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ORIGINAL ARTICLE

Characterization of some quality attributes of vacuum fried yellow fleshed cassava chips from different varieties using designed experiment

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Abstract

A two-level full factorial design was used to explore the influence of process conditions on the qualities of fried chips from TMS 01-1368, TMS 01-1371, and TMS 01-1412 cultivars of yellow fleshed cassava roots under vacuum. Frying temperature (122°C and 129°C), frying time (8 and 10 min), and vacuum pressure (9.91 and 14.91 cmHg) were used to evaluate changes in color, texture, shrinkage, moisture, oil, and carotenoid contents. Frying temperature, vacuum pressure, and frying time at linear, quadratic, and interaction terms showed significant ($p < .05$) effect on the qualities and carotenoid contents of fried chips from yellow fleshed cassava cultivars. The coefficients of determination (R^2) of all responses were > 0.75. Increased frying temperature and time reduced the L^* value. The optimized solutions for fried chips are 129°C/9.91 cmHg/9.57 min for TMS 01-1371; 122°C/14.49 cmHg/8 min for TMS 01-1371; 122°C/ 9.91 cmHg/9.95 min for TMS 01-1412.

Novelty impact statement

- Classical experimental design was used to optimize vacuum frying processing of yellow fleshed cassava roots.
- Different optimized vacuum frying processing conditions were obtained for three varieties.
- Vacuum fried chips were superior to the ones fried under atmospheric condition with minimum oil content, maximum textural properties, and carotenoid contents.
- Fried chips from TMS 01-1368 had lower oil content and breaking force value than others.

1 | INTRODUCTION

Cassava (*Manihot esculenta* Crantz), popularly called manioc, mandioca, tapioca, or yucca, is one of the major staples and root crop that is extensively cultivated in many developing countries. Its production across the world in the last 2 years is about 277.81 million tons with Nigeria being the largest producer with approximately 50.98 million tons since the last decade (FAOSTAT, 2020). According to Blagbrough et al. (2010), cassava is currently among the most consumed staple foods owing to their starch percentage, and they provide about 37% of calories in human nutrition. Cassava consumption in Nigeria accounts for approximately 238 kcal dietary calorie on a daily basis among populace (Odunze, 2019). Despite being a good source of carbohydrates and energy, cassava has very low level of micronutrients. Vitamin A deficiency (VAD) which causes eye damage, and when severe it can result in blindness particularly in growing children, is one of the most serious public health problems in many developing countries. There is an increasing incidence of VAD in the sub-Saharan region with over 30% of children less than 5 years affected (Bolarinwa et al., 2017). Consumption of carotene-rich food is the best intervention for VAD, and cassava can be an excellent source by fortifying with pro-vitamin A content, perhaps, this would increase their carotene content. Bechoff et al. (2015) reported that novel cassava varieties are distinguished from conventional varieties through an evident yellow flesh, unlike the white fleshed varieties that are void of carotenoids/β-carotene. In Nigeria, biofortified cassava cultivars were developed and introduced to small- to medium-scale farmers in 2014 by the International Institute of Tropical Agriculture (IITA). García-Segovia et al. (2016) characterized cultivars of yellow fleshed cassava and found out they contain negligible quantities of cyanogenic glucosides which is safe for consumption after processing, for example, frying.

Value can be added to cassava roots by processing into snacks through deep fat frying. This method involves immersing the product in hot oil at a temperature higher than that of the boiling point of water (Yamsaengsung & Moreira, 2002). Frying has been known to impart a golden color, crisp texture, and pleasant flavor on fried products. The process involves the transfer of heat and mass within the product in an opposite direction, for example, in starchy materials, moisture and few soluble matters inside the product escapes and allows fat infiltration (Liu-Peng et al., 2005). Owing to the high temperature and vulnerability of the product exposed to oxygen during the conventional frying method which can impinge on heat-labile β-carotene inherent in yellow fleshed cassava root, vacuum frying would be advantageous. According to Granda et al. (2004), vacuum frying implies frying with a temperature lower than that of atmospheric pressure, and it has shown to be a better substitute to conventional frying, due to the excellent quality and healthier products that have been obtained. Frying under vacuum conditions involves lowering the boiling point of oil and water in the material by heating them below a negative pressure in the absence of oxygen (Fan et al., 2005; Shyu et al., 2005). Vacuum frying is an excellent approach for maximizing the nutritional quality of fried snacks, by reducing oil uptake and oil deterioration. It removes moisture from the product so as to attain necessary texture without extreme darkening (Shyu et al., 2005). Variation in composition among cultivars such as the levels of β-carotene and starch content would influence browning, flavor development, and textural quality which is associated with Maillard reaction during frying (Mottram et al., 2002; Stadler et al., 2002). Processing conditions are significant parameters that should be monitored so as to produce acceptable fried samples with superior quality since higher temperature and longer frying duration result in loss of β-carotene contents and could also induce higher oil absorption. Owing to the prevalence of the obesity epidemic in high-income countries and even in low- and middle-income countries, oil uptake is reported as the most important dietary critical point of fried products (FAO, 2002).

Consumers' transition to healthier food has prompted food industries to frequently explore raw materials and processes that would address these nutritional concerns in terms of fat intake in fried foods, and at the same time still satisfy their taste buds with the desired crispy texture and taste. Several authors have reported high-quality fried products, such as potato chips, banana slices, apples, carrot chips, and apple chips, using vacuum conditions (Akinpelu et al., 2014; Da Silva & Moreira, 2008; Dueik et al., 2010; Esan et al., 2015; Garayo & Moreira, 2002; Shyu & Hwang, 2001; Sobukola Dueik & Bouchon, 2013; Sobukola et al., 2013; Yamsaengsung et al., 2011; Yamsaengsung & Ngamnuch, 2005). This study envisaged using the novel yellow fleshed cassava cultivar as a source of vitamin A by processing with vacuum frying. Selecting the appropriate cultivar and process condition would be advantageous in ensuring that a maximum level of β-carotene is retained at the point of consumption. In addition, there are limited studies on vacuum fried cultivars of yellow fleshed cassava root slices and also to explore the influence of process variables and cultivar on the final quality of vacuum fried products. This study would be very useful in product development, most especially in terms of quality and nutrition considering the popularity of fried snacks. Hence, the effect of vacuum frying process parameters on the qualities of chips produced from three cultivars of yellow fleshed cassava roots was investigated and optimum processing conditions was obtained. The optimum vacuum fried chips were compared to atmospheric fried samples.

2 | MATERIALS AND METHODS

2.1 | Cassava root cultivars and preparation into slices

Freshly harvested cultivars of yellow fleshed cassava roots (TMS/01-1368, TMS/01-1371, and TMS/01-1412) from the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria were used while frying oil (refined bleached and deodorized palm olein oil rich in omega-3 and containing no cholesterol) was procured from a local market. Fresh roots were sorted, cleaned under running water and peeled with a sharp carving knife. Roots were sliced into a width of 40 mm diameter using a vegetable slicer (model ART: NO: SF-923-1, Texas, USA). Starch on the slices' surface was removed by immersing in a water bath (30°C, 10 min), while excess surface water was removed by placing the slices between moistened towel as per the method of Esan et al. (2015).

2.2 | Vacuum frying experiments

A vacuum fryer (model no: VF 8.0, SitusMESIN, Indonesia) was used for the experiment. Compositional differences could influence processing conditions, so cultivars were processed separately. The experiment started by heating the vacuum vessel for about 1 hr using a desired frying temperature. Eight slices of cassava root were placed into the frying medium as soon as the oil temperature reaches the targeted value, covered with a lid the vessel is then removed in the course of waiting for the desired vacuum level. Frying starts at this stage and the basket is lowered into the hot oil. The vacuum is broken once the slices have been fried at the set time, subsequently, the basket is lifted from the oil and the vacuum fried cassava chips removed and left to cool before further analysis is carried out.

2.3 | Physicochemical properties determination of raw yellow fleshed cassava roots

The analytical methods of AOAC (2000) was used to determine the chemical composition of the yellow fleshed cassava roots. Starch, amylose, and bulk density (loose and packed) were evaluated using the procedures of Wang and Kinsella (1976). The hydrogen cyanide and carotenoid content of raw roots were analyzed using HPLC as per the method of Rao and Hahn (1984) and Howe and Sherry (2006), respectively.

