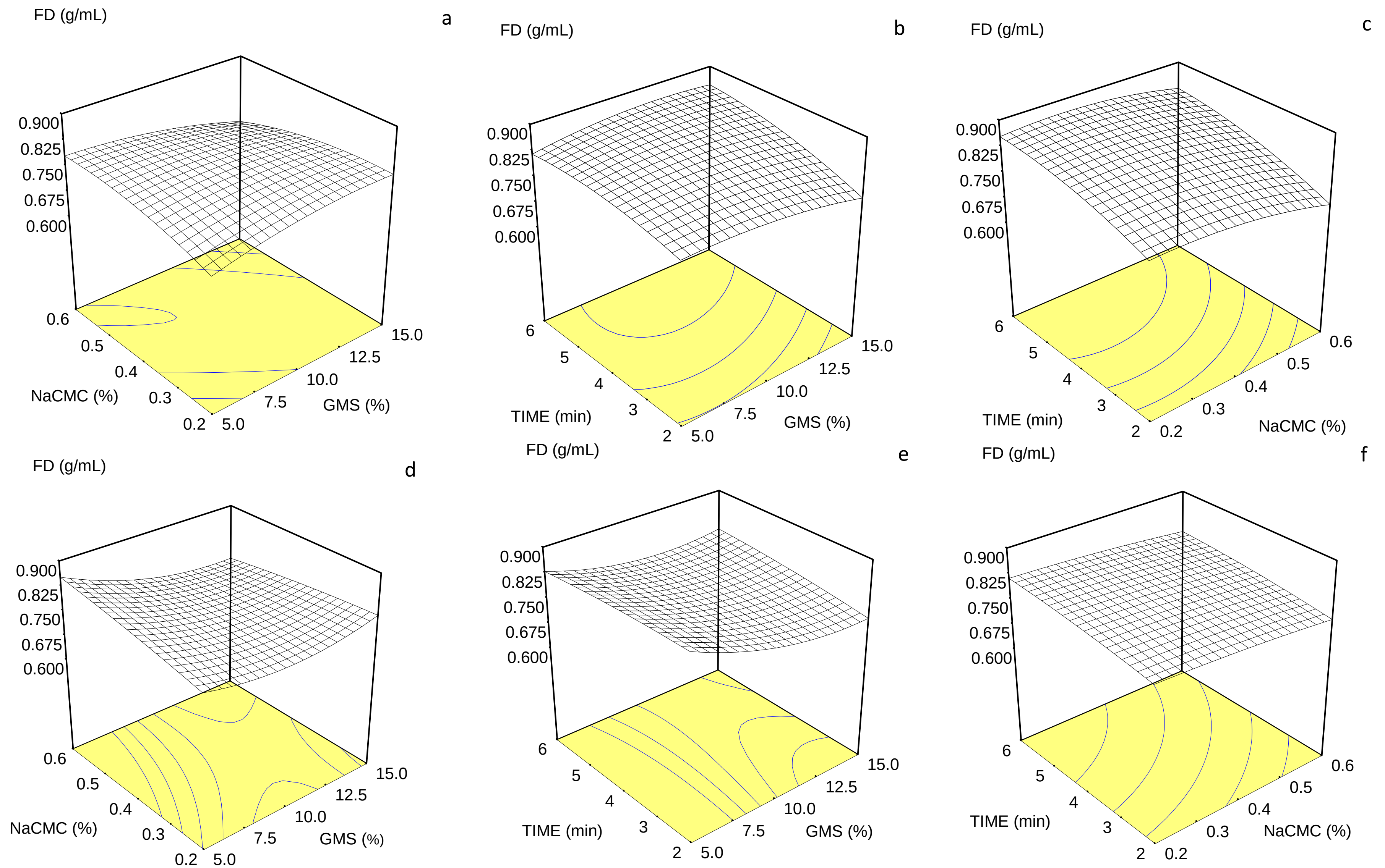


Figure 3-2: Response surface plot of foam density (FD) for white cassava (a-c) and yellow cassava (d-f) showing the influence of concentration of foaming agent (GMS) and stabilizer (NaCMC) and whipping time (TIME)

Table 3-4: Total carotenoids content (TCC) and color parameters (W, L^*, a^*, b^*, H^*, C^*, E^*, $\Delta E^*_{yellow\text{-}white}$) of cassava pulp, optimal foam** and foam powder

	TCC (µg/g), db	W (%)	L^*	a^*	b^*	H^*	C^*	E^*	$\Delta E^*_{yellow\text{-}white}$
Cassava pulp									
white	$1.22^{d} \pm 0.09$	$77.49^{c} \pm 1.36$	$78.11^{e} \pm 1.32$	$-1.14^{b} \pm 0.09$	$5.08^{de} \pm 0.41$	$-77.29^{d} \pm 0.61$	$5.21^{de} \pm 0.42$	$78.28^{c} \pm 1.29$	0.00 ± 0.00
yellow	$21.30^{a} \pm 0.32$	$61.86^{e} \pm 6.80$	$72.38^{f} \pm 3.53$	$-7.28^{d} \pm 0.64$	$25.15^{a} \pm 6.30$	$-73.27^{c} \pm 2.60$	$26.20^{a} \pm 6.23$	$77.28^{d} \pm 1.25$	$21.88^{a} \pm 6.74$
Cassava foam									
white	$0.72^{d} \pm 0.11$	$86.04^{b} \pm 0.41$	$86.41^{c} \pm 0.42$	$-1.41^{b} \pm 0.05$	$2.85^{e} \pm 0.31$	$-63.51^{a} \pm 2.37$	$3.18^{e} \pm 0.28$	$86.47^{b} \pm 0.42$	0.00 ± 0.00
yellow	$16.43^{b} \pm 0.70$	$71.80^{d} \pm 0.27$	$83.62^{d} \pm 0.11$	$-8.38^{e} \pm 0.09$	$21.36^{b} \pm 0.32$	$-68.58^{b} \pm 0.19$	$22.95^{b} \pm 0.32$	$86.71^{b} \pm 0.14$	$19.99^{a} \pm 0.49$
Cassava foam powder									
white	$1.47^{d} \pm 0.91$	$91.14^{a} \pm 0.26$	$95.52^{a} \pm 0.08$	$-0.77^{a} \pm 0.03$	$7.59^{d} \pm 0.26$	$-84.24^{e} \pm 0.15$	$7.64^{d} \pm 0.26$	$95.82^{a} \pm 0.07$	0.00 ± 0.00
yellow	$14.56^{c} \pm 1.84$	$80.27^{c} \pm 1.80$	$93.45^{b} \pm 0.76$	$-1.68^{c} \pm 0.16$	$18.53^{c} \pm 1.68$	$-84.78^{e} \pm 0.71$	$18.61^{c} \pm 1.67$	$95.29^{a} \pm 0.46$	$11.17^{b} \pm 1.84$

** prepared at optimal conditions (14.97 % GMS, 0.51 % NaCMC, 2.07 min Time for white cassava and 14.29 % GMS, 0.6 % NaCMC, 2 min Time for yellow cassava). Means in column followed by same superscript are not significantly different ($P \geq 0.05$). $\Delta E^*_{yellow\text{-}white}$ is total color difference between yellow-flesh and white-flesh cassava pulp, foam, or foam powder with white cassava color values as reference).

As expected, white cassava pulp, optimal foam, and powder had significantly lower TCC than those of yellow cassava.

White cassava pulp, optimal foam, and powder had no significant difference in TCC between each other, but TCC of yellow cassava pulp was significantly higher than for its optimal foam and TCC of the optimal foam was also considerably higher than for the powder.

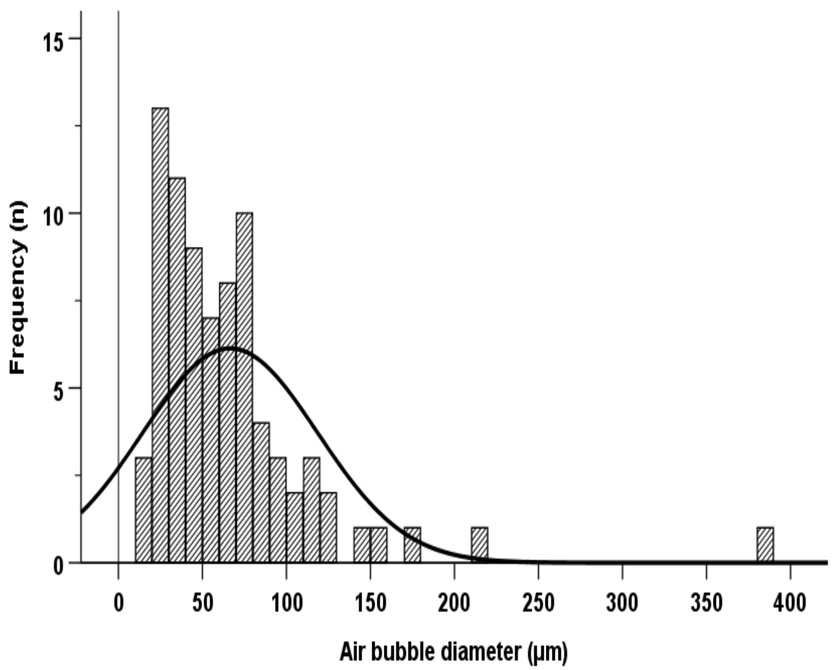
Average air bubble size (Table 3-5) of optimal yellow cassava foam (80.35 µm) was not significantly different from that of white cassava foam (66.49 µm). The foam bubbles had multi-modal, asymmetric size distribution (Figure 3-3). Air bubble size distribution of optimal white cassava foam skewed more positively to smaller size intervals than for yellow cassava foam. The size of 75 % of air bubbles measured in optimal foams was below 79.1 µm for white cassava foam, and below 101.4 µm for yellow cassava foam. Micrographs of cassava pulp (Figure 3-4 (a, b)) showed it consists mostly of starch granules and had no notable air bubbles, while morphology of the optimal foams (Figure 3-4 (c, d)) revealed round shaped air cells with thin lamella and distant plateau borders between air cells. Electron micrographs of cassava foam powder (Figure 3-4 (e, f)) clearly reveal the hydrocolloids interaction on surface of powder particles of smooth and rough-edged (due to milling) starch granules.

Total cyanogenic potential (Table 3-6) reduced significantly (P = 0.004) from 141.5 µg/g to 20.5 µg/g for fresh white cassava root and white cassava foam powder, respectively, while a significant reduction (P = 0.006) from 667.8 µg/g to 84.3 µg/g was also recorded for fresh yellow cassava root and yellow cassava foam powder, respectively. The use of cassava varieties with low total cyanogens would, therefore, be preferred in making cassava foams or powder for foods. With such consideration, the total cyanogenic content of the products produced from them could probably comply with limit (≤10 µg/g) of allowed total cyanogens for cassava products as set by *Codex Alimentarius Commission* (FAO, 1991).

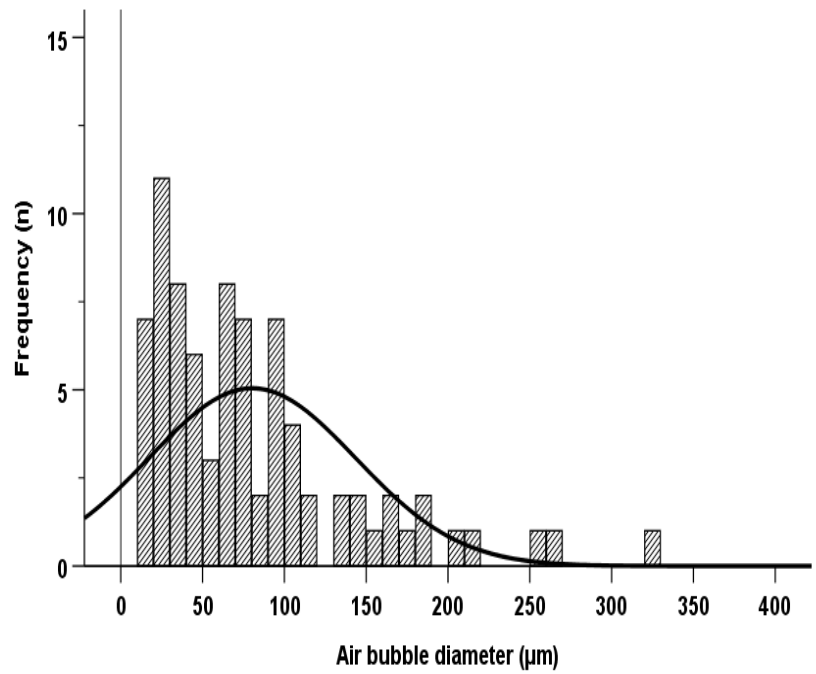
Table 3-5: Morphology and size of air bubbles of optimal cassava foams (n = 80)

	Shape	Mean ± std. dev. (μm)	Median (μm)	Mode (μm)	Interval (μm)
White-flesh	Round	$66.49^{a} \pm 52.03$	54.95	46.57^{*}	17.65 - 385.80
Yellow-flesh	Round	$80.35^{a} \pm 63.27$	65.47	14.71^{*}	14.71 - 324.50

Means in column followed by same superscript(s) are not significantly different (P ≥ 0.05). * Multiple modes exist. The smallest value is shown.



(a)



(b)

Figure 3-3: Distribution of air bubble diameter in optimal white cassava (a) and yellow cassava (b) foams

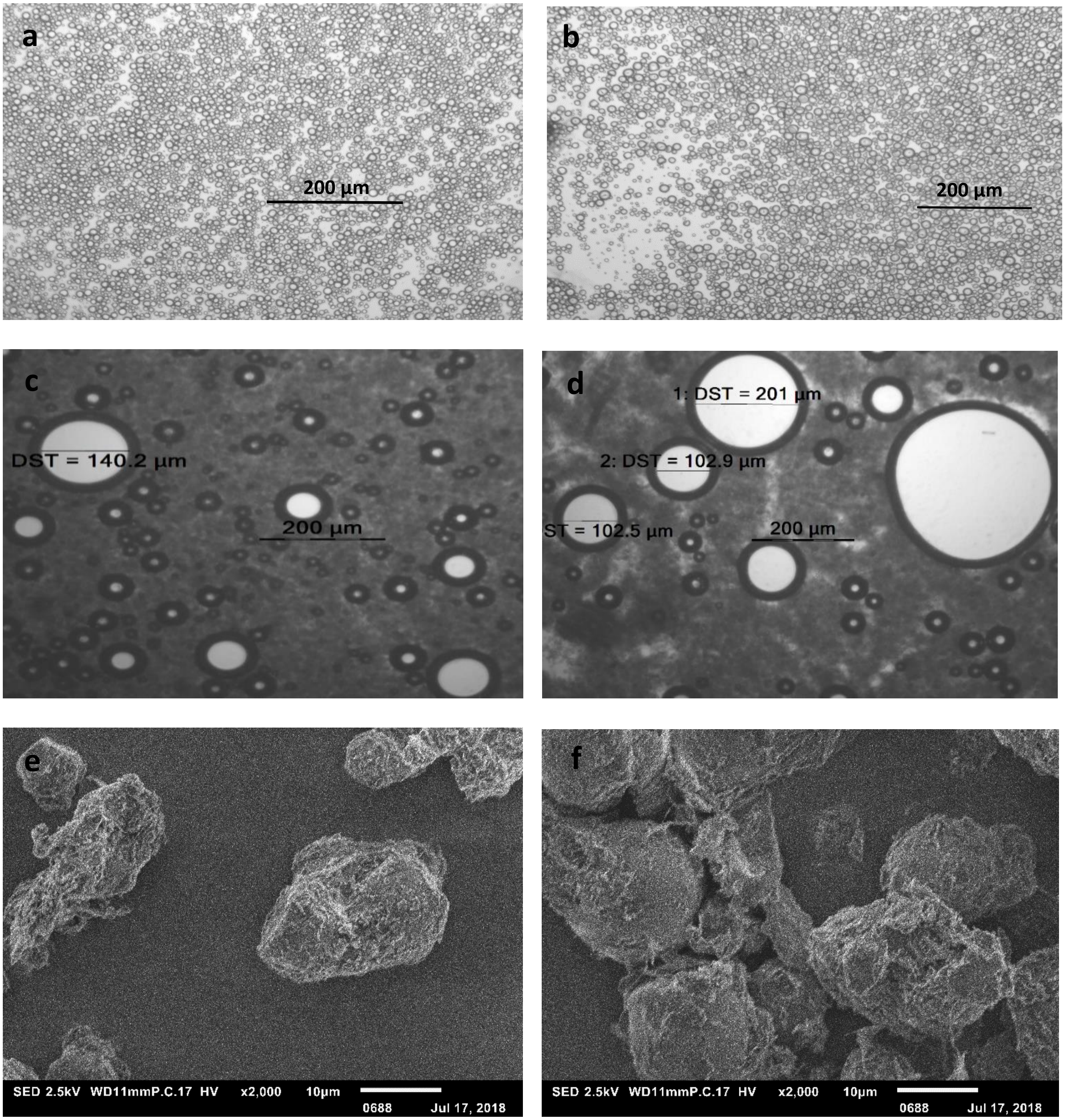


Figure 3-4: (a) White cassava pulp (100 x magnification) (b) Yellow cassava pulp (100 x magnification) (c) Optimal white cassava foam (40 x magnification) (d) Optimal yellow cassava foam (40 x magnification) (e) White cassava foam powder (f) Yellow cassava foam powder

Table 3-6: Total cyanogenic potential (HCN eq.) of fresh white and yellow cassava roots and foam powder

	HCN eq. (µg/g fw)	
Variety	White	Yellow
Fresh root	141.5^{a} ± 9.2	667.8^{a} ± 47.1
Foam powder	20.5^{b} ± 4.7	84.3^{b} ± 46.6

Means in column followed by same superscript are not significantly different (P≥0.05).