2.4 | Quality attributes of fried samples

The methodology described by AOAC (2000) was adopted for determining the moisture and oil content of fried yellow fleshed cassava root slices. Color parameters using the *L*, *a*, *b* coordinates were obtained as per the method of Esan et al. (2015) using Adobe Photoshop 6.0 software (Adobe Systems Inc., California, USA). L^*, a^*, b^* were calculated using the equations below (Yam & Papadakis, 2004).

$$L^* = \frac{L}{255}.100 \tag{1}$$

$$a^* = a.\frac{240}{255} - 120 \tag{2}$$

$$b^* = b.\frac{240}{255} - 120 \tag{3}$$

Color difference between fried and raw slices was calculated using Equation (4).

$$\Delta E = \left[\left(L_0^* - L^*\right)^2 + \left(a_0^* - a^*\right)^2 + \left(b_0^* - b^*\right)^2\right]^{1/2} \tag{4}$$

2.4.1 | Carotenoid determination

The standardized procedure documented in HarvestPlus handbook as per Kimura and Rodriguez-Amaya (2004) was used to extract the carotenoid content of fried slices. Precautions were observed to avoid any undesirable alteration in this pigment due to their sensitivity to ultraviolent (UV) ray, extreme temperature, prooxidants, and/or similar compounds. UV filters were employed when samples were exposed to laboratory light or direct sunlight. Five grams of test samples were added into a mortar containing 30 ml of cold acetone and pulverized with a pestle until smooth. Buckner funnel with Whatman No 1 filter paper was used to filter the mixture through suction. The extraction process was terminated following a visible colorless and clear residue. The acetone extract was poured into a separating funnel containing 20 ml of petroleum ether, while distilled water was slowly added down the funnel walls. At the end, two phases were obtained; in the petroleum ether phase, brine solution (NaCl) of about 150–200 ml was used to break any suspension, and then passed through a glass funnel and the final solution was collected in a 25-ml volumetric flask, whereas, in the aqueous acetone phase, the lower component is completely discarded to remove acetone.

The absorbance of the extract was read using absorption spectrophotometry (Cecil CE2021, Cambridge, UK), at an absorbance of 450 nm. The methodology of Kimura and Rodriguez-Amaya (2004) was adopted in reading the absorption coefficient of β-carotene present in petroleum ether (2,592) using Equation (5).

$$\text{Total carotenoid content}\,(\mu\text{g/g, wet basis}) = \frac{A_{\text{total}} \times \text{volume (ml)} \times 104 \times (\text{DF})}{A_{1\,\text{cm}}^{1\%} \times \text{sample weight}} \tag{5}$$

where A_{total} equals absorbance at 450 nm; Volume (ml) equals total volume of extract (25 ml), and $A_{1\,cm}^{1\%}$ equals 2,592 (absorption coefficient of β-carotene in petroleum ether [PE]).

The methodology of Howe and Sherry (2006) was adopted for HPLC analysis. A PE extract of approximately 15 ml was collected and dried under nitrogen. The sample was diluted in 1 ml of methanol/dichloroethane (50:50 v/v) and 50 μl was injected into the HPLC system. Carotenoid qualification was done using a water HPLC system (Water Corporation, Milford, MA), comprising of a guard column, a carotenoid column of 4.6 × 250 mm, 3 μm (C30 YMC), binary pump (626), autosampler (717), and a photo diode array detector (2,996). Methanol (100%) and methyl tert-butyl ether (100%) were used as samples A and B, respectively, while isocratic elution was done at a runtime of 15 min using 1 ml/min.

2.4.2 | Texture and shrinkage determinations

The texture of fried chips was analyzed using an Instron Universal Texture Analyzer as per the method of Da Silva and Moreira (2008). A steel ball probe (P/0.25 s) was used to break fried chips positioned over a hollow cylinder at a moving speed of 5 mm/s covering a 5.0-mm distance. The breaking force (Newton) which was the maximum force needed to break the chips was used as the marker for texture. Shrinkage was determined by measuring the difference between the area of raw slices before frying and fried slices using a planimeter as per the procedure of Das et al. (2013). The percentage shrinkage of fried slices was calculated as per Equation (6).

$$\text{Shrinkage}\,(\%) = \frac{A1 - A2}{A1} \tag{6}$$

where *A*1 equals area of raw slices; *A*2 equals area of fried slices.

2.4.3 | Microstructure analysis

The methodology described by Sobukola et al. (2013) was modified and used. Petroleum ether was used to remove fat from the surfaces of both the optimized vacuum and atmospheric (control) fried samples for 2 hr. Varian Vacuum Evaporator PS 10E (Evey Engineering's

Warehouse, Hoboken, NJ, USA) was used to coat defatted samples with a golden film and variable pressure scanning electron microscope LEO 1420VP (LEO Electron Microscopy Ltd., Cambridge, UK) was used for analysis at an acceleration potential of 25 kV. Electron microphotographs were obtained from an Oxford7424 solid-state detector (Oxford Instruments, Oxford, UK).

2.5 | Comparison of optimized vacuum and atmospheric fried chips

The equivalent thermal driving force (ETDF) concept, that is, the difference between the frying oil temperature and the boiling point of water (at the optimized vacuum pressure for each variety), was used to compare the optimized vacuum fried samples and the atmospheric fried ones (Gazmuri & Bouchon, 2009). Consequently, the atmospheric frying temperature for varieties TMS 01-1368, TMS 01-1371, and TMS 01-1412 were 164°C, 177°C, and 170°C, respectively.

2.6 | Experimental design, process optimization, and statistical analysis

Two level-three factor full factorial design-three independent variables at two level each (upper and lower levels); frying temperature (122°C and 129°C), frying time (8 and 10 min), and vacuum pressure (9.91 and 14.91 cmHg). A total of eight experimental combinations (Table 1) were obtained and used to investigate their effects on the responses. Analyses were carried out in triplicate, hence, values presented are means of three experiments for each run. The data were fitted into quadratic polynomial models so as to obtain the regression equations. Analysis of variance (ANOVA) was used to examine the statistical significance of the terms in the regression equations for each response at $p < .05$. Numerical optimization method was used to obtained optimal vacuum fried chips based on desirability concept.

TABLE 1 Experimental runs showing combinations of independent variables

Experimental runs	Frying temperature (°C)	Vacuum pressure (cmHg)	Frying time (min)
1	122.00	14.91	10.00
2	129.00	9.91	8.00
3	122.00	14.91	8.00
4	122.00	9.91	10.00
5	122.00	9.91	8.00
6	129.00	14.91	8.00
7	129.00	9.91	10.00
8	129.00	14.91	10.00

3 | RESULTS AND DISCUSSION

3.1 | Physicochemical properties of raw yellow fleshed cassava cultivars

The moisture of tubers (74.66%), moisture of flour (2.91%–3.36%), fat (0.86%–1.58%), ash (3.59%–3.69%), protein (1.46%–2.05%), sugar (4.62%–5.05%), starch (59.69%–66.89%), amylose (28.56%–30.35%), loosed bulk density (1.50–3.00 g/ml), packed bulk density (1.72–1.94 g/ml), and hydrogen cyanide (7.15–21.03 mg/100 g) contents of TMS 01-1368, TMS 01-1371, and TMS 01-1412 cassava cultivars are shown in Table 2. Significant ($p < .05$) differences were observed in the physicochemical composition of the yellow fleshed cassava roots. According to Siqueira et al. (2009), variation observed in the chemical composition of cassava largely depends on the cultivar, time of planting and harvesting, maturity, and availability of rainfall, etc. The highest moisture content (MC) was observed in TMS 01-1368 raw cassava, while the lowest value was found in TMS 01-1412. The observed 78.53% was comparably higher than the 64.95% reported for TMS 1368 raw cassava MC by Bolarinwa et al. (2017). Fat percentage was found to be maximum in TMS 01-1412, intermediate in TMS 01-1371, and minimum in TMS 1368. The values observed in this study are not comparable to the fat content of improved cassava cultivars reported by Bolarinwa et al. (2017). The low fat percentage found signifies that the flour from cultivars will not be susceptible to rancidity and could be stored for a long time with no modification to its composition. The ash content (3.59%–3.69%) observed in this work was higher than the values reported by Akinwale et al. (2017) and Bolarinwa et al. (2017) for cassava flour. The sample from TMS 01-1412 had a higher protein percentage (2.06%) than TMS 1368 (1.54%) and TMS 01-1371 (1.46%). These values were lower than 8.10% found in TMS-1368 in the report of Ukenye et al. (2013), but, higher than the values (0.07%–0.48%) reported for *gari* processed from varieties of yellow fleshed cassava. The highest sugar and starch content was observed in TMS 1368 when compared to other varieties. Starch content found in the three cassava cultivars investigated was lower than the values reported by Akinwale et al. (2017).

Amylose content with the lowest value (28.56%) was found in TMS 1368 while the highest value (30.35%) in TMS 01-1412. The amylose content of identical cassava cultivars reported by Akinwale et al. (2017) was in range with the values experiential in this study, but higher than that of Amuzie et al. (2017). Amylose is an important quality of starch and flour ingredients with higher fractions often exhibiting excellent retrogradation (Tukomane et al., 2007). The loose and packed bulk density of three cassava varieties investigated were higher than the range of 0.67–0.91 g/ml reported by Akinwale et al. (2017) for eight varieties of cassava flour. The highest values were observed in TMS 1371 and lowest in TMS 1368. Hydrogen cyanide content of the raw root of yellow fleshed cassava cultivars was highest in TMS 1371 and lowest in TMS 1412. The values obtained in this study were within the range reported of Ndam et al. (2019),

TABLE 2 Physicochemical results of raw yellow fleshed cassava roots of different varieties

Samples	%M (Fresh)	% Fat	% Ash	% Protein	% Sugar	% Starch	% Amylose	BD (loose) g/ml	BD (packed) g/ml	HCN (mg/100 g) FW
TMS 01-1368	78.53	0.86	3.59	1.54	5.05	66.89	28.56	1.50	1.72	16.67
TMS 01-1371	75.28	1.33	3.69	1.46	4.82	59.69	30.04	3.00	1.94	21.03
TMS 01-1412	74.66	1.58	3.59	2.05	4.62	63.19	30.35	1.50	1.88	7.15

Note: Values are means of duplicate.

Abbreviations: BD, bulk density; FW, fresh weight; HCN, hydrogen cyanide; M, moisture content.

but higher than 4.07–5.20 mg/100 g reported by Chikezie and Ojiako (2013) for peeled cassava roots. Based on the recommendation of FAO/WHO (1991) hydrogen cyanide content above 10 mg/kg (dry basis) in cassava products is not tolerable. Higher values above the recommended safe limit observed in this work could be reduced by means of unit operations. Several processing methods have been employed to reduce the hydrogen cyanide content of cassava products (Bolarinwa et al., 2016).

3.2 | Color parameters of fried chips

Color parameters in terms of lightness (L^*), redness (a^*), yellowness (b^*), and color change (ΔE) are employed to measure the overall extrinsic quality of fried chips. Krokida et al. (2001) characterized the satisfactory color of fried products as golden and this attribute largely influences consumer purchase. Lightness (L^*) values ranged from 74.51% to 81.57%, 70.94 to 80.64%, and 74.81 to 80.70%, respectively, for fried chips from TMS 01-1368, TMS 01-1371, and TMS 01-1412 cassava varieties (Table 2). Sobukola et al. (2008) concluded that the color of fried chips from roots and tuber product must either be light or golden yellow and they are achievable through Maillard reaction which depends on the frying conditions, amino acids, and reducing sugars content. The L^* value obtained in this work is similar to the values (72.43–81.19) reported by Ladeira et al. (2013) for fried chips from cultivars of cassava roots grown in Brazil. Interaction terms of frying time and vacuum pressure showed a significant ($p < .05$) effect on L^* of TMS 01-1368 (Table 4). The model's coefficient of determination (R^2) and F-value were 0.95 and 7.62, respectively. Response surface plots generated, although not presented due to the large numbers, usually show the changes in responses as a result of changes in the independent variables. The lowest value was obtained in TMS 01-1368 fried at the highest frying temperature and time, and increased frying temperature reduced the L^* value. Regression analysis did not show any significant ($p > .05$) effect of independence on L^* of TMS 01-1371 and TMS 01-1412 (Tables 5 and 6). Increased frying temperature and time reduced the L^* value of TMS 01-1371, while increased vacuum pressure and frying time reduced the L^* of TMS 01-1412. High temperature accelerates nonenzymatic reaction and this rapidly decreases the L^* value of fried products (Diamante et al., 2013). Omidiran et al. (2018) found out a similar observation of reduced lightness value with increased frying temperature. Likewise García-Segovia et al. (2016) had earlier reported a minimum L^* value of fried chips with the highest vacuum pressure.

The transition of fried products' color from golden to dark brown is measured with a^* values (Pangloli et al., 2002). Frying temperature exhibited a significant ($p < .05$) reduction effect at linear terms on a^* and b^* in TMS 01-1368 (Table 4). The R^2 for a^* and b^* is 0.94 and 0.99, respectively, and this implies that the present model used is reliable. Results from this study showed that increased vacuum pressure increased the a^* value of TMS 01-1371 while increased frying time increased the a^* value of TMS 1412. Onipe et al. (2019) and Angie et al. (2020) also found out that a^* increased with increased frying temperature and time. The b^* value ranging from 14.71 to 51.64 found in the three varieties of fried yellow fleshed cassava chips was higher than the values reported for cassava chips by García-Segovia et al. (2016). The higher yellowness values obtained in this study could be linked to the high levels of carotenoids inherent in the cassava cultivars than the influence of processing conditions. The model terms had no significant ($p > .05$) effect on the b^* values of TMS 01-1371, although, it is evident from response surface plots that frying time and vacuum pressure reduced the b^* of TMS 01-1371. Regression analysis showed a negative significant ($p < .05$) effect of frying temperature at linear term on the b^* of fried chips from TMS 01-1412. This is consistent with the report of Shyu et al. (2005), where the b^* value of fried carrot chips reduced with increased frying temperature and attributed it to the loss of volatile carotenoid compounds at high temperature.

The mean values of change in color (ΔE) ranged from 13.05 to 26.97, 22.54 to 49.05, and 12.19 to 38.58 for fried chips from TMS 01-1368, TMS 01-1371, and TMS 01-1412, respectively (Table 3). Frying temperature exhibited a negative significant ($p < .05$) effect on ΔE of TMS 1412 fried cassava chips (Table 6). On the other hand, no significant ($p > .05$) effect existed in the ΔE of fried chips from TMS 01-1368 and TMS 01-1371. However, increased frying temperature, vacuum pressure and frying time reduced the ΔE of the three cassava varieties. Tan and Mittal (2006) reported a similar observation of reduced ΔE of vacuum fried donuts with increased

TABLE 3 Response surface analysis results as a function of independent variable for the yellow fleshed cassava varieties