Therefore, further processing of the cassava pulp, foam or powder would be required to produce foods or food ingredients.

3.6 Discussion

Foaming of cassava pulp into cassava foam significantly reduced density due to air entrapment. Low density of foams is an important requirement for stability in food-use and production of food powders by drying.

3.6.1 Optimization of cassava foaming

The response surface model equations satisfactorily predicted foam properties and is instrumental in selecting optimized conditions required for foaming. Foam collapse (FC) was not considered as one of the dependent variables because some had values of zero (0), which when optimised by the response surface method (RSM) regression alongside FE and FD, yielded negative optimum prediction values which is not reasonable within the range of factors considered. Increasing GMS concentration generally led to significant increase in FE and insignificant reduction in FD of yellow cassava foams. For instance, increasing GMS concentration from 5 % to 15 % at fixed NaCMC concentration of 0.4 % and fixed time of 4 min, resulted in increased expansion of yellow cassava foam from 25.1 % to 41.9 %, with corresponding reduction in FD from 0.812 g/mL to 0.79 g/mL.

However, increasing GMS concentration from 5 % to 15 % under similar conditions, resulted in increased expansion of white cassava foam from 30.1 % to 38.2 %, and increased density from 0.799 g/mL to 0.826 g/mL respectively. Similar reports have been made for concentrated yacon juice (Talita Szlapak Franco et al., 2015) and plantain (Kolawole O. Falade & Okocha, 2012b). Increasing concentration of NaCMC from 0.2 % to 0.6 % at fixed GMS concentrations of 10% and whipping time of 4 min, reduced expansion and increased density of yellow and white cassava foams. For instance, for white cassava, FE reduced from 35.9 % to 33.1 %, and FD increased from 0.790 g/mL to 0.819 g/mL. Increasing whipping time had significant effect on reduction of FE, but significantly increased FD of white cassava foam, but did not significantly affect FE and FD of yellow cassava foam. For instance, for white cassava foam, increasing whipping time from 2 min to 6 min at fixed GMS and NaCMC concentrations of 10 % and 0.4 %, respectively, resulted in reduced expansion from 40.9 % to 28.3 % and increase in density from 0.776 g/mL to 0.845 g/mL. This is contrary to findings for yacon juice (Talita Szlapak Franco et al., 2015), where increased whipping time increased FE. This could be due to the poor ability of the cassava foams to withstand sustained mechanical shear due to generation of heat which likely reduced viscosity at longer whipping times. Also, the poor protein content of cassava may predispose its foam to breakdown at longer whipping times. Whipping could improve foaming of proteins by changes in conformation and denaturation, a feature not commonly shared by most carbohydrates and lipids. Among the coefficients of main effects, concentration of NaCMC had the highest, but not necessarily, significant impact on FE and FD, by reducing FE and increasing FD. Interactions between variables also significantly influenced foam properties, for instance, interaction between concentration of GMS and NaCMC were significant, and positively influenced FE of both cassava foams. The stabilizing power of NaCMC could be due to characteristic ability of the charged hydrophilic colloid to increase viscosity (Stanley, Goff, & Smith, 1996), influence rheological properties and reduce collapse of the foams (Sangamithra, Sivakumar, Kannan, & John, 2015) by binding and adsorbing water molecules in tight conformations with other colloids (starch), unlike GMS which has stretched chain conformations due to its hydrophobic lipo-saccharide nature and steric interactions.

3.6.2 Surface color and total carotenoids content

Color perception is important in consumer preference for most foods. White cassava pulp, optimal foam, and foam powder were significantly light in color than the pulp, optimal foam and foam powder from yellow cassava. Generally, irrespective of variety, the foam powders were significantly light in color than optimal foams, which are in turn, light in color than pulps. This could be due to whitening resulting from whipping with the cream-white GMS colloid or moisture loss. As expected, the yellowness of the pulp, foam, and powder from yellow-flesh cassava was significantly higher than for white-flesh cassava. The reduction of intensity of yellowness of yellow-flesh cassava variety during processing from pulp to foam, and then to powder, could have resulted from progressive loss in TCC during the whipping and drying stages (Kandasamy, Varadharaju, & Kalemullah, 2012; Sangamithra, Sivakumar, et al., 2015) since carotenoids are susceptible to oxidation and thermal degradation (Boon et al., 2010). Whipping may have resulted in increased exposure to oxygen radicals that attack the conjugated bonds on carotenoids and probably forming some secondary compounds (Boon et al., 2010). Such decrease in total carotenoids has been reported for foam mat whipping and drying of mango (Wilson, Kadam, Chadha, & Sharma, 2012). Interestingly, about 76 % and 68 % of initial TCC in the yellow cassava pulp was retained when processed to foam and foam powder, respectively. Contrasting observation was found for yellowness (b^*) values of white cassava pulp and powder, possibly due to slight browning during drying. All cassava pulps, foams, and powders had hue angles closer to the yellow axis within the redness-yellowness spectrum of color space coordinate. Chroma was significantly higher for yellow cassava pulp, foam, and powder probably due to lower reflectance of other color wavelengths compared to white cassava pulp, foam, and powder respectively. Total color difference was higher, but not significantly different in foam powders than foams. Generally, the higher total color difference between yellow and white cassava pulp, foam, and foam powder, is also due to relatively higher TCC in materials made from yellow cassava. However, whitening effect of GMS and progressive degradation of carotenoids during foaming and drying further reduced the total color difference.

3.6.3 Microstructure

Cassava pulp consisted mostly of starch granules and apparently had few or no air bubble entrapped until whipped with GMS and NaCMC. For stable foam formation, addition of foaming agent and stabilizer is required (Bag, Srivastav, & Mishra, 2011; Sankat & Castaigne, 2004). This could be due to the poor composition of flexible fibrillar proteins (Graham & Phillips, 1976) in cassava. The round shape of foam air bubbles is conferred due to equal surface tension and internal pressure supported by the lamella layer and plateau border around the bubbles. Similar morphology have been reported for apple juice foams (Raharitsifa et al., 2006). Foam collapse occurs when lamella thins out, surface tension increase, or internal pressure increased (Raharitsifa et al., 2006). The positive skewed asymmetric distribution of air bubble size in the optimal foams is due to presence of higher numbers of smaller sized air bubbles, which have lower surface tension, and assist good foam structure for subsequent drying (Kolawole O. Falade & Okocha, 2012b). The smaller sized air bubbles in optimal white cassava foam may explain its marginally higher FE and lower FD than yellow cassava foam. Similar distribution pattern has been reported for starfruit foam (Karim & Wai, 1999). Overall, average air bubble size for both varieties was not significantly different, perhaps due to genetic similarities between them. This could have an influence on the rheology of the foams in food systems where formation of larger air bubble sizes with time could make the foam susceptible to collapse, resulting in lower viscosity.

The morphology of cassava foam powder is shown in Figure 3-4, and is typical of foam powders with porous surface. In this case, the foam powder is primarily made up of starch granules and other constituents in a continuous matrix with the hydrocolloids (GMS and NaCMC). Some degree of superficial association between the starch granules and other constituents is maintained by the porous hydrocolloids matrix, which could render the foam powder reconstitutable and serve some functional purpose in foods.

3.6.4 Total cyanogenic potential

The cyanogenic potential of cassava and its products is important in its safe consumption as food. The reduction in total cyanogens after foaming and drying may have been due to release of endogenous linamarase from tissue matrices to hydrolyse linamarine during pulping and whipping before drying. Hence, foaming of cassava could be a useful detoxification operation prior to drying. However, further processing may be considered for the pulp before foaming and drying in attaining more reduction in cyanogenic potential to safe limits (<10 µg/g) set by *Codex Alimentarius Commission* (FAO, 1991). For instance, the cassava pulp may be subjected to some fermentation under controlled conditions for further reduction of cyanogenic glucosides before whipping to foams and dried. Literature has shown that fermentation assists in satisfactory detoxification of cassava (Ayetigbo et al., 2018; Julie A. Montagnac et al., 2009b). Alternatively, exogenous linamarase (Nwokoro, 2016) may be added to cassava pulp and allowed sufficient activity under suitable conditions before foaming and drying. This was not considered in this work since pulping, foaming, and drying were conducted successively. More studies in achieving further detoxification is in progress.

3.7 Conclusion & recommendations

In finding other pathways for utilizing cassava, foam powders were produced from two varieties of the crop by optimizing the foaming process conditions, such as the concentrations of foaming agent and stabilizer, and the whipping time. Response surface models adequately estimated foam properties, allowing the prediction of optimal conditions for making foams from cassava pulp. The optimal foams were stable, due to low tendency to collapse, therefore, making them possible to be dried into powder. Foams from white and yellow cassava varieties differ in terms of microstructure, total carotenoids content, color and cyanogenic toxicity. Cassava foam powder may be useful in foam- or cream-based foods as ingredient to functionally substitute animal-based ingredients in vegetarian diets if varieties with low total cyanogenic glucosides are used or suitable additional processing is conducted to reduce the total cyanogenic glucosides to acceptable limits. Studies on rheological properties, functional properties, drying kinetics and actual food use of cassava foam or foam powder are recommended.

3.8 Conflict of Interest

The authors declare no conflict of interest.

3.9 Acknowledgement

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4 Part III: Drying kinetics and effect of drying conditions on selected physicochemical properties of foam from yellow-fleshed and white-fleshed cassava (*Manihot esculenta*) varieties

4.1 Abstract

Fresh cassava is highly susceptible to rapid post-harvest physiological deterioration due to the high water activity. Therefore, foam mat drying was considered as an alternative drying technique for preservation. The drying kinetics of white-fleshed cassava foam (air volume fraction = 0.26, overrun = 36.0 %) and yellow-fleshed cassava foam (air volume fraction = 0.24, overrun = 32.2 %) were studied. The influence of temperature and foam thickness on moisture removal ratio (MR), drying rate, diffusivity and some important physicochemical properties of the cassava foams (CSF) during drying were researched and compared with those of non-foamed cassava pulp (NFP). The cassava foams were dried to foam powders at temperatures of 50 ^{o}C, 65 ^{o}C and 80 ^{o}C and foam thicknesses of 6 mm, 8 mm and 10 mm. The CSF exhibited two falling rates. The CSF powders had significantly lower total cyanogenic glucosides content compared to the NFP powder, and a high retention of total carotenoids. The dry foam powders had higher lightness/luminosity (L*) values than dry pulp powders. Micrographs revealed interactions between starch granules and the hydrocolloids but microstructure was not affected by increasing temperatures.

Keywords: Cassava foam; Foam thickness; Cyanogenic glucosides; Falling rate; Moisture diffusion; Microstructure

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Highlights

- Drying rate of cassava foams occurred over two falling rate regimes
- Yellow cassava foam powder retained up to 82 % and 36 % of carotenoids in pulp and root
- The cyanogenic potential of cassava foams reduced to safe levels by foam mat drying
- Foam mat drying of cassava evidently influenced microstructure and colour values

4.2 Introduction

Cassava is a very important crop to sustain livelihoods and food security for a considerable part of Africa, Asia and South America. Unfortunately, the freshly harvested cassava is susceptible to rapid postharvest physiological deterioration, which makes it almost impossible to store it over longer periods. Hence, it is imperative for cassava to be processed immediately after harvest. Of the various processes that have been developed to process cassava into edible foods, drying, boiling, pounding, pressing, steaming and frying are quite common in West Africa. However, these processes often do not reduce the cyanogenic potential low enough for immediate consumption (Montagnac et al., 2009), especially when cassava varieties with a higher cyanogenic glucosides content are used. In such cases, retting, fermentation and hydraulic pressing are usually considered alone or in combination with other processes, to reduce the cyanogenic potential to acceptable levels before further processing. However, fermentation and hydraulic pressing processes are time consuming, require high industrial investment, lead to lower retention of carotenoids in yellow cassava, may produce off-flavour products (for instance in *fufu*) and has a negative environmental impact often associated with the usually practiced uncontrolled fermentation and pressing. The yellow-fleshed cassava variety is targeted at improving vitamin-A provision of populations deficient of this nutrient. Sun drying of cassava as pellets or chips commonly practised in the developing regions often does not reduce cyanogenic glucosides to acceptable levels due to bulk exposure and non-intricate contact between linamarin and linamarase. Freeze-drying and flash drying did not reduce total cyanogenic potential of cassava roots to acceptable levels, as reported in a review (Montagnac et al., 2009). In this study, foam-mat drying was considered as a simple drying technique to dry cassava pulp, reduce cyanogenic glucoside toxicity to safe levels without the need for fermenting and pressing, while enhancing carotenoids retention in yellow cassava. In addition, a more functional and attractive foam powder can be produced compared to non-foamed cassava flour (Asokapandian et al., 2016; Azizpouret al., 2014). Improving the value addition and utilization of cassava by producing cassava foam and foam powder to be used as food or food ingredient is a contribution to recent agricultural government policies in developing countries who are keen on improving the utilization of cassava in the cassava value chain. This is particularly true because the value addition and diversification of cassava utilization beyond starch and flour production is still underdeveloped, apart from the common use of cassava for the production of food products such as *gari*, *fufu*, *lafun* and animal feed. A good understanding of the drying behaviour of cassava foams into foam powders could contribute in this respect, as foams and foam powders are potentially suitable for use as food foam or for cream-based applications.

Reports are available in the literature on the foaming of cassava (Ayetigbo et al., 2019; Kaisangsri et al., 2012; Salgado et al., 2008) for food and non-food use. However, none has addressed the drying kinetics of cassava foam, and the effect of foam mat drying conditions on the microstructure, cyanogenic glucosides, colour, and especially, the carotenoids content of yellow-fleshed cassava in comparison to white-fleshed cassava. Therefore, in this work, the drying of cassava foam into foam powder was undertaken with a focus to understand the influence of drying conditions such as temperature and foam thickness on the drying kinetics. In addition, the influence of the drying conditions on some physicochemical properties such as colour, total carotenoids content, cyanogenic glucosides content, and morphological properties of cassava foam (CSF) powder was studied and compared to non-foamed pulp (NFP) powder.

4.3 Materials and Methods

A waxed white-fleshed variety of cassava, imported to Germany from Costa Rica, was bought from a store in Stuttgart, Germany. A waxed yellow-fleshed variety (TMS-IBA 011368) harvested from the cassava research farm of the International Institute of Tropical Agriculture (IITA), Nigeria was shipped by airfreight. The roots were stored briefly at 3 ^{o}C before use. Glycerol monostearate (GMS) as a food grade foaming agent, and sodium carboxy-methylcellulose (NaCMC) as a stabiliser were also purchased (MRS Scientific Ltd., Essex, UK).

4.3.1 Production of cassava foam

Previous experiments (Ayetigbo et al., 2019) with optimization by response surface methodology have revealed that optimal white cassava foam can be produced by whipping the white cassava pulp (1.5 ^{o}Brix, moisture content 9.31 g/g db) with about 15 % GMS colloid (20 % w/w) and 0.5 % NaCMC for about 2 min, while optimal yellow cassava foam can be produced by whipping the yellow cassava pulp (1.8 ^{o}Brix, moisture content 15.67 g/g db) with about 14 % GMS colloid (20 % w/w) and 0.6 % NaCMC for 2 min. From cassava foam and pulp density data obtained in previous report (Ayetigbo et al., 2019), the air volume fraction (ϕ) and foam overrun (*FO*) of the optimal cassava foams were calculated (Franco et al., 2015b):

$$\phi = 1 - \frac{\rho_f}{\rho_p} \tag{4-1}$$

$$FO = \left(\frac{\rho_p}{\rho_f} - 1\right) \cdot 100\ \% \tag{4-2}$$

where ρ_f is the foam density (g/cm^3) and ρ_p is the pulp density (g/cm^3), neglecting air density.

The pulp prepared to produce foam was initially kept overnight (12 h) under refrigeration (3 ^{o}C) to allow for some interaction between endogenous linamarin and linamarase while avoiding a possible off-flavour that may result from fermentation if kept at room temperature. The average moisture content of the white and yellow cassava foams was 8.01 g/g db and 9.53 g/g db, respectively.

4.3.2 Drying of cassava foam

The optimal foams were dried in a cabinet dryer (Hordentrockner HT 15, Innotech Ingenieurgesellschaft mbH, Altdorf, Germany). The dryer has a dimension of 1.4 m x 1.75 m x 2.3 m, drying space of 15.7 m^2, 51 perforated trays stacked 100 mm from one another, and a maximum capacity of 160 kg per batch. The dryer is operated with two fans with a control unit maintaining constant air velocity (U-control, Ziehl-Abegg, Künzelsau, Germany) as well as a temperature control unit and a display. The foams were carefully filled and spread evenly into stainless steel pans, 360 mm long and 150 mm wide, with heights of 6 mm, 8 mm and 10 mm, regarded as the foam thickness (*F*) in this study. The pans were placed in the centre position of the dryer. The average air velocity in the drying chamber position was 0.87 m/s. The foams were dried at different temperatures 50, 65 and 80 ^{o}C until the mass of the dry foam sheet remained unchanged in two consecutive measurements. Measurements of mass were taken in 2 h intervals. Drying was conducted in duplicates. The dried foam flakes scraped from the pans were gently milled into powder using a coffee blender (Alaska KM 150S, Fulltrade International GmbH, Düsseldorf, Germany). From previous laboratory trials, the optimal drying conditions for white CSF was 80 ^{o}C and 10 mm foam thickness, while the optimal drying conditions for yellow CSF was 80 ^{o}C and 8 mm foam thickness. Therefore, NFP was also dried applying a temperature of 80 ^{o}C and a foam thickness of 10 mm for white NFP, and 8 mm for yellow NFP.

4.3.3 Drying kinetics

Applying Fick's second law of diffusion, Crank (1975) developed a mathematical solution to describe diffusion of mass by solving the terms of the Fourier series for mass transfer in a slab under certain assumptions as:

$$\eta = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}exp(-(2n+1)^2\cdot\frac{\pi^2}{4L^2}\cdot D_{eff}\cdot t) \qquad (4\text{-}3)$$

where D_{eff} (m^2/s) is the effective moisture diffusivity, L (m) is half the thickness of the slab, t (s) is the time, n is the number of terms in the series and η is a dimensionless concentration. In this study, the numerical solution for the first three terms of the series was considered (equation 4-4), as additional terms had insignificant changes on the solution.

The dimensionless moisture removal ratio MR was calculated from the following equation (Singh et al, 2011):

$$MR = \frac{8}{\pi^2}\cdot exp(-\pi^2\frac{D_{eff}\cdot t}{4L^2}) + \frac{8}{9\pi^2}\cdot exp(-9\pi^2\frac{D_{eff}\cdot t}{4L^2}) + \frac{8}{25\pi^2}\cdot exp(-25\pi^2\frac{D_{eff}\cdot t}{4L^2}) = \frac{MC_t - MC_e}{MC_0 - MC_e} \qquad (4\text{-}4)$$

where MC_t (g/g) is the moisture content at a given time, MC_0 (g/g) is the initial moisture content, and MC_e (g/g) is the equilibrium moisture content. MR was calculated as the ratio of MC_t to MC_0 since the equilibrium moisture content MC_e was considered negligible:

$$MR = \frac{MC_t}{MC_0} \qquad (4\text{-}5)$$

Diffusivity was determined by non-linear regression fitting of equation (4-4). From the derived diffusivity, the relationship between temperature and diffusivity was affirmed by an Arrhenius-type equation (4-6), and activation energy and diffusion constant were determined graphically:

$$D_{eff} = D_o\cdot exp[\frac{-E_a}{R(T+273.15)}] \qquad (4\text{-}6)$$

where D_{eff} (m^2/s) is the effective diffusivity, D_o (m^2/s) is the diffusion constant, E_a (J/mol) is the activation energy, R is the universal gas constant (8.3144598 J/mol K) and T (°C) is the temperature.

Drying rate (*DR*) was calculated as:

$$DR = \frac{MC_t - MC_{t+\Delta t}}{\Delta t} \quad (4\text{-}7)$$

where $MC_{t+\Delta t}$ is the instantaneous moisture content (db) at time $t + \Delta t$, which is the time interval (h).

The relationship between the *DR* and moisture content during drying was modelled by the Rational Model (Tjørve, 2003):

$$DR = (a + b \cdot MC) \cdot \frac{1}{1 + c \cdot MC + d \cdot MC^2} \quad (4\text{-}8)$$

where *MC* (g/g) is the moisture content in dry basis, and *a*, *b*, *c*, and *d* are the model coefficients.

4.3.4 Colour

The colour of foam was measured at the beginning and the end of the drying process using a colorimeter (Chromameter CR 410, Konica Minolta, Sensing Inc., Tokyo Japan). The optical sensor lens was set at 2° observer and illuminated by D65 light. Colorimeter was calibrated with a standard white tile (Y = 93.0, x = 0.3167, y = 0.3338). Measurements of L^* (lightness-darkness), a^* (redness-greenness) and b^* (yellowness-blueness) colour values were taken remotely in six replications using a software interface (CM-S100w SpectraMagic NX, version 2.7). Colour differences between white and yellow cassava foam powders was calculated as ΔL^*, Δa^*, Δb^*. Total colour difference (ΔE^*), which represents difference between total colour values of yellow and white cassava foam powders was determined, with colour values of white cassava foam powder as reference. The equations used are as shown below:

$$\Delta L^* = L^*_{yellow} - L^*_{white} \quad (4\text{-}9)$$

$$\Delta a^* = a^*_{yellow} - a^*_{white} \quad (4\text{-}10)$$

$$\Delta b^* = b^*_{yellow} - b^*_{white} \quad (4\text{-}11)$$

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (4\text{-}12)$$

4.3.5 Total carotenoids content (TCC)

The method described by Ceballos et al. (2012) was used to determine the total carotenoids content (µg/g) of foam powder from yellow cassava. A sample of about 3 g was vortexed (IKA Genius model VG3, IKA laboratory equipment, Staufen, Germany) with 10 mL of acetone in a falcon tube and allowed to stand for 10 min. The mixture was homogenized (Ultra-Turrax T 25, IKA Labortechnik, Janke & Kunkel GmbH & Co. KG, Staufen, Germany) with 10 mL of petroleum ether for a minute. The homogenate was centrifuged at 3000 rpm for 10 min at 10 °C and the carotenoids-rich phase was separated. This extraction-separation process was repeated three times with half the initial volume of the extraction solvents. All extracts were combined and washed three times with 10 mL of 0.1M NaCl solution and centrifuged as described earlier. The refined organic phase was pipetted, adjusted to 15 mL with petroleum ether and the absorbance was read at 450 nm with a spectrophotometer (DR 6000, Hach Lange GmbH, Berlin, Germany). The TCC was calculated as described by Jaeger DeCarvalho et al. (2012).

4.3.6 Total cyanogenic glucosides content (TCG)

The total cyanogenic potential of cassava foam powder, assayed as total HCN equivalent, µg/g, was determined by a modified picrate paper kit method (Bradbury et al., 1999). Linamarase was extracted according to the method of Haque and Bradbury (2004). About 0.1 g of the sample was filled into a plastic vial, and 1 mL of 0.1M sodium phosphate buffer (pH 6) and 0.1 mL of the linamarase extract was added. A picrate paper glued to a plastic strip was inserted into the vial right above the mixture without contact, and the vial was capped tightly. An incubation at 30 °C for 24 h allowed the release of free hydrocyanide (HCN) from the mixture. Standard linamarin concentrations (0.4, 0.8 and 1.6 µmol) and a blank were subjected to a similar procedure. The reacted picrate paper was eluted in 5 mL of distilled water for 45 min and the absorbance was measured at 510 nm by a spectrophotometer (Hach Lange DR 6000, Hach Lange GmbH, Berlin, Germany). The TCG was determined from the calibration curve of linamarin standards.

4.3.7 Microscopic imaging

A microscopic study of foam powder was conducted using a remission scanning electron microscope (JSM-IT 100, JEOL GmbH, Freising, Germany) at an accelerating voltage of 5 kV and a probe current of 17 mA at 11-15 mm working distance. Samples were glued to carbon discs or copper sticking tape on the end of a gold-plated cylinder and placed on the sample platform. Images were displayed and captured digitally on an interface of a dedicated software (In Touch Scope, version 1.090, JEOL Technics Ltd., Freising, Germany).

4.4 Statistical analyses

Data were presented as mean ± standard deviation. Separation of means by Duncan ad hoc test and analysis of variance (ANOVA) was conducted using SPSS 16.0® (SPSS Inc., Chicago, Illinois, USA). Multiple regression analysis was made by Microsoft Excel® 2007 (Microsoft, Redmond, WA, USA). Mathematical fitting of experimental data was carried out using Curve Expert professional 2.6. The accuracy of the model fit was evaluated by coefficient of determination (R^2), root mean square error (RMSE), and Chi square (χ^2) (Ferrari and Hubinger, 2008; Franco et al., 2017; Kim et al., 2009; Salim et al., 2016).

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{n}(X_{exp}-X_{pred})^2}{\sum_{i=1}^{n}(X_{exp}-\overline{X}_{exp})^2}\right) \quad (4\text{-}13)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_{pred}-X_{exp})^2} \quad (4\text{-}14)$$

$$\text{Chi square } (\chi^2) = \sum_{i=1}^{n}\frac{(X_{exp}-X_{pred})^2}{X_{pred}} \quad (4\text{-}15)$$

where X_{exp} are the measured values, X_{pred} are the predicted values, and n is the number of observations.

4.5 Results and discussion

4.5.1 Drying kinetics

4.5.1.1 Moisture removal ratio (MR) of cassava foams during drying

The MR decreased as temperature increased (Fig 4-1) for all the cassava foams during drying. An increase in foam thickness resulted in an increased MR for the drying of the cassava foams. In comparison, MR of the NFP was lower than that of the corresponding cassava foam at any given time during drying. Hence, the drying conditions favoured a more rapid drying of the NFP. This may be due to the occlusion of starch and other constituents of cassava in the matrices of the stabilizer and foaming agent. In addition, the effect of gelatinisation of starch, presence of several air bubbles and the increased solids content and viscosity in the foam (Franco et al., 2015) may restrict diffusion during drying. This is contrary to some results published in other works (Kandasamy et al., 2014; Rajkumar et al., 2007), but similar to the report of Chaux-gutiérrez et al. (2017) on non-foamed mango pulp, which took a shorter time to dry at 60 ^{o}C than mango pulp foamed with a commercial grade emulsifier blend. Also, non-foamed egg white dried faster than Xanthan gum foamed egg white on the same mass basis in the work of Muthukumaran et al. (2008).

Therefore, foam mat drying did not necessarily lead to a reduced drying time in this work. For example, when dried at 80 ^{o}C, 10 mm thickness for white cassava and 80 ^{o}C, 8 mm thickness for yellow cassava, the experimental average drying time (to 10 % MC) for white and yellow NFP was 4.3 h and 4.0 h, respectively, compared to 9.2 h and 5.9 h for the respective CSF. The drying times of the CSF were similar to those in other reports (Asokapandian et al., 2016; Kandasamy et al., 2014; Rajkumar et al., 2007), where the drying