Variety	Runs	Y_1	Y_2	Y_3	Y_4	Y_5 (N)	Y_6 (%)	Y_7 (%)	Y_8 (%)	Y_9 (μg/g)	Y_{10} (μg/g)	Y_{11} (μg/g)	Y_{12} (μg/g)	Y_{13} (μg/g)	Y_{14} (μg/g)
TMS 01-1368	1	77.61	−6.17	31.57	26.97	8.96	12.50	25.44	6.68	1.43	0.32	3.42	1.47	6.64	20.35
	2	76.50	−5.01	21.07	16.61	6.17	12.50	25.60	4.63	1.51	0.33	3.15	0.20	5.19	17.75
	3	77.10	−7.80	28.39	24.26	11.57	5.00	25.09	7.19	1.66	0.34	3.82	1.72	7.54	20.46
	4	81.57	−6.90	32.29	27.87	14.73	25.00	25.20	6.02	1.54	0.31	3.41	1.51	6.76	20.53
	5	79.71	−7.96	30.94	26.69	13.67	37.50	24.80	7.38	1.56	0.29	4.41	1.78	8.04	18.70
	6	77.96	−5.19	20.34	15.78	6.30	37.50	26.43	4.68	1.43	0.31	3.34	1.34	6.42	15.57
	7	74.51	−4.35	16.90	13.05	6.80	12.50	25.45	4.57	1.48	0.33	3.27	1.38	6.46	17.65
	8	79.04	−6.15	31.32	26.68	8.27	25.00	25.46	4.07	1.45	0.30	3.33	1.37	6.46	17.82
TMS 01-1371	1	78.39	−5.15	25.11	22.54	13.95	5.36	26.27	4.91	1.89	0.33	4.53	1.67	8.42	22.07
	2	78.96	−3.03	39.23	36.30	10.63	5.36	24.36	4.37	1.95	0.38	4.15	1.61	8.10	20.21
	3	80.64	−9.46	38.62	36.61	20.73	21.14	24.89	5.94	1.43	0.25	4.29	1.60	7.56	22.26
	4	79.16	−5.36	44.45	41.68	15.90	29.02	22.44	4.57	1.55	0.28	4.47	1.62	7.93	22.41
	5	73.71	−1.89	51.64	49.05	13.43	21.14	22.83	5.17	1.62	0.36	4.63	1.79	8.39	21.74
	6	77.66	−3.36	42.81	39.94	14.10	21.14	23.68	5.17	1.71	0.35	4.58	1.73	8.37	22.33
	7	70.94	−3.21	38.26	36.45	12.35	13.25	23.92	3.97	1.92	0.37	5.05	1.75	9.08	26.02
	8	76.87	−2.71	36.38	33.56	17.05	21.14	24.03	3.96	1.87	0.34	5.03	1.73	8.96	25.32
TMS 01-1412	1	74.81	−5.64	29.50	27.61	6.57	66.67	23.82	6.04	1.27	0.29	3.02	1.49	6.06	17.77
	2	75.39	−5.25	21.44	19.71	10.63	50.00	22.40	5.32	1.18	0.26	2.90	1.38	5.72	16.01
	3	78.07	−6.88	40.98	38.58	12.95	58.33	23.29	8.41	1.33	0.31	3.18	1.60	6.41	17.27
	4	77.12	−7.38	26.99	25.12	14.60	58.33	22.12	7.74	1.38	0.28	3.67	1.64	6.97	19.09
	5	80.70	−4.56	37.27	34.52	5.50	66.67	22.67	7.79	1.28	0.27	3.51	1.62	6.68	18.92
	6	80.19	−4.23	14.71	12.19	5.53	66.67	25.74	5.41	1.28	0.29	2.93	1.41	5.91	17.48
	7	77.58	−3.98	23.94	21.45	9.25	66.67	25.63	5.10	1.35	0.33	2.88	1.48	6.04	17.66
	8	76.34	−3.75	23.57	21.29	11.13	58.33	26.55	4.82	1.33	0.31	3.19	1.56	6.40	17.31

Note: where Y_1, Lightness; Y_2, Redness; Y_3, Yellowness; Y_4, ΔE (Change in color); Y_5, Texture; Y_6, Shrinkage; Y_7, Oil content; Y_8, Moisture content; Y_9, 13-cis; Y_{10}, 15-cis; Y_{11}, Trans; Y_{12}, 9-cis; Y_{13}, Total β-carotene; Y_{14}, Total carotenoid; Values are means of duplicate.

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TABLE 4 Regression coefficients of the responses of fried chips from TMS 01-1368 as a function of independent variables

Coefficients	Y_1	Y_2	Y_3	Y_4	Y_5 (N)	Y_6 (%)	Y_7 (%)	Y_8 (%)	Y_9 (μg/g)	Y_{10} (μg/g)	Y_{11} (μg/g)	Y_{12} (μg/g)	Y_{13} (μg/g)	Y_{14} (μg/g)
β	78.00	−6.19	26.60	22.24	9.56	20.94	25.43	5.65	1.51	0.32	3.52	1.35	6.69	18.60
X_1	−1.00	1.02*	−4.19*	−4.21	−2.67*	0.94	0.30*	−1.16*	−0.04	-	−0.25*	−0.27	−0.56*	−1.40*
X_2	−0.07	−0.14	1.30	1.18	−0.78	−0.94	0.17	2.14E-003	−0.02	2.52E-003	-	0.13	-	−0.06
X_3	-	0.30	1.42	1.40	-	−2.19	-	-	−0.03	-	−0.16	0.09	−0.11	0.48
X_1X_2	1.57*	−0.36	2.12	2.02	1.18*	10.31	-	-	−0.01	−0.02*	0.10	0.15	0.23	-
X_1X_3	-	−0.37	-	0.43	-	-	−0.23*	0.15	0.03	−1.95E-003	0.19	0.22	0.43	0.05
X_2X_3	0.21	-	2.12	2.00	-	0.94	−0.11	0.04	-	−5.35E-003	-	-	-	-
$X_1X_2X_3$	0.37	-	1.66	-	0.63	-	-	−0.18	0.03	-	-	−0.15	-	0.54
R^2	0.95	0.94	0.99	0.92	0.96	0.87	0.93	0.93	0.93	0.91	0.91	0.91	0.91	0.92
F-value	7.62	6.18	67.92	1.87	19.31	2.62	10.62	4.98	2.31	7.60	7.43	1.61	7.40	4.89

*Significant values at 5% level; β, Intercept; X_1, Frying temperature; X_2, Vacuum pressure; X_3, Frying Time; Y_1, Lightness; Y_2, Redness; Y_3, Yellowness; Y_4, ΔE (change in color); Y_5, Texture; Y_6, Shrinkage; Y_7, Oil content; Y_8, Moisture content; Y_9, 13-cis; Y_{10}, 15-cis; Y_{11}, Trans; Y_{12}, 9-cis; Y_{13}, Total β-carotene; Y_{14}, Total carotenoid.

vacuum pressure and frying time, although they observed increased ΔE with increased frying temperature.

3.3 | Texture (breaking force) of fried chips

Texture is one of the most sought after attributes of fried products. It reflects the crispiness or crunchiness of fried foods and determines its chewing quality (Maity et al., 2014). Hardness was the texture parameter measured. It is an index of the amount of force required to fracture a fried product by means of a compression or puncture technique. The texture means value of fried chips from TMS 01-1368, TMS 01-1371, and TMS 01-1412 ranged from 6.17 to 14.73 N, 10.63 to 20.73 N, and 5.50 to 14.60 N, respectively (Table 3). Texture results varied among fried chips from three yellow fleshed cassava cultivars at the same frying temperature, vacuum pressure, and frying time conditions. This could be explained with the variation of starch content innate in each cultivar. Given this, starch content among other factors contributes to the texture of fried foods (Esan et al., 2015). Significant ($p < .05$) effect in the frying temperature at linear terms, and interaction between frying temperature and vacuum pressure existed in the hardness of fried chips from TMS 01-1368. A high R^2 value of 0.96 (Table 4) was observed and this is an indicator that the present model used is an excellent predictor of hardness as influenced by independent variables. Interaction terms of frying temperature, vacuum pressure, and frying time had a positive significant ($p < .05$) effect on hardness of fried chips from TMS 01-1412 with a high R^2 value of 0.85 (Table 6).

Highest hardness values were observed in all the chips from the three cassava cultivars at lowest frying temperature, while lowest values were observed at the highest frying temperature except fried chips from TMS 01-1412. Results obtained from TMS 01-1412 fried chips showed that maximum crispiness (lowest value) was observed at the lowest conditions of frying temperature, vacuum pressure, and frying time (Table 3). This observation agrees with the study of Oyedeji et al. (2017) where they reported maximum moisture loss and changes in product microstructure in vacuum fried chips with lesser frying time. However, lower hardness values were observed with increased frying temperature in fried chips from TMS 01-1368 and TMS 01-1371. This could be attributed to the fact that a sufficient amount of moisture has been lost at maximum frying temperature which resulted in a crispy product. A combination effect of maximum frying temperature and time leads to dehydration of fried products at bubble-end point, and this confers hardness, consequently making them difficult to break. According to Onipe et al. (2019), maximum frying temperature and time leads to dehydration effect in fried products where crust is formed, thus leading to a crispy product. Based on the report of Maity et al. (2014), chips crust developed at 100°C were harder than crust developed at 80°C, because a significant modification had occurred at the maximum temperature. Similarly, Sobukola et al. (2008) reported that fried products tend toward crispness as frying progresses.