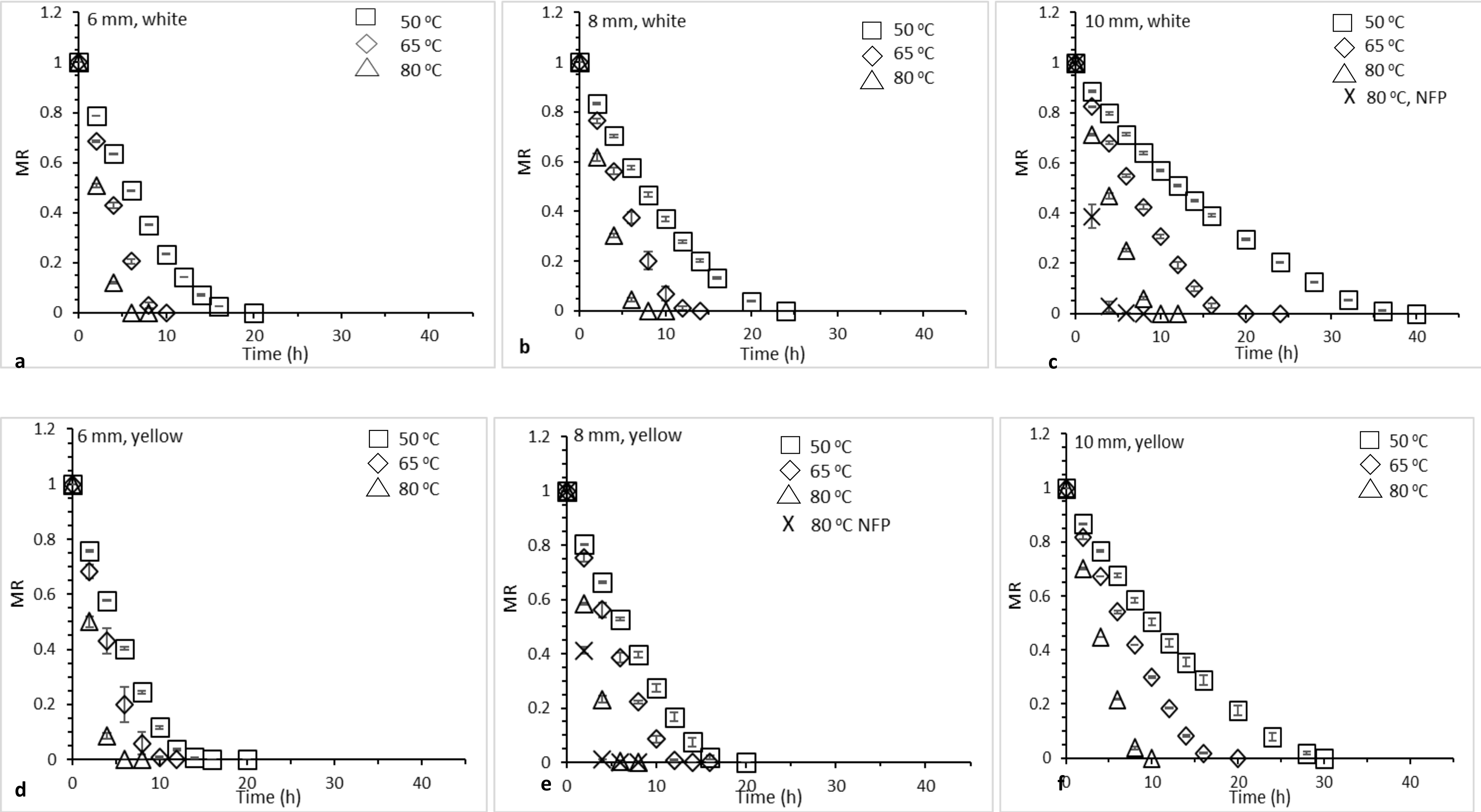

Figure 4-1 Effect of temperature and foam thickness on moisture removal ratio (*MR*) during drying of white cassava foam (a-c) and yellow cassava foam (d-f). NFP = non-foamed pulp. Error bars represent standard deviation

time increased with foam thickness and decreased with temperature increase. The influence of air bubbles may affect drying characteristics of the foams compared to the pulp. The white cassava foam had significantly higher air volume fraction (ϕ) of 0.26, compared to that of yellow cassava foam which was 0.24. Similarly, the foam overrun (*FO*) of white cassava foam was 36.0 %, significantly higher than for yellow cassava foam of 32.2 %. These may have contributed to the differences in the drying kinetics. Higher ϕ and *FO* indicate greater degree of air incorporation in foam, which may influence heat transfer.

4.5.1.2 Drying rate of cassava foams and non-foamed cassava pulp during drying

The cassava foams had sigmoidal drying rate versus moisture content profiles, undergoing two falling rates during drying as shown exemplarily in Fig 4-2. The Rational model fitted the first falling rate accurately (R^2 = 0.8971 – 0.9999, RMSE = 7.35 x 10^{-6} - 0.0439, χ^2 = 2.23 x 10^{-10} – 0.0197), and the second falling rate accurately (R^2 = 0.9974 – 0.9999, RMSE = 7.55 x 10^{-7} – 0.0175, χ^2 = 3.32 x 10^{-12} – 0.0514), thereby signifying a distinction between the two falling rates. The coefficients of the model and the estimated boundary moisture contents (0.0459 – 1.531 g/g) where the first falling rate transits into the second falling rate are shown in Table 4-1. The first falling rate is characterised by a steep drying rate gradient in the early phases of drying, which decelerated with further drying. The second falling rate period is characterised by a steeper descent in the drying rate. This drying pattern may be due to a rapid rate of moisture diffusion at the free moisture-rich upper layers of the foam at inception of drying. The diffusion then decreases due to a reduced moisture transfer from underlying layers to the upper layers, possibly due to numerous air bubbles in the foam causing low thermal conductivity. The continual loss of air bubbles due to surface tension may have resulted in opening up of ‘honey-comb-like’ pores. This process may have improved the moisture removal until diffusion increased again and a steep second falling rate occurred. This drying rate pattern is also documented in the work of Cooke et al. (1976) and Sankat and Castaigne (2004) on the foaming of mango puree and ripe banana, respectively, and is characteristic of some food foams

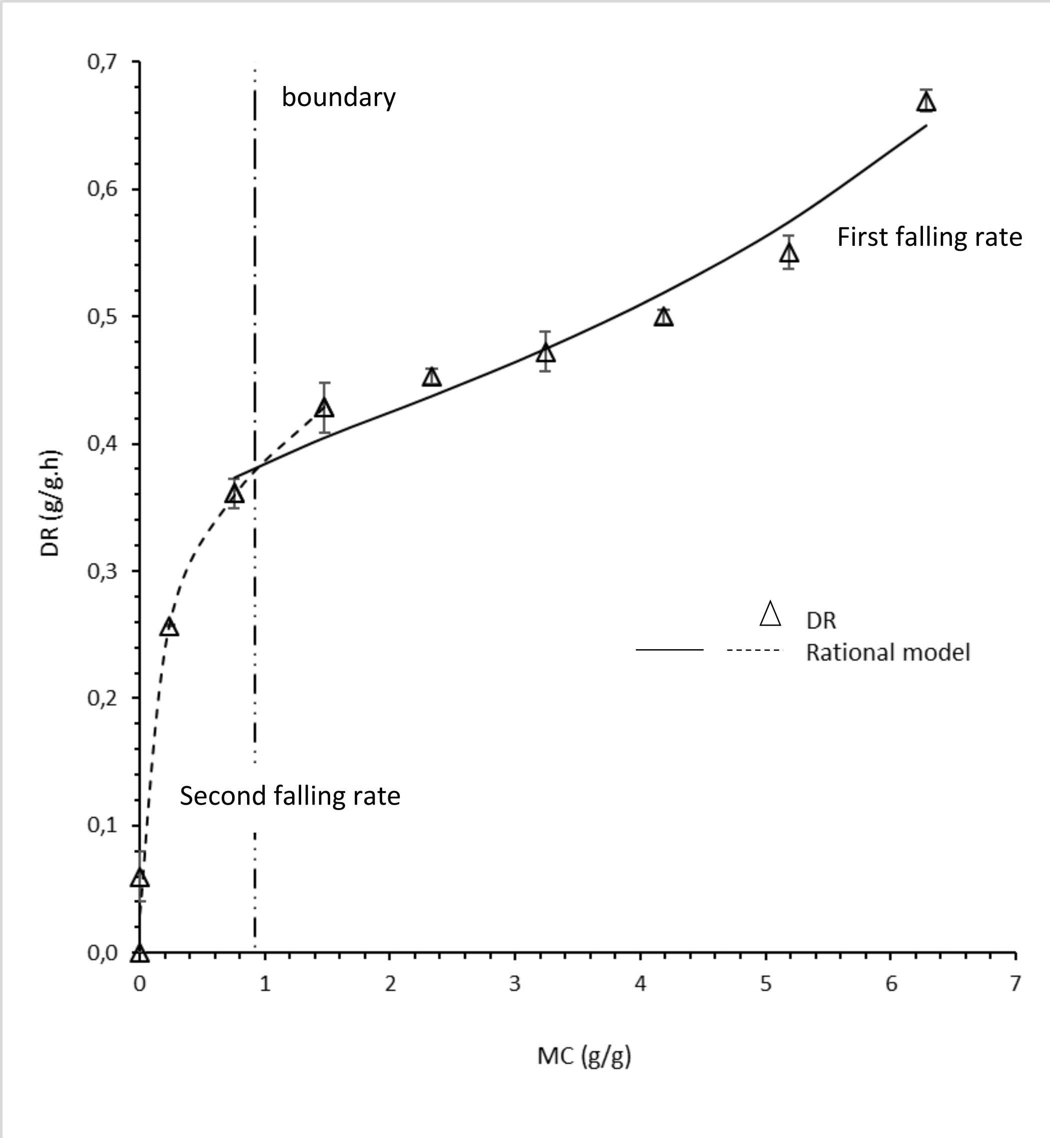

Figure 4-2 Drying rate (DR) versus moisture content (MC) course showing first falling rate and second falling rate fitted by Rational model and the boundary between both falling rates (65 ºC, 10 mm, white cassava foam)

Table 4-1 Model coefficients and accuracy for drying rate (DR) versus moisture content (MC) relationship, and estimated boundary moisture content between the two falling rates during drying of white and yellow cassava foams and non-foamed pulp (NFP)

Rational model	Coefficients. accuracy										NFP
Foam thickness		6 mm			8 mm			10 mm			10 mm
Temperature		50 ºC	65 ºC	80 ºC	50 ºC	65 ºC	80 ºC	50 ºC	65 ºC	80 ºC	80 ºC
					White						
First falling rate	a	-10.875	0.00559	0.162	0.0149	-0.0257	0.0200	0.0238	-0.405	0.0205	-0.0274
	b	56.859	20.420	293.241	0.895	4.215	34.403	1.439	18.174	35.765	15.664
	c	141.114	26.471	207.670	2.683	6.136	28.268	9.402	48.388	48.025	5.327
	d	-11.743	-1.837	-13.793	-0.219	-0.285	-1.481	-0.919	-3.292	-2.876	-0.0507
	R^2	0.9612	0.9988	0.9999	0.9775	0.9899	0.9999	0.9868	0.9613	0.9999	0.9999
	RMSE	0.0312	0.00665	0.000014	0.0168	0.0134	0.000148	0.00924	0.0179	0.000710	0.000514
	χ^2	0.0115	0.000189	1.07×10^{-9}	0.00471	0.00119	5.03×10^{-8}	0.00333	0.00457	2.24×10^{-6}	6.51×10^{-6}
Second falling rate	a	0.0466	0.109	0.000777	0.0725	0.0466	0.000668	0.0222	0.0275	0.00132	0.000499
	b	1.241	6.539	432.689	0.737	2.702	175.975	1.191	2.745	115.686	12.736
	c	3.443	5.788	283,212	2.096	3.447	128.365	7.057	7.093	123.723	3.615
	d	-0.616	0.869	4.915	-0.0312	-0.0557	57.269	-0.0271	-0.898	68.542	0.0999
	R^2	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999
	RMSE	3.21×10^{-6}	7.55×10^{-7}	4.28×10^{-6}	8.72×10^{-6}	1.34×10^{-5}	3.94×10^{-6}	0.00019	0.0175	3.70×10^{-6}	0.00258
	χ^2	4.05×10^{-10}	3.32×10^{-12}	3.09×10^{-8}	1.39×10^{-9}	8.16×10^{-9}	6.39×10^{-10}	1.35×10^{-6}	0.0514	2.30×10^{-9}	0.0399
	Total χ^2	0.0115	0.000189	3.19×10^{-8}	0.00471	0.00119	5.09×10^{-8}	0.00333	0.0560	2.24×10^{-6}	0.0399
	Estimated boundary MC (g/g)	1.061	0.600	0.932	1.531	0.900	0.404	0.928	0.920	0.465	0.255
					Yellow						8 mm
											80 ºC
First falling rate	a	0.0365	-74.341	0.277	0.0447	0.306	0.0455	0.0195	0.837	0.0291	-0.517
	b	8.535	364.151	226.655	10.705	7.862	71.889	1.519	6.564	14.217	139.271
	c	14.926	349.483	125.865	24.855	12.526	49.563	6.467	15.669	14.346	33.134
	d	-1.027	-16.503	-5.443	-1.686	-0.796	-2.145	-0.513	-1.004	-0.637	-0.966
	R^2	0.9316	0.9859	0.9999	0.8971	0.9757	0.9999	0.9640	0.9640	0.9899	0.9999
	RMSE	0.0427	0.0343	7.35×10^{-6}	0.0439	0.0255	2.53×10^{-5}	0.0177	0.0205	0.0196	$8,67\times10^{-5}$
	χ^2	0.0115	0.00409	2.23×10^{-10}	0.0197	0.00387	1.61×10^{-9}	0.00776	0.00518	0.00134	1.85×10^{-7}
Second falling rate	a	0.00702	0.0332	0.000289	0.0421	0.000939	0.0228	0.0707	0.0392	0.169	0.0115
	b	2.276	4.213	828.062	2.150	13.974	59.091	0.826	3.348	7.239	18.983
	c	3.380	5.210	447.077	3.761	23.128	36.431	3.525	6.059	6.315	0.486
	d	-0.264	-0.946	0.517	0.100	-2.273	0.257	-0.364	-0.0510	0.0104	0.158
	R^2	0.9998	0.9999	0.9999	0.9999	0.9999	0.9999	0.9974	0.9999	0.9999	0.9999
	RMSE	0.00386	1.05×10^{-5}	4.17×10^{-6}	7.60×10^{-6}	8.79×10^{-5}	7.28×10^{-6}	0.00382	0.000948	6.21×10^{-6}	0.00624
	χ^2	0.00433	3.56×10^{-9}	4.01×10^{-9}	2.53×10^{-9}	1.67×10^{-5}	4.10×10^{-9}	0.000376	9.36×10^{-6}	1.93×10^{-10}	0.00774
	Total χ^2	0.0158	0.00409	4.23×10^{-9}	0.0197	0.00389	5.72×10^{-9}	0.00813	0.00519	0.00134	0.00774
	Estimated boundary MC (g/g)	1.009	0.900	0.761	0.663	0.766	0.0459	0.636	0.736	0.339	0.212

that exhibit falling rates as has been reported in other literature (Kandasamy et al., 2014; Rajkumar et al., 2007). Similarly, the NFP had two falling rates and a higher drying rate and dried more rapidly than the cassava foams. This could be due to the more rapid moisture diffusion between the drying air, upper layer, and the underlying layers, particularly, since fewer air bubbles are present to suppress thermal conductivity.

Generally, as foam thickness increased, the initial drying rate decreased, drying time increased and moisture content was higher, at fixed drying points (Fig 4-3). However, as drying temperature increased, initial drying rate increased, drying time decreased and moisture content was lower, at fixed drying points. Generally, the moisture content at the region where the first falling rate transits into the second falling rate decreased as temperature and foam thickness increased. The Rational model coefficients had no trend with temperature and foam thickness.

4.5.1.3 Effective moisture diffusivity (D_{eff}) and activation energy (E_a) of cassava foams during drying

The drying of the cassava foams occurred at the falling rates periods, and is a diffusion-controlled process (McMinn and Magee, 1999). Generally, the effective moisture diffusivity (R^2 = 0.9024 – 0.9696) increased significantly with temperature but not with foam thickness (Table 4-2). Increasing diffusivity with increase in temperature may have resulted from an increased excitation of water molecules breaking off from the matrices of the foams. Similar findings have been reported for foamed shrimps (Azizpour et al., 2013; Azizpour et al., 2014). The D_{eff} was slightly higher for yellow cassava foams than for white cassava foams, therefore, varietal differences may have influenced moisture diffusivity. Diffusion constant (D_o) was not significantly influenced by foam thickness either, but white cassava foams had corresponding higher D_o than yellow cassava foams.

The E_a (Table 4-2) for drying of white (37 – 44 kJ/mol) and yellow (31 – 38 kJ/mol) cassava foams did not significantly change with increasing foam thickness.

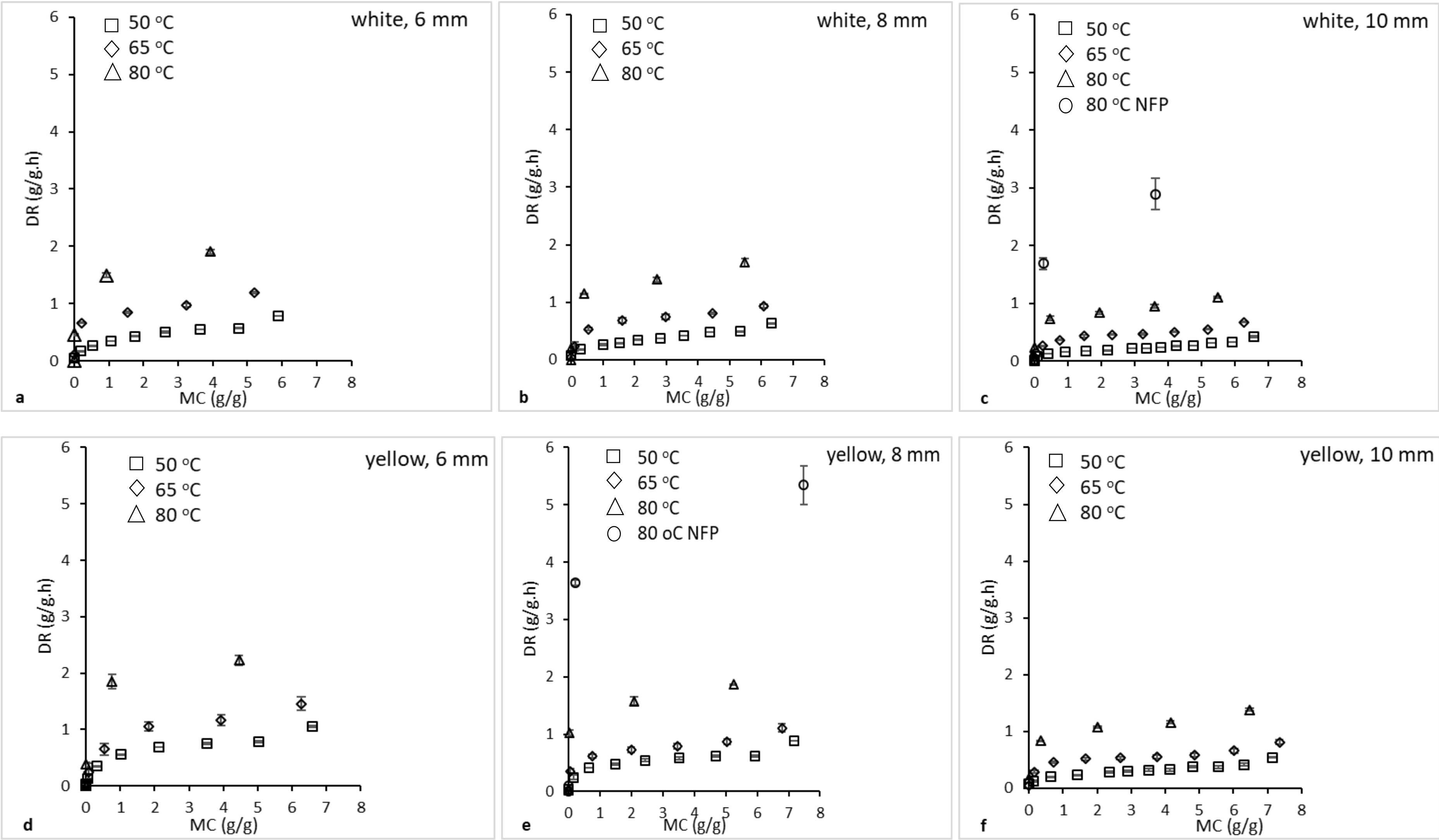

Figure 4-3 Effect of temperature and foam thickness on the drying rate (DR) versus moisture content (MC) relationship when drying white cassava foam (a-c) and yellow cassava foam (d-f). NFP = non-foamed pulp; error bars represent standard deviation.

Table 4-2 Effective diffusivity (D_{eff}) and activation energy (E_a) during the drying of white and yellow cassava foams

Foam thickness (mm)	6			8			10		
Temperature (°C)	50	65	80	50	65	80	50	65	80
				White					
D_{eff} x 10^{-10} (m^2/s)	4.7 ± 0.00^{f}	8.5 ± 0.4^{e}	15.3 ± 0.2^{c}	6.1 ± 0.2^{f}	11.2 ± 1.3^{d}	20.1 ± 0.9^{b}	5.5 ± 0.1^{f}	11.5 ± 0.5^{d}	22.2 ± 0.4^{a}
D_o x 10^{-4} (m^2/s)			5.2 ± 0.5^{b}			9.1 ± 7.7^{b}			71.1 ± 1.2^{a}
E_a (kJ/mol)			37.4 ± 0.3^{b}			37.6 ± 2.6^{b}			43.9 ± 0.0^{a}
				Yellow					
D_{eff} x 10^{-10} (m^2/s)	5.9 ± 0.1^{e}	8.8 ± 1.9^{d}	16.0 ± 0.4^{b}	7.7 ± 0.5^{de}	11.2 ± 0.8^{c}	22.4 ± 0.6^{a}	6.9 ± 0.5^{de}	11.6 ± 0.1^{c}	22.8 ± 0.1^{a}
D_o x 10^{-4} (m^2/s)			0.6 ± 0.2^{a}			2.2 ± 1.8^{a}			9.7 ± 7.3^{a}
E_a (kJ/mol)			31.0 ± 0.5^{b}			33.4 ± 2.6^{ab}			37.7 ± 2.4^{a}

Mean and standard deviation in rows followed by same letters are not significantly different ($P \leq 0.05$).

The E_a of white cassava foams was significantly higher than for yellow cassava foams during drying when considering similar foam thickness. The E_a values presented in this work are close to those values reported in the literature for other foamed foods (Azizpour et al., 2013). The diffusivity of non-foamed white cassava and yellow cassava pulp was 5.7 x 10^{-9} m^2/s (R^2 = 0.9614 – 0.9790) and 3.5 x 10^{-9} m^2/s (R^2 = 0.9579 – 0.9665), respectively, and significantly higher than those of the corresponding white cassava foam and yellow cassava foam, respectively. This is contrast to the work on drying muskmelon foam where non-foamed materials had lower diffusivities (Asokapandian et al., 2016).

4.5.2 Physicochemical properties of cassava foams during drying

4.5.2.1 Total carotenoids content (TCC)

An important characteristic of the yellow-fleshed cassava is its higher carotenoids content compared to the conventional white-fleshed one, which has a negligible content or no content of carotenoids (Ayetigbo et al., 2018). In this work, TCC of dried CSF powders ranged between 7.77 – 11.74 µg/g (Table 4-3), compared to 14.29 µg/g for NFP powder, thereby apparently retaining between 54 – 82 % of the initial TCC in the pulp powder. However, compared to fresh yellow cassava root, the foam powder retained 24.1 – 36.3 % of the total carotenoids, while NFP powder retained 44.2 %. This is advantageous, considering that pulp was further subjected to whipping into foam and some loss of carotenoids may have occurred before both were dried to powders. The retention of carotenoids is similar to those found in the work of Ayetigbo et al. (2019). The TCC of the yellow CSF powders were higher than those of oven-dried yellow cassava flour, and yellow cassava dried by sun drying and oven drying in other studies (Oliveira et al., 2010; Vimala et al., 2011). There was a significant reduction in TCC of the cassava foams with increasing temperature during drying, but foam thickness did not significantly affect TCC. Kandasamy et al. (2014) and Rajkumar et al. (2007) have reported a significant reduction in β-carotenes during the drying of papaya and mango foams, respectively, with similar trends at increasing temperature and foam thickness. The loss of TCC may be associated with thermal degradation and oxidation due to the hot air drying, as similarly reported for tomato foam powder by Sramek et al. (2015).

Table 4-3 Effect of drying temperature and foam thickness on total carotenoids content (TCC), total cyanogenic glucosides content (TCG), and colour of white and yellow cassava foam powder in comparison to non-foamed pulp (NFP) powder

				6 mm			8 mm			10 mm			NFP
				50 ºC	65 ºC	80 ºC	50 ºC	65 ºC	80 ºC	50 ºC	65 ºC	80 ºC	
TCC (µg/g)	Yellow			10.96 ± 0.83^{b}	11.12 ± 0.15^{b}	9.44 ± 1.46^{bc}	11.17 ± 0.74^{b}	7.78 ± 0.15^{c}	10.39 ± 1.50^{bc}	11.74 ± 1.40^{ab}	7.77 ± 0.57^{c}	10.94 ± 1.88^{b}	14.29 ± 1.42^{a}
TCG (µg/g HCN, db.)	White			11.20 ± 6.53^{d}	12.93 ± 8.09^{d}	6.89 ± 0.78^{d}	5.99 ± 2.80^{d}	27.12 ± 1.13^{c}	38.02 ± 1.31^{b}	5.62 ± 0.48^{d}	23.61 ± 1.86^{c}	29.09 ± 0.03^{c}	67.87 ± 6.03^{a}
	Yellow			0.65 ± 0.00^{c}	0.78 ± 0.65^{c}	5.90 ± 2.20^{b}	1.31 ± 0.44^{bc}	3.59 ± 2.94^{bc}	1.58 ± 0.42^{bc}	3.91 ± 0.93^{bc}	3.19 ± 1.06^{bc}	1.14 ± 0.23^{bc}	264.89 ±5.10^{a}
Colour	White	Start of drying	L*	86.68 ± 0.49^{ab}	86.93 ± 0.69^{a}	86.36 ± 0.21^{abc}	86.13 ± 0.11^{bcd}	85.92 ± 0.08^{cd}	85.65 ± 0.97^{d}	86.41 ± 0.40^{abc}	86.58 ± 0.18^{ab}	86.99 ± 0.33^{a}	75.61 ± 0.63^{e}
		End of drying		90.51 ± 0.91^{g}	91.92 ± 0.18^{cd}	91.31 ± 0.19^{def}	91.23 ± 0.92^{ef}	92.37 ±0.09^{bc}	90.88 ± 0.36^{fg}	92.78 ± 0.58^{b}	93.46 ± 0.35^{a}	91.71 ± 0.32^{de}	92.89 ± 0.63^{ab}
		Start of drying	a*	-1.36 ± 0.03^{b}	-1.36 ± 0.03^{b}	-1.55 ± 0.03^{g}	-1.43 ± 0.03^{c}	-1.48 ± 0.02^{ef}	-1.51 ± 0.02^{f}	-1.44 ± 0.02^{cd}	-1.38 ± 0.02^{b}	-1.46 ± 0.02^{de}	-1.26 ± 0.01^{a}
		End of drying		-1.21 ± 0.06^{b}	-1.36 ± 0.05^{cd}	-1.57 ± 0.03^{e}	-1.27 ± 0.08^{bc}	-1.31 ± 0.03^{c}	-1.02 ± 0.11^{a}	-1.42 ± 0.04^{d}	-1.42 ± 0.03^{d}	-1.21 ± 0.12^{b}	-2.47 ± 0.11^{f}
		Start of drying	b*	2.74 ± 0.14^{f}	3.29 ± 0.16^{d}	3.88 ± 0.15^{b}	2.58 ± 0.10^{g}	2.49 ± 0.14^{g}	3.67 ± 0.11^{c}	3.22 ± 0.13^{d}	3.04 ± 0.09^{e}	3.33 ± 0.13^{d}	6.21 ± 0.08^{a}
		End of drying		5.33 ± 0.24^{f}	6.21 ± 0.22^{e}	8.12 ± 0.09^{c}	5.68 ± 0.36^{f}	6.01 ± 0.16^{ef}	9.63 ± 0.44^{b}	7.12 ± 0.29^{d}	7.34 ± 0.34^{d}	9.72 ± 0.48^{b}	22.91 ± 1.79^{a}
	Yellow	Start of drying	L*	83.66 ± 0.10^{bc}	83.90 ± 0.09^{ab}	84.48 ± 0.09^{a}	83.62 ± 0.14^{bc}	83.53 ± 0.20^{bc}	83.02 ± 0.97^{c}	83.57 ± 0.08^{bc}	83.53 ± 0.02^{bc}	83.73 ± 0.09^{b}	63.54 ± 1.28^{d}
		End of drying		88.16 ± 0.38^{e}	88.83 ± 0.29^{d}	89.94 ± 0.40^{c}	88.02 ± 0.52^{e}	90.03 ± 0.28^{c}	90.61 ± 0.30^{ab}	89.03 ± 0.53^{d}	90.32 ± 0.21^{bc}	90.92 ± 0.63^{a}	88.27 ± 0.64^{e}
		Start of drying	a*	-8.48 ± 0.07^{f}	-8.39 ± 0.03^{e}	-8.17 ± 0.03^{c}	-8.28 ± 0.05^{d}	-8.36 ± 0.05^{e}	-3.15 ± 0.08^{b}	-8.39 ± 0.04^{e}	-8.16 ± 0.01^{c}	-3.18 ± 0.03^{b}	-2.38 ± 0.05^{a}
		End of drying		-9.23 ± 0.09^{f}	-7.93 ± 0.05^{d}	-7.85 ± 0.08^{d}	-9.02 ± 0.08^{f}	-7.92 ± 0.19^{d}	-2.65 ± 0.14^{b}	-8.49 ± 0.31^{e}	-7.42 ± 0.09^{c}	-2.75 ± 0.28^{b}	-2.25 ± 0.57^{a}
		Start of drying	b*	21.62 ± 0.17^{b}	21.57 ± 0.23^{bc}	21.32 ± 0.11^{cd}	21.07 ± 0.20^{d}	21.31 ± 0.16^{cd}	16.20 ± 0.19^{f}	21.41 ± 0.30^{bc}	20.57 ± 0.14^{e}	15.48 ± 0.23^{g}	24.91 ± 0.36^{a}
		End of drying		29.94 ± 0.31^{b}	21.15 ± 0.92^{ef}	22.35 ± 0.50^{de}	29.46 ± 0.47^{b}	23.41 ± 1.12^{d}	18.59 ± 0.53^{g}	27.21 ± 1.49^{c}	21.79 ± 0.51^{e}	20.09 ± 1.09^{fg}	52.03 ± 3.34^{a}
			ΔL*	-2.36	-3.09	-1.37	-3.21	-2.34	-0.28	-3.75	-3.14	-0.79	-4.61667
			Δa*	-8.03	-6.57	-6.29	-7.75	-6.61	-1.63	-7.08	-6.00	-1.55	0.215
			Δb*	24.61	14.93	14.23	23.78	17.41	8.96	20.09	14.45	10.37	29.115
			ΔE*	25.99	16.60	15.61	25.21	18.76	9.11	21.63	15.96	10.51	29.48

Mean and standard deviation in rows followed by same letters are not significantly different ($P \leq 0.05$). ΔL^*, Δa^*, and Δb^* are differences between mean colour values of yellow and white cassava foam powders, with colour values of white cassava foam powder as reference. ΔE^* represents the total colour difference.

4.5.2.2 Total cyanogenic glucosides (TCG) of cassava foams during drying

The TCG of CSF powders after drying ranged between 0.65 – 38.02 µg/g db, while TCG of non-foamed white and yellow cassava pulp powder was 67.87 µg/g db and 264.89 µg/g db, respectively (Table 4-3). Foam mat drying significantly reduced TCG of original white and yellow cassava pulp to 8.3 - 56.0 % and 0.2 – 2.2 %, respectively. The safe limit for the TCG content in cassava flour and associated products in food use is 10 µg/g (Codex Alimentarius Commission, 2013). Increasing the drying temperatures led to significantly higher TCG of white cassava foams after drying, but no particular trend for yellow cassava foams was observed. The increasing TCG with temperature may be due to a decreased drying time and consequently, a reduction in time available to breakdown linamarin. In addition, higher temperatures could have considerably altered the activity of endogenous linamarase responsible for the breakdown of linamarin (Montagnac et al., 2009). Notably, the yellow CSF powder has a relatively lower TCG compared to the white CSF powder and may therefore be safer to be used in foods. In our previous report (Ayetigbo et al., 2019), we did not subject the pulp to a holding time (12 h) before whipping as in this study. The holding period may have allowed more time for endogenous linamarase activity to further reduce TCG in the pulp, which may have led to a lower TCG in CSF powders.