TABLE 5 Regression coefficients of the responses of fried chips from TMS 01-1371 as a function of the independent variable

Coefficients	Y_1	Y_2	Y_3	Y_4	Y_5 (N)	Y_6 (%)	Y_7 (%)	Y_8 (%)	Y_9 (µg/g)	Y_{10} (µg/g)	Y_{11} (µg/g)	Y_{12} (µg/g)	Y_{13} (µg/g)	Y_{14} (µg/g)
β	77.04	−4.27	39.56	37.02	14.77	17.19	24.05	4.76	1.74	0.33	4.59	1.69	8.35	22.80
X_1	−0.93	1.19	−0.39	−0.45	−1.24	−1.97	-	−0.39	0.12*	0.03*	0.11	0.02	0.28	0.68
X_2	1.35	-	−3.83	−3.85	1.69	-	0.67*	0.24	−0.02	0.02*	0.02	−4.91E-003	−0.02	-
X_3	-	-	−3.51	-	0.05	−1.25E-003	-	−0.40	0.07	2.80E-003	0.18	-	0.25	1.16
X_1X_2	−0.19	0.94	4.26	4.04	0.35	5.92	−0.81*	−0.04	−0.06	-	-	0.03	0.06	0.15
X_1X_3	−1.50	−0.05	1.66	1.90	1.12	1.97	−0.13	−1.19E-003	-	−4.56E-003	0.16	0.03	0.15	1.04
X_2X_3	−0.06	1.08	-	−1.66	-	−3.94	-	−0.16	0.09	0.02*	-	-	-	−0.46
$X_1X_2X_3$	1.87	−0.87	0.11	-	1.31	-	−0.12	-	-	−0.02*	−0.11	−0.05*	−0.22	−0.24
R^2	0.95	0.84	0.96	0.76	0.88	0.94	0.90	0.99	0.90	0.99	0.91	0.96	0.94	0.99
F-value	2.86	2.02	3.70	1.26	1.24	6.01	7.10	28.15	6.79	77.72	4.20	9.11	2.57	13.25

*Significant values at 5% level; β, Intercept; X_1, Frying temperature; X_2, Vacuum pressure; X_3, Frying Time; Y_1, Lightness; Y_2, Redness; Y_3, Yellowness; Y_4, ΔE (change in color); Y_5, Texture; Y_6, Shrinkage; Y_7, Oil content; Y_8, Moisture content; Y_9, 13-cis; Y_{10}, 15-cis; Y_{11}, Trans; Y_{12}, 9-cis; Y_{13}, Total β-carotene; Y_{14}, Total carotenoid.

3.4 | Shrinkage

Shrinkage occurs as a result of rapid moisture loss in fried products. The shrinkage percentage mean values of fried chips from TMS 01-1368, TMS 01-1371, and TMS 01-1412 ranged from 5.00% to 37.50%, 5.36% to 29.02%, and 50.00% to 66.67%, respectively (Table 3). Regression analysis showed that frying temperature, vacuum pressure, and frying time did not have a significant ($p > .05$) effect on the shrinkage of fried chips from TMS 01-1368 and TMS 01-1371 cultivar (Tables 4 and 5). Quadratic terms of frying temperature, vacuum pressure, and frying time had a significant ($p < .05$) effect on the shrinkage percentage of fried chips from TMS 01-1412 with an R^2 value of 0.90 (Table 6). In this study, higher frying temperature increased the shrinkage percentage and this could be explained with the rapid removal of moisture through evaporation at high temperature. The degree of shrinkage is dependent on moisture transfer within the fried product and at high oil temperature and extended frying time resulting in elevated mass and heat diffusivity, maximum moisture loss, and higher volume shrinkage (Garayo & Moreira, 2002). A similar observation with this study has been reported by Maity et al. (2014) and Yamsaengsung et al. (2011) where shrinkage percentage increased as frying temperature and time progressed. In addition, increased vacuum pressure reduced the shrinkage percentage of fried chips from the three cultivars of yellow fleshed cassava. Garayo and Moreira (2002) also reported less shrinkage of potato chips with higher vacuum pressure, which they ascribed to the resistance of chips to volume reduction due to rigid structure formed at high pressure.

On the other hand, fried chips from TMS 01-1412 cultivars had highest shrinkage percentage, than the other two cultivars. From this study, TMS 01-1412 had higher amylose content than TMS 01-1368 and TMS 01-1371 (Table 3). Amuzie et al. (2017) also reported high amylose content for TMS 01-1371. The high amylose fractions could have contributed to the lower shrinkage percentage observed in this study. Based on the findings of Ziaiifar et al. (2008) and Lisinska and Golubowska (2005), starch granules absorb water within the product matrixes at high temperatures and swell, then turn into bubbles on the surface of the product. Product matrixes begin to shrink owing to moisture loss and then produce pores which leave more space on the surface for moisture to move out and this results in a porous and shrivel volume. Irrespective of the frying conditions, the pores become bigger and increase in number owing the amount of moisture loss. Therefore, product shrinkage could be associated with the extent at which starch gelatinizes due to the percentage of starch inherent in the product.

3.5 | Oil content

The oil content mean values of fried chips from TMS 01-1368, TMS 01-1371, and TMS 01-1412 ranged from 24.80% to 26.43%, 22.44% to 26.27%, and 22.12% to 26.55%, respectively (Table 3). A significant ($p < .05$) increasing effect of frying temperature, and interaction

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terms of frying temperature and frying time were recorded for the oil content of fried chips from TMS 01-1368 cultivar with an R^2 value of 0.93 for the model (Table 4). In fried chips from TMS 01-1371, vacuum pressure at linear terms and interaction of frying temperature and vacuum pressure showed a significant ($p < .05$) effect on the oil content (R^2 of model = 0.90; Table 5). Frying temperature significantly ($p < .05$) influenced the oil content of fried chips from TMS 01-1412 with a model R^2 value of 0.89 (Table 6). Higher frying temperature, frying time, and vacuum pressure significantly ($p < .05$) increased the oil content of the three yellow fleshed cassava cultivars which could be attributed to the modification in the product surface arrangement. The degradation of product cell walls and/or tissues as a result of moisture loss at increased frying temperature and time encourages percolation of oil into the samples. Shyu and Hwang (2001) found out that the capability of oil to pass through a product is related to the amount of moisture loss within the product at bubble end-point during frying. Hence, the removal of moisture within product matrices damages the cell arrangement and this allows oil absorption within the damaged regions. Studies have found out that increased frying temperature and time increased the oil content of fried products (Maity et al., 2014; Mariscal & Bouchon, 2008) which supports the observation in the present study. Increased vacuum pressure increased the oil content of the fried chips which could be explained with the expansion of the product capillaries with more pressure and this increases moisture evaporation which consequently allows oil uptake (Tan & Mittal, 2006).

In addition, the morphological properties of starch granules in terms of porosity, percentage, and size play a significant role in the

TABLE 6 Regression coefficients of the responses of fried chips from TMS 01-1412 as a function of the independent variables

Coefficients	Y_1	Y_2	Y_3	Y_4	Y_5 (N)	Y_6 (%)	Y_7 (%)	Y_8 (%)	Y_9 (μg/g)	Y_{10} (μg/g)	Y_{11} (μg/g)	Y_{12} (μg/g)	Y_{13} (μg/g)	Y_{14} (μg/g)
β	77.53	−5.21	27.30	25.06	9.52	61.46	24.03	6.33	1.30	0.29	3.16	1.52	6.27	17.69
X_1	-	0.91	−6.38*	−6.40*	-	−1.04	1.05*	−1.17*	-	6.09E-003	−0.18*	−0.07	−0.26	−0.57
X_2	−0.17	0.09	-	-	-	-	0.82	−0.16	-	7.44E-003	−0.08	-	−0.08	−0.23
X_3	−1.06	-		−1.19	0.87	-	0.50	−0.40	0.03*	0.01	-	-	-	0.27
X_1X_2	1.06	0.23	−1.66	−1.78	−0.33	1.04	-	-	0.02	-	0.17*	0.04	0.21	0.51
X_1X_3	-	0.42	4.14*	3.90*	0.19	1.04	0.51	0.20	0.02	0.01	0.03	0.04	0.11	-
X_2X_3	−0.71	-	0.64	-	-	-	-	-	−0.04*	−9.14E-003	-	−9.65E-003	−0.06	-
$X_1X_2X_3$	−0.79	−0.61	0.95	-	2.81*	−5.21*	-	-	-	-	-	0.02	0.10	−0.27
R^2	0.89	0.90	0.97	0.9714	0.85	0.90	0.89	0.90	0.91	0.96	0.92	0.94	0.94	0.95
F-value	3.12	3.40	14.59	25.52	4.38	7.01	6.22	6.44	7.77	10.35	8.26	6.56	2.74	6.96

*Significant values at 5% level β, Intercept; X_1, Frying temperature; X_2, Vacuum pressure; X_3, Frying Time; Y_1, Lightness; Y_2, Redness; Y_3, Yellowness; Y_4, ΔE (change in color); Y_5, Texture; Y_6, Shrinkage; Y_7, Oil content; Y_8, Moisture content; Y_9, 13-cis; Y_{10}, 15-cis; Y_{11}, Trans; Y_{12}, 9-cis; Y_{13}, Total β-carotene; Y_{14}, Total carotenoid.