4.5.2.3 Colour of cassava foams during drying

The dry foam powders had significantly higher L* values as higher temperatures and foam thicknesses were employed (Table 4-3). Falade and Onyeoziri (2012) and Sangamithra et al. (2015) have reported an increase in L* after foaming and drying yam and muskmelon into powder, respectively. At the onset of drying, L* values of NFP of white (75.61) and yellow (63.54) cassava were significantly lower than those of white CSF and yellow CSF. The whitening introduced by GMS colloid may have contributed to the increased L* values of the foams. Drying from foam to foam powder generally increased the L* values, likely due to a loss of moisture and total carotenoids during drying. Colour difference in lightness (ΔL*) between yellow and white CSF powders increased with temperature, but no trend with increasing foam thickness, suggesting that the yellow CSF powders were less luminous with reference to white CSF powders.

Drying at increasing temperatures and foam thicknesses led to increasing a* values for yellow CSF powders, but no particular trend was observed for white CSF powders. This may be due to browning reaction as temperature and drying time increased. The a* colour value of white NFP was significantly higher than for the white CSF at the onset of drying, but was significantly lower at the end of drying. Therefore, the white CSF powder was less 'red' than the white NFP powder. However, a* value for yellow NFP and NFP powder were significantly higher than those of the CSF and CSF powder, respectively at the onset and at the end of drying. This signifies an intensification of the 'redness' in colour during drying, as documented for muskmelon foam (Sangamithra et al., 2015). Difference in redness-greenness (Δa*) between yellow and white CSF powders increased with temperature and foam thickness, thus showing that browning may have occurred increasingly between both varieties with that of yellow CSF powders being more intense.

During drying, the b* (yellowness) colour of white CSF powder significantly increased with increasing temperatures and foam thicknesses. This could be due to browning reactions, which significantly increased the yellowness with increasing temperature and drying time. However, for yellow CSF powders, b* values decreased significantly with increase in temperature and foam thickness. This may be due to degradation of carotenoids as influenced by increasing temperature and drying time (Boon et al., 2010). Asokapandian et al. (2016) have reported a significant decrease in b* values as temperature increased in the drying of shrimp foams. The b* values were significantly higher for white NFP and yellow NFP than for the white CSF and yellow CSF, respectively, at the onset of drying. A similar trend was observed for the NFP powder and CSF powder at the end of drying. This may be due to the GMS colloid introduced when whipping pulp to foam, and carried over during the drying from foam to foam powder. In addition, the loss of carotenoids in the yellow NFP during whipping and drying may have contributed to these outcomes (Sangamithra et al., 2015). Interestingly, all the CSF have a significantly lower yellowness compared to the corresponding CSF powders regardless of the variety, thereby making the foam powders seem more attractive. This may be due to the conversion of trans-β-carotenes to the more intense cis- forms as reported in the literature (Ceballos et al., 2012). Difference in yellowness (Δb*) between yellow CSF powders and white CSF powders decreased with increasing temperature, due to carotenoids degradation.

Overall colour differences (ΔE*) between yellow CSF and white CSF powders decreased as temperature increased but no trend with foam thickness.

4.5.2.4 Microstructure of cassava foam powder during drying

The microstructure (Fig 4-4) of the white and yellow NFP powder showed that it consisted primarily of whole and fragmented starch granules with smooth edges. The CSF powders had similar characteristics, but in addition, the starch granules formed a complex matrix with the hydrocolloids, which resulted in an association of the granules, thus, stabilizing the multi-phase foam. Comparing the foam powders dried at different temperatures did not reveal any considerable changes in the microstructure, but there seems to be a greater degree of granule-hydrocolloid association in the yellow CSF powders. Similar observations were made by Franco et al. (2016) for microstructure of yacon juice powder. This suggests foaming could potentially protect heat-sensitive components, such as starch, and the cellular structure during drying.

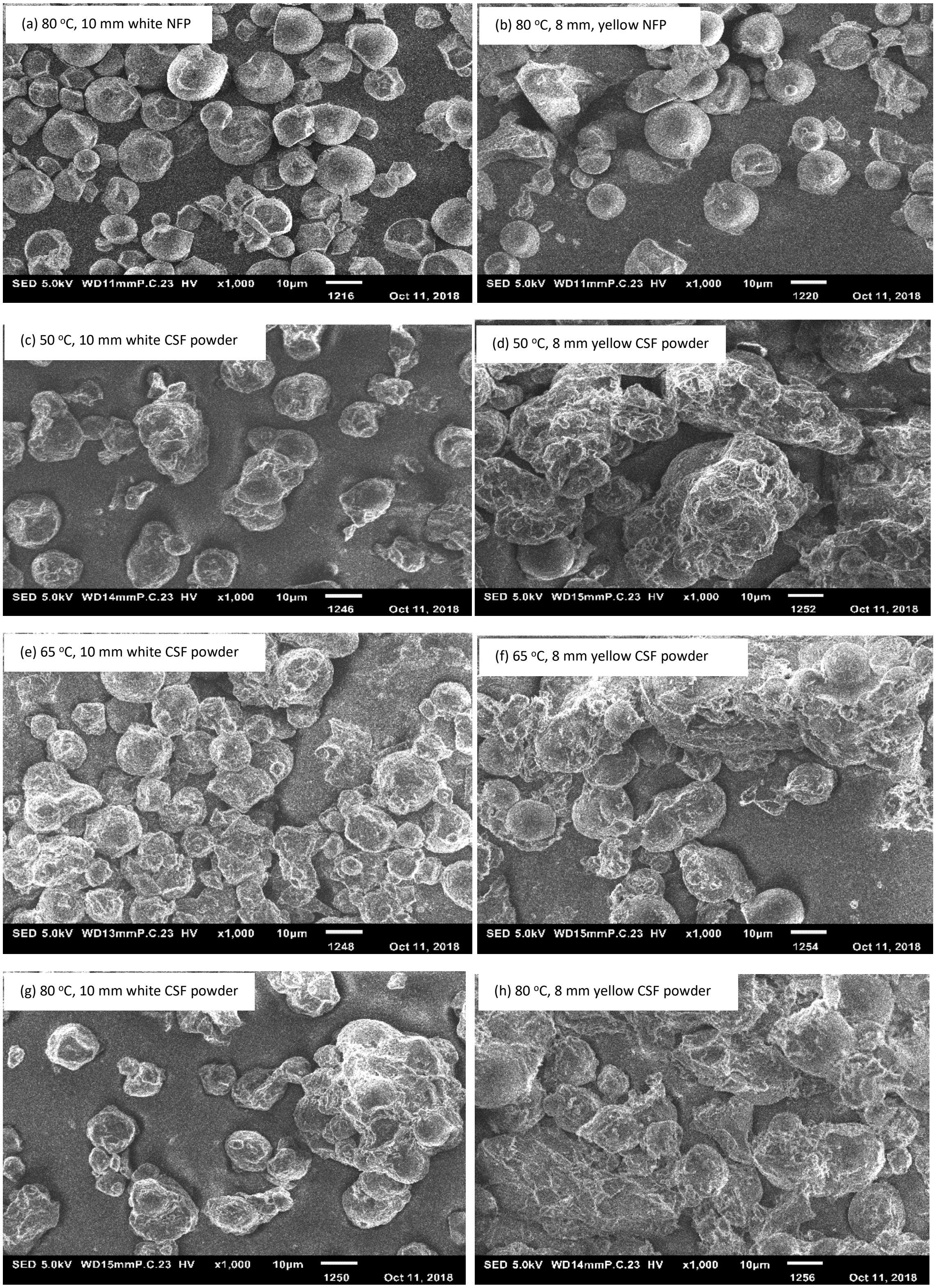

Figure 4-4 Microstructure of non-foamed pulp (NFP) powders (a, b) and cassava foam (CSF) powders (c - h)

4.6 Conclusions and recommendations

It has been shown that the various drying conditions in terms of temperature and foam thickness had significant influence on the drying kinetics and physicochemical properties of white and yellow cassava foams. Cassava foams exhibited two falling rates during drying. Effective moisture diffusivity increased with increase in temperature but not with foam thickness. White cassava foam can be appropriately dried at a temperature of 80 ^{o}C and foam thickness of 10 mm, while yellow cassava foam may be dried at temperature of 80 ^{o}C and foam thickness of 8 mm. Although, foam mat drying did not reduce the drying time for cassava foams compared to non-foamed cassava pulp, it is recommended for processing cassava because it preserved the carotenoids content, reduced total cyanogenic glucosides to safe levels, improved colour, and preserves the native starch and cellular microstructure. On the other hand, the non-foamed cassava had unacceptably high total cyanogenic glucosides content and poor colour. We also recommend that other foaming techniques and choice of foaming agent/stabilizer be considered in order to reduce drying time.

Therefore, foam mat drying may be regarded as a mild drying technique for yellow cassava compared to adverse drying methods such as sun drying, drum drying, or conventional oven drying. Aside being a simple process that produces no effluents, the process may improve the functional properties of cassava, but further research is required to corroborate these.

4.7 Conflict of Interest

The authors declare no conflict of interests. Collaborations and funding have been duly acknowledged.

4.8 Acknowledgement

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5 General discussion

Cassava is an important crop of immense significance for food security in many parts of Africa, Asia and South America, because it serves as a source of industrial biomass, food, feed and livelihoods (Montagnac, Davis, & Tanumihardjo, 2009). The value chain of cassava is incomplete without a robust utilization network, especially as food, for an ever-increasing world population. Therefore, numerous varieties of cassava are increasingly being studied for their properties due to the genetic diversity of the varieties. In fact, some cassava varieties are now bred to target certain consumer preferences due to the quality traits they possess (Abass, Awoyale, Sanni, & Shittu, 2017). Basically, two varieties of cassava are more common in many parts of cassava cultivating regions, based on the flesh colour. The conventional white-fleshed cassava varieties are recognised as more popular among farmers, but the yellow-fleshed cassava varieties are increasingly gaining acceptance among agronomists, researchers, food processors and some farmers due to the carotenoids-rich nature of the varieties. Nonetheless, the use of cassava as food is affected by some challenges such as the rapid post-harvest physiological deterioration of cassava, presence of cyanogenic glucosides and the relatively poor functional and nutritional properties of cassava. The processing of cassava is a vital step to render cassava safe, nutritious and storable, thereby producing edible forms in which cassava can be used as food or as ingredient in food preparation. One of such processing approaches that can introduce value addition to cassava is the foam mat drying (FMD) of cassava. Although, FMD is not a new technology, it is recently, increasingly finding application in the processing of roots, tubers and other starchy crops into stable foams that can be dried into foam powder. Generally, the FMD process is a simple and inexpensive process that can be used in the village food industry, and can be scaled up for use in industrial manufacture of food powders. In addition, the food powders are often convenient to use, with better functionality and nutrient retention than the corresponding flours. Governments of developing countries such as Nigeria and Ghana have also initiated programs to stimulate all value chains relating to utilization of cassava in the last two decades (Nweke, 2004; Odum, 2015). Therefore, the study embarked on understanding the inclination of stakeholders in the cassava value chain to preference for the yellow-fleshed cassava varieties over the white-fleshed cassava varieties from the perspective of comparing their properties, and how considerations for sustainability influenced this preference. Furthermore, the actual production of cassava foam and foam powder from the cassava varieties under optimal process conditions was conducted and some properties related to the physicochemical and functional nature, nutrition, and safety were compared between both varieties.

5.1 Sustainability from the perspective of the properties of cassava from white-fleshed and yellow-fleshed varieties

Comparison of the properties of different varieties of agricultural produce are often undertaken to select or recommend certain varieties due to the unique merits they may possess, and as a means to screen varieties during breeding programs. In part I of the study, a review of the comparison of the properties of the white-fleshed and yellow-fleshed varieties studied in various regions of the world were made, with recommendations for sustained production of yellow-fleshed cassava. From the findings, it can be can inferred that the varieties can be used interchangeably if macro-nutrients such as protein, lipids, carbohydrates, and physical and functional properties of the cassava products are of interest to processors. However, the significant merits yellow-fleshed cassava has from viewpoint of sensory appeal (taste, colour) and carotenoids content (Talsma, 2014) play a role in its preferred adoption by some food processors and farmers. Nonetheless, the local subsistent farmers sometimes prefer the white-fleshed cassava varieties due to perceived resistance to diseases, deterrence to pests, parasites, and yield. Also, some processors still price the relatively higher dry matter and starch content of white-fleshed cassava, but have to grapple with problems of its usually higher cyanogenic toxicity. For cultivation and utilization of yellow-fleshed cassava varieties to be considered sustainable, the challenges of its adoption by local subsistent/small-scale farmers, food processors and other stakeholders must be resolved. Therefore, the peculiar advantages offered by the properties of yellow-fleshed cassava varieties over white-fleshed cassava varieties such as its better nutrients content, post-harvest stability (Chavez et al., 2000; Talsma, 2014) and relative ease of harvest and post-harvest handling (Gonzalez, Perez, Cardoso, Andrade, & Johnson, 2011) should be considered. The suggestions recommended to resolve the adoption gap, such as aggressive reorientation programs, incentives, government subsidies and policy development can stimulate a sustainable plan to improve integration of yellow-fleshed cassava varieties in developing countries.

The effects of the different processing techniques on the properties of yellow and white cassava varieties reviewed from many publications (Anggraini, Sudarmonowati, Hartati, Suurs, & Visser, 2009; H. Ceballos et al., 2012; Gu, Yao, Li, & Chen, 2013; B. Maziya-Dixon, Adebowale, Onabanjo, & Dixon, 2005; Busie Maziya-Dixon, Awoyale, & Dixon, 2015; Montagnac et al., 2009; Oliveira, Lucia de Carvalho, Nutti, Jose de Carvalho, & Fukuda, 2010; Taleon, Sumbu, Muzhingi, & Bidiaka, 2019; Vimala, Thushara, & Nambisan, 2010) suggest increased interest in yellow cassava varieties. However, the challenge posed by the effect of these processing techniques lead to the necessity to recommend milder, environmentally-friendly processing techniques, especially, for the yellow-fleshed cassava varieties, in order to minimize loss of nutrients and functionality.

5.2 Preparation of cassava foam and foam powder

Based on the recommendations from the review, in part II of the study, FMD was considered as a mild, environmental-friendly processing technique in processing cassava, with the idea of developing other forms in which cassava can be processed into, reducing total cyanogenic glucosides (TCG), retaining total carotenoids content (TCC) (for yellow-fleshed cassava), and developing a functional foam powder. The main difference between cassava flour and cassava foam powder is based on the use of hydrocolloids in FMD, which confers improved functional and physicochemical properties on the foam powder. Because of the poor foaming property of cassava, a foaming agent (GMS) and a stabilizer (NaCMC) was required to produce a stable foam. The choice of the foaming agent and stabilizer is based on the availability, properties, inexpensiveness and acceptance as safe food-grade agents useful in vegetarian diet. Selecting other foaming agents or stabilizer may result in a different set of responses and properties, for instance, the use of egg white may significantly increase TCC and yellowness (b^*) in the cassava foam and foam powder, but a less stable foam during drying (Raharitsifa, Genovese, & Ratti, 2006). Preliminary trials conducted in this work has revealed egg albumen as inappropriate for FMD of cassava for this reason. Nevertheless, GMS is a lipid-based foaming agent which may not be desirable for low-calorie formulations.