TABLE 7 Optimized vacuum frying processing conditions for different varieties of yellow fleshed cassava fried chips

Processing conditions	TMS-1371	TMS-1368	TMS-1412
Frying temperature (°C)	129	122	122
Vacuum pressure (cmHg)	9.91	14.49	9.91
Frying time (min)	9.57	8	9.95

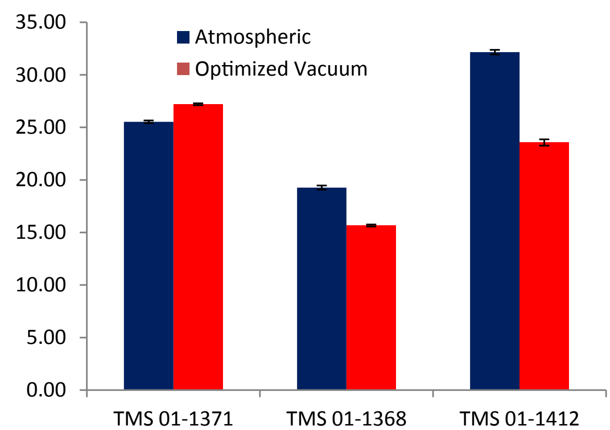

FIGURE 1 Oil content (%) of yellow fleshed cassava fried chips at atmospheric and optimized vacuum frying conditions

quantity of oil uptake of the resultant fried chips. Granules characterized with high amylose content would release more fractions during frying which provide a barrier that inhibits oil penetration in the fried product (Ahamed et al., 1997). However, Chen et al. (2017) reported a contradictory result that products with higher amylose content react more with lipids, hence, provide a hydrophobic helical hollow space that encourages more oil absorption. According to Chisenga et al.'s (2019) study on starch morphology of yellow fleshed cassava varieties, it was documented that their granular sizes varied between small to medium. Starch granules with small size rupture easily when they come in contact with heat and thereby increase the porosity of the product which leads to more oil absorption. Rupturing of granules occurs when the matrixes can no longer withstand the force initiated at high temperatures. Subsequently, the resulting pores are filled with oil and/or vapor depending on the frying duration (Huang & Fu, 2014). Surface nature contributes to the amount of oil that would be drained and absorbed at the cooling phase, for this reason, more oil would be absorbed in fried samples with extremely ruptured matrixes.

3.6 | Moisture content

The main effect of the model for moisture content values of resultant fried chips from varieties of yellow fleshed cassava corresponded to frying temperature ($p < .05$) at linear terms. A significant reducing effect existed between frying temperature and the moisture content of the fried chips from TMS 01-1368 (Table 4) and TMS 01-1412 (Table 6) varieties. A high R^2 value of 0.93 (TMS 01-1368) and 0.90 (TMS 01-1412) was obtained which indicates a significant model. These observed values would provide an excellent mathematical fit for the regression coefficient values (Tables 4 and 6). The mean values of moisture content of the fried chips from TMS 01-1368, TMS 01-1371, and TMS 01-1412 ranged from 4.07% to 7.38%, 3.96% to 5.94%, and 4.82% to 8.41%, respectively (Table 3). Lowest moisture content was observed in resultant fried chips from the three yellow fleshed cassava cultivars at the highest frying temperature, vacuum pressure, and frying time. There is a rapid reduction in the moisture content of fried chips, mostly owing to the loss of moisture from the surface and internal free water at increased frying temperature. The unbound moisture inside the product

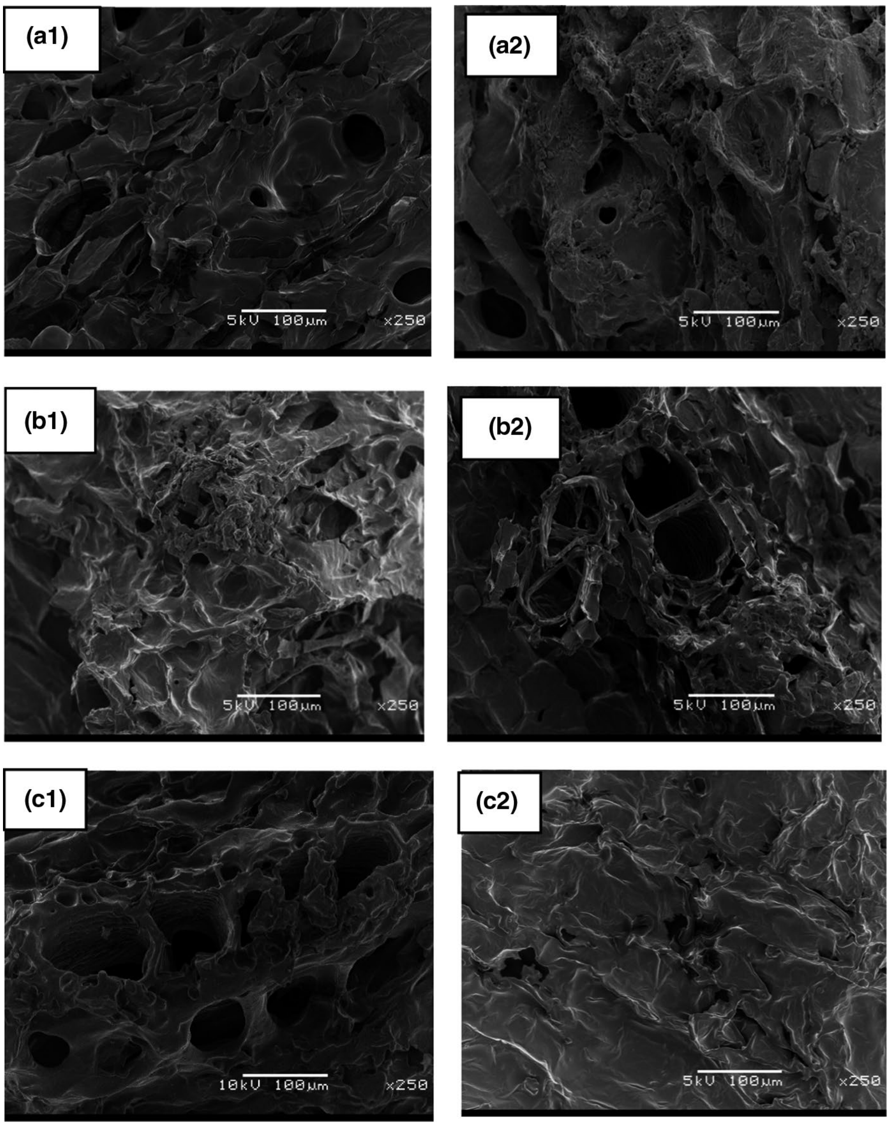

FIGURE 2 Micrographs of fried yellow fleshed cassava chips under atmospheric (1) and optimized vacuum (2) frying conditions for TMS 01-1368 (a), TMS 01-1371 (b) and TMS 01-1412 (c), respectively

moves to the surface of the product as vapor at temperatures above 100°C. As observed in this work, frying temperature considerably reduced the moisture content of the fried chips. This result agrees with the findings previously reported on the influence of frying temperature on moisture content of fried product. Maity et al. (2014) found out that at 100°C, the moisture content of the resultant fried chips was lower than the chips processed at lower temperatures of 80°C and 90°C. A similar frying temperature effect on fried product moisture content has been reported by Omidiran et al. (2018).

Under the same processing conditions, the moisture content of fried chips from three cultivars of yellow fleshed cassava varied from each other. This could be attributed to their internal structure configuration that discourages rapid moisture loss during processing. According to the investigation by Laryea et al. (2019), the moisture content of French fries from 10 cultivars of orange fleshed sweet potatoes varied significantly and was attributed to the influence of their genetic configuration. Since moisture retention in fried foods is largely dependent on the porosity of matrixes created by the action of heat, therefore, maximum moisture content evident in fried chips from TMS 01-1412 implies that their internal configuration limits moisture loss. Minimum moisture content is desirable in fried chips, because it corresponds to superior crispiness. Fried chips from TMS 01-1371 may have the best crispiness and excellent storage qualities.