The applicability of response surface method to optimize foaming conditions provides the possibility to estimate foaming response variables (foam expansion and foam density) from known range of independent variables (concentration of foaming agent and stabilizer and whipping time) by accurate regression models, and a solution for optimal foaming conditions that can be validated for the models. Studying a much wider range and levels of process variables (such as pulp concentration, whipping temperature, speed and method) and responses for foaming cassava is recommended to provide a much more robust model in future research on cassava foaming. In other publications, the air volume fraction and foam overrun are regarded as equally suitable response variables to measure the extent of foaming (Franco, Ellendersen, Fattori, Granato, & Masson, 2015; Raharitsifa et al., 2006; Sramek, Schweiggert, Van Kampen, Carle, & Kohlus, 2015).

During the stages of pulping of cassava, to the whipping of the cassava pulp to foam, and drying to foam powder, the properties of cassava is subject to changes in density, colour, microstructure, and TCC and TCG contents. Nonetheless, the properties found similar for both varieties (foam density, foam collapse, foam air bubble size, size interval, size distribution, foam morphology and powder microstructure) indicate the close genetic nature of both varieties. An interesting merit FMD offered was the high retention of TCC in the foam powder due to the mild nature of FMD process, and reduction of exposure to degradation by oxidation (Boon, McClements, Weiss, & Decker, 2010), consequent of the protection by the foam matrix. The progressive decline of TCC and colour values

(b^*, $\Delta E^*_{yellow\ -\ white}$) could be correlated and useful in estimation of each other, especially for the yellow-fleshed cassava variety. Furthermore, the significant decline of TCG during FMD has proved advantageous as cellular linamarin and linamarase may have been released to intricately interact over time to reduce cyanogenic glucosides toxicity. While the TCG content of the foam powder produced did not fall within the recommended safe limit suggested by the *Codex Alimentarius Commission*, albeit, the foam powder may be regarded as being within the limits of food regulation in Asian countries like Indonesia or Thailand (Ndubuisi & Chidiebere, 2018).

5.3 Drying of cassava foams, and effect on selected physicochemical properties

In part III of the study, a closer look into the drying of the optimally produced cassava foam under varying drying conditions (temperature and foam thickness) and the influence on the drying kinetics and selected properties of the cassava foam powder produced were investigated. This is because the drying process often alters structural, nutritional, physical and chemical characteristics of biological materials. Nevertheless, drying also reduces moisture content to desired levels where water is not available for biochemical spoilage, and reduces problems associated with handling. Basically, the traditional sun drying method of drying cassava in bulk often results in a less attractive colour (Falade & Onyeoziri, 2012), severe loss of carotenoids, contamination and inefficient detoxification due to insufficient contact between linamarase and linamarin. The conventional oven drying of cassava is simple, and flexible for batch processing of cassava flour, but often lead to significant loss of physicochemical, functional and sensory properties, apart from the flour not often reaching safe cyanogenic toxicity levels. Flash drying, on the other hand, requires a large capital outlay and skilled expertise in design, maintenance and use, but is a rapid drying technique to produce high quality cassava flour (HQCF) on industrial scale. In spite of this, flash drying is often preceded by time-consuming preliminary operations such as hydraulic pressing, which result in leaching of nutrients and toxic cyanogenic run-offs into the environment. Other drying techniques such as freeze-drying and spray drying are expensive for practical consideration in developing countries. The FMD process could be considered as an alternative technique to dry cassava. However, some demerits can be associated with the FMD technique too. The challenge of relatively lower throughput, often resulting from the need to spread cassava into thin layer before drying, can limit its amenability to a continuous process. In this work, the yield of dry cassava foam powder is about 10 % of the wet mass of cassava foam produced at onset of each drying batch. Also, there may be a risk of case hardening if cassava foams are not stable during drying. This problem was not encountered because the foams were quite stable prior to and during drying. Nevertheless, there may be a need to include anti-agglomeration agents to the cassava foam powders, as agglomeration was observed in the microstructure. This may increase production costs for cassava foam powder.

Regarding the drying kinetics of the cassava foam, two different falling rates identified by Rational model fits, seem to infer that there may be a transit/boundary moisture content between both falling rates. The two drying rates show that the drying behaviour of cassava foam is somewhat different from that of many agricultural produce where a falling rate, or a constant rate and a falling rate are often observed during drying. This finding may influence how drying systems and regimes could be designed to minimize energy expense and drying time. For instance, if microwave or infrared drying is employed to dry the cassava foam in the first falling rate, it may reduce the overall drying time and gross drying energy, particularly as most of the drying occurred in this period. The lower drying rates and higher drying time of the cassava foam compared to the non-foamed cassava pulp is unexpected, and may be due to the presence of several air bubbles and the viscosity of the cassava foams which insulates them from efficient thermal conductivity and the restriction of moisture diffusion. This demerit is outweighed by positive outcomes such as high retention of carotenoids, reduction of cyanogenic glucosides to safe levels, better sensory appeal (colour), preserved microstructure of the cassava foam powders and improved functional properties. The introduction of a holding time of about 12 h for cassava pulp before foaming and drying has improved the reduction of TCG to safe levels recommended by the *Codex Alimentarius Commission*, especially for the yellow-fleshed variety, as this was not considered in prior experimental protocol. This principle is usually employed in cassava processing where size reduction and holding time significantly contribute to ensuring sufficiently reduced TCG in final products.

5.4 Outlook

The FMD technique has been in practice for decades. While the technique is commonly used for liquid foods like fruits and vegetables juice, dairy, eggs, etc., it is recently, increasingly being used for processing root and tuber crops and other starch-based crops. This study has explored new forms into which cassava may be processed (cassava foam and cassava foam powder) from two varieties of cassava, and investigated how the process has influenced the properties of the cassava varieties.

However, a few recommendations are suggested for future research to further reduce knowledge gaps on foam mat drying of cassava. First, an optimization of the foaming and drying conditions for the white and yellow-fleshed cassava may be carried out based on other important properties such as total carotenoids content, extent of starch degradation, colour, total cyanogenic glucosides content and other physical, chemical and functional parameters in such a way that drying time and energy will be reduced. For this reason, the choice of other foaming agents, stabilizers, and other variables for foaming may be considered. There may also be the need to test a much wider range of cassava varieties of different flesh colour, particularly those varieties which a lot of research effort to improve the nutrients has been vested. Cassava varieties with low cyanogenic glucosides and high micronutrients contents are particularly recommended for FMD. Regarding the drying method used for the foams, drying techniques such as microwave drying, spray drying, flash drying, infra-red drying or vacuum drying, may also be considered, since these techniques often result in reduced drying times and products of high quality. The low material loading density being common in foam mat drying techniques due to the low foam thickness requirement, often results in relatively lower productivity compared to drying techniques such as flash drying, solar drying and oven drying. Therefore, the design of FMD systems with higher throughput is recommended to improve yield of dry foam powder. This may be achieved by foam-spray drying, belt conveyor drying with short residence time, microwave-assisted foam drying, infra-red belt drying or ultrasonic-assisted drying.

There is also the need to conduct further research in understanding the physical properties of the cassava foam and foam powder under varying conditions found in the food processing industry. Such physical properties may include density (bulk, packed, particle), porosity, flow properties (coefficient of friction, angle of repose), compressibility (Hausner ratio, Carr’s index), particle size, rehydration, hygroscopicity, and sorption isotherms. In addition, an investigation into the influence of foam mat drying on functional and rheological properties of cassava foam and foam powder under the process conditions commonly encountered during food processing should be embarked on to buttress the practical advantages of the technique.

Finally, the food use and sensory evaluation and acceptance of food produced from cassava foam and foam powder should be researched.

As a concluding remark, it can be inferred that the overall aim of increasing value addition in cassava utilization may be achieved if a process such as FMD is considered in producing cassava products, especially as government policies are currently geared towards this goal in developing countries.

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6 Summary

Cassava ranks high amongst the top food security and industrial crops in many parts of Africa, S. America and Asia by contributing as food, feed and industrial biomass to hundreds of millions of people in these regions. Although cassava can be regarded as a resilient crop able to withstand drought and poor agronomic conditions, many efforts have been invested into the development of improved breeds of cassava that portray desirable traits such as increased root, flour and starch yields, reduced toxicity, reduced pest/disease susceptibility and improved nutrient content. A breeding program that stands out among these breeding efforts is the development of colored-flesh cassava variants, especially the biofortified yellow-fleshed cassava with significantly increased pro-vitamin A carotenoids content, compared to the white-fleshed cassava variants. Also, the steady increase in the cultivation of cassava over the recent decades has spurred national governments of developing countries to focus on improving the utilization value web of cassava by creating policies to encourage food and non-food use of cassava.

Therefore, the concept of sustainability in adopting yellow-fleshed cassava is of concern to the stakeholders in the cassava value chain. The argument for adoption may not be fully understood without detailed knowledge on the properties of the yellow–fleshed cassava varieties and their products, and how they compare to those of the conventional white-fleshed cassava varieties and their products. Therefore, the subtle differences between the properties of both cassava varieties was reviewed. Generally, chemical, pasting and physicochemical properties such as amylose and starch contents, dry matter, carotenoids content and viscosity vary significantly between the two varieties. The physical properties of both varieties of cassava, such as morphology, thermal, crystallinity, color, and density properties were largely similar. In light of these, recommendations were made on how to bridge the gap between the adoption of yellow-fleshed cassava compared to white-fleshed cassava based on the advantages the properties of yellow-fleshed cassava and its products has to offer.

Due to the high susceptibility of cassava to rapid post-harvest physiological deterioration as a result of its high water activity, various processing techniques have been developed to preserve cassava and process it into food or non-food products. Foam mat drying was considered as a technique to produce cassava foam, which is another form in which cassava may be used as an ingredient to produce cream-based products. In order to optimally foam yellow and white cassava pulp, some variables were considered such as the concentration of the foaming agent, 20 %w/w glycerol monostearate colloid, GMS (5, 10, 15 %), concentration of stabilizer, sodium carboxymethyl cellulose, NaCMC (0.2, 0.4, 0.6 %) and whipping time (2, 4, 6 min). Using Box-Behnken experimental design, two responses were measured: foam expansion (FE, %) and foam density (FD, g/mL). Results showed that 14.97 % GMS, 0.51 % NaCMC and 2.07 min were the optimal conditions for foaming white cassava pulp into a foam that expanded by 52.63 % and had a density of 0.75 g/mL. For yellow cassava, the pulp required 14.29 % GMS, 0.6 % NaCMC and 2 min whipping to yield a foam of 48.25 % expansion and a density of 0.76 g/mL. Predicted optimal FE and FD were close to the validated values. Accurate quadratic response model equations were generated to estimate the FE and FD of the cassava foams under the different foaming variables considered. The optimal foams were quite stable with a low volume collapse (1.26 – 1.79 %). Foaming significantly reduced the density of cassava pulp. The optimal cassava foams were dried into foam powder. Furthermore, significant changes were found in color (L^*, a^*, b^*, C^*, E^*, H^*, % W, $\Delta E^*_{yellow-white}$) and total carotenoids content as cassava was progressively processed from pulp into foam and to foam powder for both varieties. The optimal foams from both varieties had air bubbles of similar average size, and the distribution of the bubble sizes were asymmetric, positively skewed toward small sized bubbles (79.1 – 101.4 µm). The foam powders' microstructure revealed a close association between the hydrocolloids and starch. Foam mat drying also had the potential of significantly reducing the total cyanogenic glucosides of both cassava varieties.

In order to closely study and compare the effect of drying conditions on drying kinetics (moisture ratio, diffusivity, dying rate) of white and yellow cassava foams, and the effect of various drying conditions on selected physicochemical properties of cassava foam powder, the drying of cassava foam was conducted at different temperatures (50, 65, 80 ^{o}C) and foam thicknesses (6, 8, 10 mm). Yellow cassava foam dried faster than white cassava foam at all the drying conditions considered. The drying rate profiles of the foams revealed two falling rates. The moisture content at which the first falling rate transits into the second falling rate largely decreased with increase in temperature and foam thickness. Moisture diffusivity also increased with temperature but not with foam thickness during drying of the foams, with activation energy ranging between 31 – 44 kJ/mol. The yellow cassava foam powders had a significantly lower total cyanogenic glucosides (TCG) content compared to white cassava foam powders, and was lower than the safe TCG (10 µg/g) level recommended by Codex Alimentarius for cassava flour. A high retention of total carotenoids was observed for yellow cassava foam powder. Dried foam powders had lighter (L^*) colour than non-foamed cassava pulp powder. Micrographs revealed that the microstructure was not affected by increasing drying temperatures, but the starch and the hydrocolloids in yellow cassava foam powder were more closely associated than that of white cassava foam powder.

7 Zusammenfassung

Maniok gehört in vielen Teilen Afrikas, Südamerikas und Asiens zu den Pflanzen mit der höchsten Nahrungsmittelsicherheit und ist eine der wichtigsten Nutzpflanzen, da er als Nahrungsmittel, Futtermittel und industrielle Biomasse für Hunderte von Millionen Menschen in diesen Regionen dient. Obwohl Maniok als widerstandsfähige Kulturpflanze gilt, die Dürre und schlechte agronomische Bedingungen übersteht, wurde viel in die Entwicklung verbesserter Maniokrassen investiert, die wünschenswerte Eigenschaften aufweisen, wie höhere Erträge an Wurzeln, Mehl und Stärke, geringere Toxizität, geringere Anfälligkeit für Schädlinge/Krankheiten und verbesserten Nährstoffgehalt. Ein Züchtungsprogramm, das hervorsticht, ist die Entwicklung von Maniok-Varianten mit farbigem Fleisch, insbesondere die biofortifizierte gelbfleischige Maniok mit einem signifikant höheren Gehalt an Pro-Vitamin-A-Carotinoiden im Vergleich zu den weißfleischigen Maniok-Varianten. Auch die stetige Zunahme des Maniokanbaus in den letzten Jahrzehnten hat die nationalen Regierungen der Entwicklungsländer dazu veranlasst, sich auf die Verbesserung der Nutzung von Maniok zu konzentrieren, indem sie Maßnahmen zur Förderung der Verwendung von Maniok als Nahrungsmittel und im Non-Food-Bereich geschaffen haben.

Daher ist das Konzept der Nachhaltigkeit bei der Akzeptanz von gelbfleischigem Maniok für die Akteure in der Maniokwertschöpfungskette von Bedeutung. Das Argument für die Annahme von Maniok kann nur dann vollständig verstanden werden, wenn man die Eigenschaften der gelbfleischigen Manioksorten und deren Produkte genau kennt und weiß, wie sie sich im Vergleich zu den konventionellen weißfleischigen Manioksorten und deren Produkten verhalten. Deshalb wurden die subtilen Unterschiede zwischen den Eigenschaften der beiden Manioksorten analysiert. Im Allgemeinen unterscheiden sich die chemischen, pastösen und physikalisch-chemischen Eigenschaften wie Amylose- und Stärkegehalt, Trockensubstanz, Carotinoidgehalt und Viskosität zwischen den beiden Sorten erheblich. Die physikalischen Eigenschaften beider Manioksorten, wie Morphologie, Thermik, Kristallinität, Farbe und Dichteeigenschaften, waren weitgehend ähnlich.

Vor diesem Hintergrund wurden Empfehlungen ausgesprochen, wie die Lücke zwischen der Akzeptanz von gelbfleischiger Maniok im Vergleich zu weißfleischiger Maniok überbrückt werden kann, und zwar aufgrund der Vorteile, die sich aus den Eigenschaften der gelbfleischigen Maniok und ihrer Produkte ergeben.

Aufgrund der hohen Anfälligkeit der Maniokpflanze für eine rasche physiologische Verderbnis nach der Ernte infolge ihrer hohen Wasseraktivität wurden verschiedene Verarbeitungstechniken entwickelt, um Maniok zu konservieren und zu Nahrungsmitteln oder Non-Food-Produkten zu verarbeiten. Die Schaummattentrocknung wurde als eine Technik zur Herstellung von Maniokschaum betrachtet, eine weitere Form, bei der Maniok als Zutat zur Herstellung von Produkten auf Rahmbasis verwendet werden kann. Um gelben und weißen Maniokzellstoff optimal aufzuschäumen, wurden einige Variablen berücksichtigt, wie die Konzentration des Aufschäummittels, 20 Gew.-% Glycerinmonostearat-Kolloid, GMS (5, 10, 15 %), die Konzentration des Stabilisators, Natriumcarboxymethylcellulose, NaCMC (0,2, 0,4, 0,6 %) und die Aufschäumzeit (2, 4, 6 min). Unter Verwendung des experimentellen Designs von Box-Behnken wurden zwei Reaktionen gemessen: Schaumausdehnung (FE, %) und Schaumdichte (FD, g/mL). Die Ergebnisse zeigten, dass 14,97 % GMS, 0,51 % NaCMC und 2,07 min die optimalen Bedingungen für das Aufschäumen von weißem Maniokzellstoff zu einem Schaum waren, der um 52,63 % expandierte und eine Dichte von 0,75 g/mL aufwies. Bei gelber Maniok brauchte der Pulp 14,29 % GMS, 0,6 % NaCMC und 2 min Aufschlagdauer, um einen Schaum mit 48,25 % Expansion und einer Dichte von 0,76 g/mL zu erhalten. Die vorhergesagten optimalen FE- und FD-Werte lagen nahe an den validierten Werten. Es wurden genaue quadratische Antwortmodellgleichungen erstellt, um die FE und FD der Maniok-Schäume unter den verschiedenen betrachteten Schaumvariablen abzuschätzen. Die optimalen Schäume waren recht stabil mit einem geringen Volumenkollaps (1,26 - 1,79 %). Das Schäumen reduzierte die Dichte des Maniokzellstoffs signifikant. Die optimalen Maniok-Schäume wurden zu Schaumpulver getrocknet. Darüber hinaus wurden signifikante Veränderungen in der

Farbe (L*, a*, b*, C*, E*, H*, % W, $\Delta E^*_{gelb-weiß}$) und im Gesamtgehalt an Carotinoiden festgestellt, da beide Maniok Sorten nach und nach von der Pulpe zu Schaum und zu Schaumpulver weiterverarbeitet wurde. Die optimalen Schäume beider Sorten wiesen Luftblasen von ähnlicher durchschnittlicher Größe auf, und die Verteilung der Blasengrößen war asymmetrisch, positiv in Richtung kleiner Blasen (79,1 - 101,4 µm) gerichtet. Die Mikrostruktur der Schaumpulver zeigte eine enge Verbindung zwischen den Hydrokolloiden und der Stärke. Die Schaummattentrocknung hatte auch das Potenzial, die gesamten cyanogenen Glukoside beider Manioksorten signifikant zu reduzieren.

Um den Einfluss der Trocknungsbedingungen auf die Trocknungskinetik (Feuchtigkeitsverhältnis, Diffusionsvermögen, Färbungsrate) von weißem und gelbem Maniokschaum sowie den Einfluss verschiedener Trocknungsbedingungen auf ausgewählte physikalisch-chemische Eigenschaften von Maniokschaumpulver genau zu untersuchen und zu vergleichen, wurde die Trocknung von Maniokschaum bei verschiedenen Temperaturen (50, 65, 80 °C) und Schaumdicken (6, 8, 10 mm) durchgeführt. Gelber Maniok-Schaum trocknete unter allen betrachteten Trocknungsbedingungen schneller als weißer Maniok-Schaum. Die Profile der Trocknungsraten der Schäume zeigten zwei fallende Raten. Der Feuchtigkeitsgehalt, bei dem die erste Fallgeschwindigkeit in die zweite Fallgeschwindigkeit übergeht, nahm mit zunehmender Temperatur und Schaumdicke weitgehend ab. Das Feuchtigkeitsdiffusionsvermögen nahm ebenfalls mit der Temperatur zu, jedoch nicht mit der Schaumdicke während der Trocknung der Schäume, mit einer Aktivierungsenergie zwischen 31 – 44 kJ/mol. Die gelben Maniok-Schaumpulver wiesen im Vergleich zu den weißen einen signifikant niedrigeren Gesamtgehalt an cyanogenen Glukosiden (TCG) auf und lagen unter dem vom Codex Alimentarius für Maniokmehl empfohlenen sicheren TCG-Wert (10 µg/g). Bei gelbem Maniokschaumpulver wurde eine hohe Retention der Gesamtcarotinoide beobachtet. Getrocknete Schaumpulver hatten eine hellere (L*) Farbe als nicht geschäumtes Maniokpulver. Mikroaufnahmen zeigten, dass die Mikrostruktur durch steigende Trocknungstemperaturen nicht beeinträchtigt wurde, aber die Stärke und die Hydrokolloide in gelbem Maniokschaumpulver waren enger miteinander verbunden als die des weißem Maniokschaumpulver.

8 Affidavit

Pursuant to Sec. 8 (2) of the University of Hohenheim's doctoral degree regulations for Dr.sc.agr.

1. For the dissertation submitted on the topic:

   Foam mat drying of cassava and associated properties: comparison between white-flesh and yellow-flesh varieties

   I hereby declare that I independently completed the doctoral thesis.

2. I only used the sources and aids documented and only made use of permissible assistance by third parties. In particular, I properly documented any contents, which I used – either by directly quoting or paraphrasing – from other works.
3. I did not accept any assistance from a commercial doctoral agency or consulting firm.
4. I am aware of the meaning of this affidavit and the criminal penalties of an incorrect or incomplete affidavit.

I hereby confirm the correctness of the above declaration. I hereby affirm in lieu of oath that I have, and to the best of my knowledge, declared nothing but the truth and have not omitted any information.

14 June 2021, Stuttgart

………..

(Place, Date) (Signature)

9 Curriculum Vitae

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	Powder. In: Filling Gaps and Removing Traps for sustainable Resources Management. Book of Abstracts, Eric Tielkes (Eds.). TROPENTAG 2019, Kassel-Göttingen, Germany. Cuvillier Verlag, Germany, Page 388. • Tropentag **2018**. Global food security and food safety: The role of Universities. Conference presentation- *Optimisation of Cassava Foaming for Foam-Mat Drying, and Use in cream-based foods*. September, 17-19, University of Ghent, Belgium. • Madridge Food Tech Conference **2018**. The 2nd International Conference on Food Science and Bioprocess Technology. October 1-2. Frankfurt, Germany. • GlobE Status Seminar **2017**. Securing the global food supply- New technologies for increasing the economic value of cassava in Nigeria (BiomassWeb), October 16-17. Berlin, Germany.
Publications:	• **Ayetigbo, O.**, Latif, S., Abass, A., & Müller, J. (**2021**). Dataset on influence of drying variables on properties of cassava foam produced from white- and yellow-fleshed cassava varieties. *Data in Brief* 107192. https://doi.org/10.1016/j.dib.2021.107192. • **Ayetigbo, O.**, Latif, S., Abass, A., & Müller, J. (**2021**). Drying kinetics and effect of drying conditions on selected physicochemical properties of foam from yellow-fleshed and white-fleshed cassava (*Manihot esculenta*) varieties. *Food and Bioproducts Processing 127*, 454-464. https://doi.org/10.1016/j.fbp.2021.04.005 • **Ayetigbo, O.**, Latif, S., Abass, A., & Müller, J. (**2020**). Drying Kinetics and Characterization of Dried Osmotically-Pretreated White-flesh and Yellow-Flesh Cassava (*Manihot Esculenta*). Book of Abstracts. In: Food and Nutrition Security and its resilience to Global Crises. Book of Abstracts, Eric Tielkes (Eds.). TROPENTAG 2020 Virtual Conference. DITSL, Witzenhausen, Germany. Page 232. • Falade, K.O., Ibanga-Bamijoko, B. & **Ayetigbo, O.E.** (**2019**). Comparing properties of starch and flour of yellow-flesh cassava cultivars and effects of modifications on properties of their starch. *Journal of Food Measurement and Characterization 13*, 2581-2593. https://doi.org/10.1007/s11694-019-00178-5. • **Ayetigbo, O.**, Latif, S., Abass, A., & Müller, J. (**2019**). Osmotic dehydration kinetics of biofortified yellow-flesh cassava in contrast to white-flesh cassava (*Manihot esculenta*). *Journal of Food Science and Technology 56* (9), 4251 - 4265. https://doi.org/10.1007/s13197-019-03895-3. • **Ayetigbo, O.**, Latif, S., Abass, A., & Müller, J. (**2019**). Preparation, optimization and characterization of foam from white-flesh and yellow-flesh cassava (*Manihot esculenta*) for powder production. *Food Hydrocolloids 97*, 105205. https://doi.org/10.1016/j.foodhyd.2019.105205 • **Ayetigbo, O.**, Latif, S., Abass, A., & Müller, J. (**2018**). Comparing characteristics of root, flour and starch of biofortified yellow-flesh and white-flesh cassava variants, and sustainability considerations: A Review. *Sustainability* 10(9), 3089-3120. https://doi.org/10.3390/su10093089 • **Ayetigbo, O.**, Latif, S., Abass, A., & Müller, J. (**2018**). Osmotic dehydration kinetics and effects on desorption isotherms, color, shrinkage and other properties of white-flesh and biofortified yellow-flesh cassava during dehydration. Poster. The 2nd International Conference on Food Science and Bioprocess Technology, October 1-2, Frankfurt, Germany. http://dx.doi.org/10.18689/2577-4182.a2.007. • Falade, K.O. & **Ayetigbo, O.E.** (**2017**). Effects of tempering (annealing), acid hydrolysis, low-citric acid substitution on chemical and physicochemical properties of starches of four yam (*Dioscorea spp.*) cultivars. *Journal of Food Science and Technology 54*(6), 1455-1466. doi 10.1007/s13197-017-2568-x • **Ayetigbo, O.**, Latif, S., Abass, A., & Muller, J. (**2017**). Effects of temperature and concentration of osmotic solution on osmotic dehydration kinetics of cassava. Poster. GlobE seminar: Improving food security in Africa through increased system productivity of biomass-based value webs (WP 5.1), 16-17 Oct., Berlin, Germany.

	• **Ayetigbo, O.**, Latif, S., Abass, A., & Müller, J. (**2017**). Optimization of cassava foaming for foam-mat drying, and use in cream-based foods. Poster. GlobE seminar: Improving food security in Africa through increased system productivity of biomass-based value webs (WP 5.1), 16-17 Oct., Berlin, Germany. • Falade, K.O. & **Ayetigbo, O.E.** (**2015**). Effects of annealing, acid hydrolysis and citric acid modifications on physical and functional properties of starches from four yam (*Dioscorea* spp.) cultivars. *Food hydrocolloids 43*, 529-539. doi.org/10.1016/j.foodhyd.2014.07.008
Reviewer, Teaching & Supervisory roles:	• Reviewer for Journal of Food Science and Technology (Springer), Journal of Food Measurement and Characterization (Springer), Agriculture and Natural Resources (Elsevier), Food and Bioproducts Processing (Elsevier), CyTA Journal of Food (Taylor & Francis), Journal of Food Science (Wiley Online Library), International Journal of Food Properties (Taylor & Francis), Starch/Staerke (Wiley online Library). • Teaching Post-harvest Technology of Food and Bio-based Products (4403-550) Module, Institute of Agricultural Engineering, Tropics and Subtropics, Universität Hohenheim, Germany. Supervision of Bachelors & Masters theses: • Christina Boura (2021). Foaming of yellow-fleshed cassava using egg albumen: physicochemical properties of pulp, foam and foam powder. *MSc. Thesis*, University of Hohenheim, Stuttgart, Germany. • Waill, Yousif Idris (2020). Physical properties of white-fleshed and yellow-fleshed cassava foam powder. *MSc. Thesis*, University of Hohenheim, Stuttgart, Germany. • Novita Wattimena Victorine (2019). Foaming and drying of yellow cassava: properties of cassava pulp, foam and foam powder, *MSc. Thesis*, University of Hohenheim, Stuttgart, Germany. • Ibanga-Bamijoko, Blessing E. (2015). Evaluation of the Physical, Physiochemical and Functional Properties of Flour and Starch produced from Cultivars of Yellow Cassava. *MSc. Thesis*, Department of Food Technology, University of Ibadan, Nigeria. • Okoronkwo Chioma Ngozi (2015). Physical properties of lima bean seeds and physico-chemical, and functional properties of the flour, starch isolate, and protein isolate. *MSc. Thesis*, Department of Food Technology, University of Ibadan, Nigeria. • Yerumoh, Oluwafemi (2014). Effect of some physical and chemical modifications on some physical, functional and pasting properties of five African rice starches. *BSc. Thesis*, Department of Food Technology, University of Ibadan, Nigeria. • Adetunji, Jesupelumi (2014). The effects of chemical and physical modifications on some starch properties from two *Fonio* cultivars. *BSc. thesis*, Department of Food Technology, University of Ibadan, Nigeria.
Awards/Scholarship:	• Federal government scholarship for higher institutions (2004/05). • Best graduating student (2005 session, Food science option). • DAAD-STIBET Thesis Completion Grant, Aug – Dec. 2019
Ancillary trainings:	• Project management (BMC, 2008), Report writing and presentation skills (MACTAY consulti 2007) • Fundamentals in management (NBC Plc, 2007), Performance management and development (N

	plc 2009), Human resource management for non-HR managers (CIPMN, 2007) • Managing third-party distribution (NBC Plc, 2009), Leadership pipeline training (NBC Plc, 2010
Skills/Programs:	Microsoft Office suite (Word, Power point, Excel), Response surface methods (RSM), Statistical package (SPSS), Modelling (Curve expert Pro®, Origin Pro®, JMP Pro), Artificial Neural Networks, Microscopy (electron, light), Image J, SOLIDWORKS, novel food formulations.
Innovations:	• Development of cassava foam, and use in cream-based foods (Ice-cream, mayonnaise) • Cassava foam powder as functional food ingredient • Citric-acid modified yam starch with high functionality in water and oil absorption
Interests:	• Research (food science, food processing, food chemistry & food biotechnology, food engineering) • Teaching with focus on drying and dehydration kinetics modelling, osmotic dehydration, sorption isotherms, and water activity • Food hydrocolloids (starch and protein isolation, modification & characterization) • Food foaming, foaming agents, stabilisers, food foam powders • Cereal (brewing, malting) and legume (fermentation) technologies • Physicochemical & Physico-functional characterisation of foods, viscosity profiling (RVA & Rheometry) • FTIR analyses • Food waste valorization
Extra-curricular activities:	• Reading, Footballing, Classic music, Movies
Languages:	• English- IELTS 2018 (Overall band 8.0)- listening 8.0, reading 8.0, writing 7.5, speaking 8.0 • English (TOEFL iBT score 104 of 120) 2015 • German (A1.1 Beginner’s German, ECTS-Points: 4, UNIcert I) 2016 • Yoruba (A1 distinction, WASSCE)
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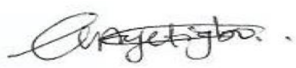

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