3.7 | Carotenoid content

The result obtained in this work showed that processing conditions had different effects on the β-carotenoid isomers, total β-carotene, and total carotenoid content of fried chips from three yellow fleshed cassava cultivars. Previous findings from literature revealed that the impact of different processing conditions on the stability of carotenes depends on the product genetic makeup and quantity prior to processing (Iglesias et al., 1997; Maziya-Dixon et al., 2000). In this study, the highest total β-carotene and the total carotenoid content was observed in fried chips from TMS 01-1371 (Table 3) and this supports the report of Maziya-Dixon et al. (2000) who found maximum total carotenoid content in TMS 01-1371 in comparison to other cultivars investigated. The independent variables' largest effect on 13-cis-β-carotene of fried chips from TMS 01-1371 (Table 5) was linear terms of frying temperature ($p < .05$), frying time ($p < .05$), and interaction terms ($p < .05$) of vacuum pressure and frying time in fried chips from TMS 01-1412 (Table 6). A significant ($p < .05$) reduction effect was recorded at linear terms of frying temperature and vacuum pressure, interaction terms of vacuum pressure and frying time, and quadratic terms of independent variable in 15-cis-β-carotene content fried chips from TMS 01-1371.

Increased frying temperature increased the 13-cis- and 15-cis-β-carotene content in fried chips. This may be ascribed to the release of carotenoids from carotene-binding proteins that might have been denatured at high frying temperature (Sulaeman et al., 2001). Also, vacuum pressure changes the product matrixes which may possibly have released the bounded β-carotene and this makes them accessible. A significant ($p < .05$) reduction effect of trans-β-carotene of fried chips was observed at linear terms at frying temperature of TMS 01-1368 (Table 4) and TMS 01-1412 (Table 6). Independent variables had no significant effect at linear, interaction, and quadratic terms on TMS 01-1371 (Table 5) fried chips. This result

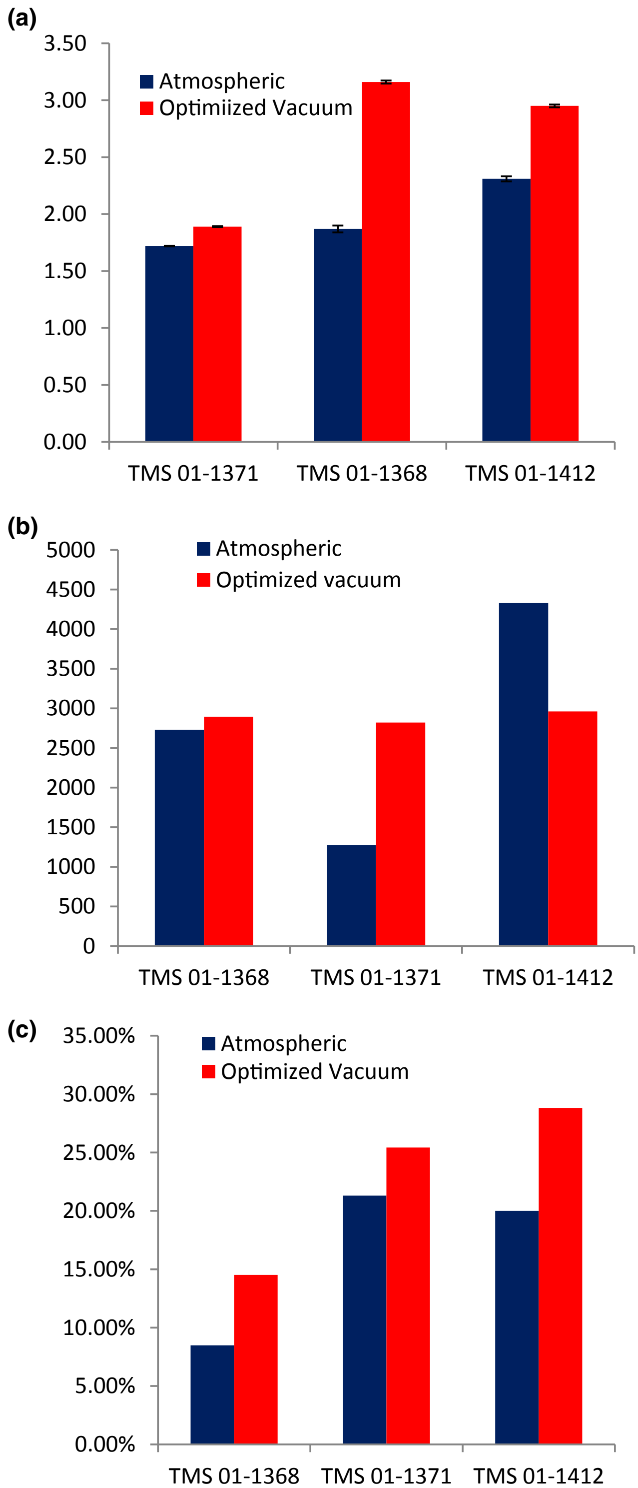

FIGURE 3 Moisture content (a), Breaking force (b) and shrinkage (c) of fried yellow fleshed cassava chips at atmospheric and optimized vacuum frying conditions

showed reduction in trans-β-carotene of fried chips at increased frying temperature. Dueik et al. (2010) also observed loss of trans-carotene percentage during thermal processing. This was attributed to their high susceptibility to isomerization and oxidation. The breakdown of trans-β-carotene with increased frying temperature resulted in increased cis-β-carotene isomers observed in this study.

A significant reduction effect of frying temperature ($p < .05$) existed in total β-carotene and total carotenoids of fried chips from TMS 01-1368 (Table 5). No significant effect was observed in the other two yellow fleshed cassava varieties. In this study, increased frying temperature reduced the total β-carotene and total carotenoids of the fried chips. A similar observation has been reported by Laryea et al. (2019) who showed a loss that ranged from 5% to 84% in the β-carotene content of 10 cultivars of sweet potato fries studied. They supported their findings with the heat-labile characteristics of carotenoids which make them easily decomposed in the presence of heat. Furthermore, Maity et al. (2014) attributed carotenoid loss in vacuum fried products to the nonexistence of oxygen in the vacuum

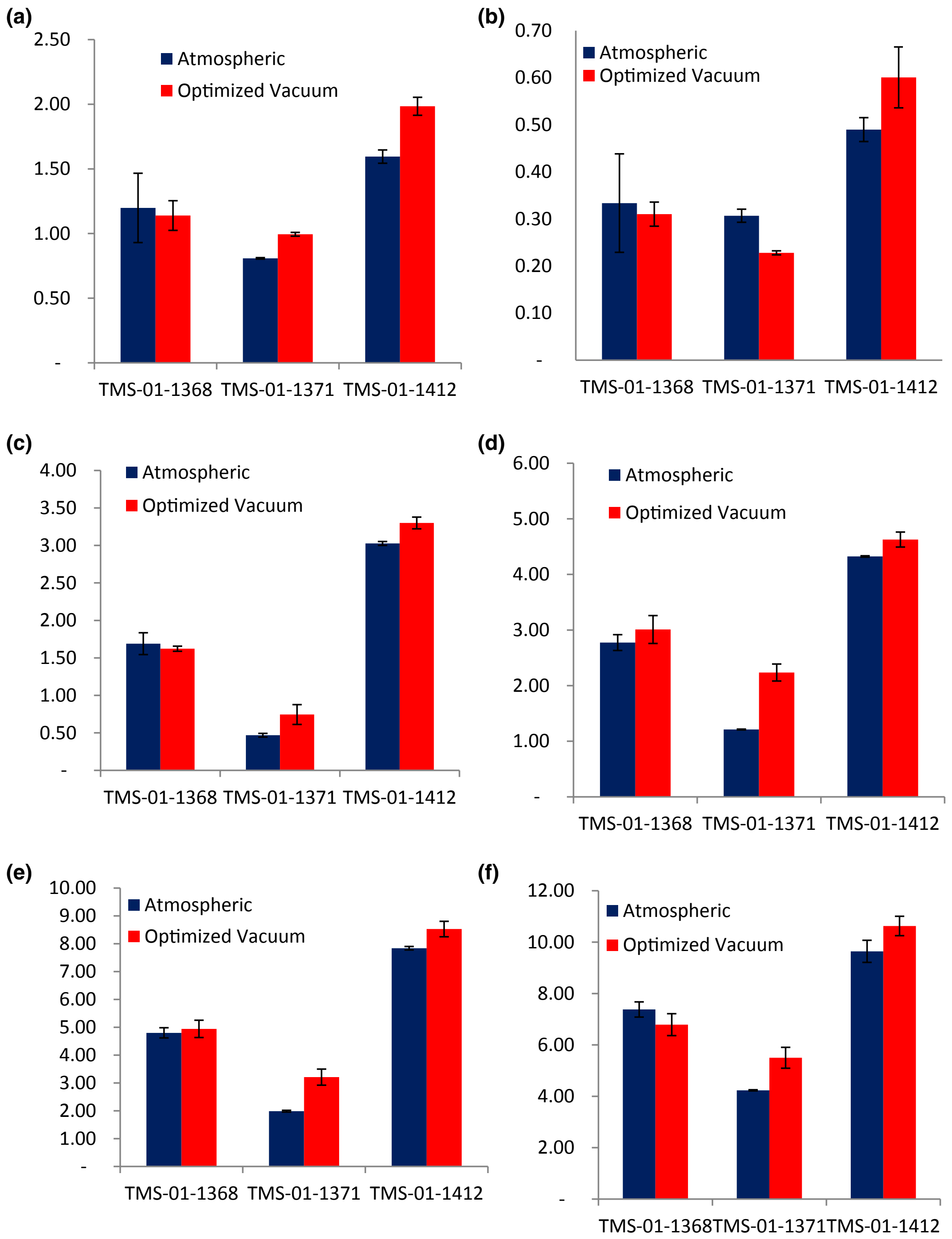

FIGURE 4 Carotenoid contents (a: 13-Cis; b: 15-Cis; c: 9-Cis; d: Trans; e: Total Beta carotene; f: Total carotenoids) of fried cassava chips of different varieties under atmospheric and optimized vacuum frying conditions

FIGURE 5 Digital images of fried yellow fleshed cassava chips under atmospheric (1) and optimized vacuum (2) frying conditions for TMS 01-1368 (a), TMS 01-1371 (b) and TMS 01-1412 (c), respectively

fryer. Reports on the deterioration of total carotenoids during heat processing have been documented in literature (Ahmed et al., 2002; Ayustaningwarno et al., 2020; Dueik et al., 2010).

4 | OPTIMIZED SOLUTION OF PROCESS VARIABLES

The numerical optimization procedure was used to find the best combination of frying temperature, vacuum pressure, and frying time by setting goals for the quality attributes of fried chips from each variety of yellow fleshed cassava. Yellowness and total carotenoids were maximized, while lightness, redness, texture (hardness), moisture, and oil content were minimized. Desirability with the highest value was selected for each variety. For TMS 01-1371, a frying temperature of 129°C, vacuum pressure of 9.91 cmHg, and frying time of 9.57 min were selected. For TMS 01-1368, a frying temperature of 122°C, vacuum pressure of 14.49 cmHg, and frying time of 8 min were selected, while for TMS 01-1412, a frying temperature of 122°C, vacuum pressure of 9.91 cmHg, and frying time of 9.95 min were selected (Table 7). Each variety was processed under these vacuum frying conditions and then compared with atmospheric frying using the concept of equivalent thermal driving force.

5 | ATMOSPHERIC VERSUS OPTIMIZED VACUUM FRIED CHIPS

Quality attributes and carotenoid contents of optimized vacuum fried chips from TMS 01-1368, TMS 01-1371, and TMS 01-1412 yellow fleshed cassava cultivars were compared with atmospheric fried samples. From this study, fried atmospheric cassava chips had higher oil content than vacuum fried ones, except for the TMS 01-1371 cultivar (Figure 1). This could be attributed to the difference in their intracellular matrixes. Figure 2 shows the micrographs of the inner sections of fried chips under vacuum (Figure 2a2,b2,c2) and atmospheric conditions (Figure 2a1,b1,c1). It is evident that vacuum fried chips from TMS 01-1368 and TMS 1412 had tiny pores unlike the atmospheric fried chips with larger sections of pores which could have encouraged the infiltration of oil. Furthermore, vacuum fried chips from TMS 01-1371 were observed to have bigger and more pores than atmospheric fried chips and this could have contributed to increased oil content. In this study, lower starch content was obtained in TMS 01-1371 cultivar which may not have fully gelatinized at low temperature under the vacuum condition, thereby resulting in more pores that allowed more moisture loss and oil replacement. This explains the reason for the high oil content observed in vacuum fried chips for this particular yellow fleshed cassava variety.

As shown in Figure 3a, Vacuum fried chips retained more moisture than atmospheric fried samples. This agrees with the findings of Oyedeji et al. (2017) who attributed the reduced rate of moisture loss in vacuum fried snacks to the lower boiling point under vacuum conditions which reduced rapid evaporation of moisture in comparison to atmospheric conditions.

The breaking force of the vacuum fried chips from the three yellow fleshed cassava cultivars did not vary from each other as shown in Figure 3b. Vacuum fried chips from TMS 01-1368 and TMS 01-1371 had a higher breaking force than atmospheric fried ones in contrast with fried chips from TMS 1412. Shrinkage percentage (Figure 3c) of vacuum fried chips from the three yellow fleshed cassava cultivars was higher than atmospheric fried ones. This means that vacuum fried chips shrank more than atmospheric fried ones which implies excess moisture loss during frying. Under atmospheric conditions, moisture within product heats up immediately after immersion in hot oil and this speeds up the rate of starch gelatinization which may have provided a barrier that reduced moisture loss (Kawas & Moreira, 2001). Vacuum condition retained the carotenoid content of fried chips from the three yellow fleshed cassava chips in comparison to atmospheric fried samples (Figure 4a-f). Similar reports have been found in literature (Ayustaningwarno et al., 2020; Oyedeji et al., 2017). The colors of optimized vacuum fried chips (Figure 4a2,b2,c2) were lighter than that of the atmospheric fried samples (Figure 4a1,b1,c1) irrespective of the varieties. Although, fried chips from TMS 01-1371 were observed to have a darker hue (Figure 4b1,b2). Garayo and Moreira (2002) found a similar result that sweet potato crisps fried under vacuum conditions were lighter than those fried under atmospheric conditions. The authors concluded that the unavailability of oxygen under vacuum conditions primarily contributed to that outcome (Figure 5).

6 | CONCLUSION

Results from this study showed that the physicochemical composition of experimental varieties of yellow fleshed cassava roots varied significantly ($p < .05$). Some quality parameters and carotenoid content of fried chips showed significant ($p < .05$) effect. Linear terms of frying temperature and interaction terms of frying temperature and vacuum pressure significantly ($p < .05$) influenced the quality characteristics of fried TMS 01-1368. The linear terms of frying temperature, vacuum pressure, and interaction terms of independent variables exhibited a significant ($p < .05$) effect on oil content and some carotenoid contents in TMS 01-137. However, for TMS 01-1412, linear terms of independent variables (frying temperature and frying time), interaction terms of frying temperature and frying time, frying temperature and vacuum pressure, and interaction of frying temperature, vacuum pressure, and frying time showed a significant ($p < .05$) effect on a good number of the quality characteristics. The optimized vacuum frying conditions obtained for TMS 01-1371, TMS 01-1368, and TMS 01-1412 were 129°C, 9.91 cmHg, and 9.57 min; 122°C, 14.49 cmHg, and 8 min; and 122°C, 9.91 cmHg, and 9.95 min for frying temperature, vacuum pressure, and frying time, respectively. Vacuum frying conditions retained the quality attributes and carotenoid content of fried chips from yellow fleshed cassava varieties more than atmospheric conditions, except for shrinkage.

CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Olajide P. Sobukola: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology. **Feyisola Ajayi:** Data curation; Software; Validation; Visualization; Writing-original draft. **Opeyemi Rachel Faloye:** Investigation; Methodology; Resources; Software; Validation; Writing-original draft. **Folake Olayinka Henshaw:** Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Supervision; Writing-review & editing. **Silfat Ajoke Sanni:** Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Supervision; Writing-review & editing. **Goke Bodunde:** Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Supervision; Writing-review & editing. **Mure Agbonlahor:** Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Resources; Supervision; Writing-review & editing.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

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