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Research Article

Effects of Combining Microwave with Infrared Energy on the Drying Kinetics and Technofunctional Properties of Orange-Fleshed Sweet Potato

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The aim of the study was to determine the effects of oven, microwave (MW), and infrared (IR) drying technology on the drying kinetics, physicochemical properties, and β-carotene retention of the dried orange-fleshed sweet potato flour (OFSP). Fresh OFSP slices were dried in an oven (40°C), MW (80 W), IR (250 W), MW-IR (80 W + 250 W), and freeze-drying (-45°C, 100 kPa) and milled into flour. Hot air at a constant temperature was applied to all thermal drying technologies (40°C, 4.5 m/s air velocity). The drying rate of the MW-IR drying method was the fastest (45 min), followed by MW (60 min), IR (120 min), and oven (180 min). The Page model was most suitable for the oven-drying method, the Lewis model for IR drying, and Henderson and Pabis for IR and Logarithmic for the MW-IR method. The pasting and thermal properties of the flours were not significantly ($p > 0.05$) affected by the different drying methods. However, IR- and MW-IR-dried flours showed a higher final viscosity when compared to other drying methods. MW-IR drying methods, IR, and MW showed a higher water solubility index, while the oven and freeze-drying methods showed a lower solubility index. MW-IR drying methods showed a higher retention of β-carotene (85.06%). MW also showed a higher retention of β-carotene (80.46%), followed by IR (66.04%), while oven and freeze-drying methods showed a lower retention of β-carotene. High β-carotene retention in the produced flour is due to the faster drying method, and these flours can be used in food-to-food fortification to address vitamin A deficiency.

1. Introduction

Micronutrient deficiency such as vitamin A is the most prevalent and known to be the leading cause of low birth weight, impaired vision, and immune system dysfunction [1]. Furthermore, noncommunicable diseases such as obesity and diabetes are rising throughout the world. The growing demand for healthy diets such as low-fat, low-calorie, high-fibre, and sugar-free products is also being noticed. The use of vegetable root crops such as orange-fleshed sweet potato (OFSP) has been adopted in most developing countries (Africa and Asia) due to its nutritional benefits such as the high content of dietary fibre, vitamins, minerals, β-carotene (provitamin A), and other antioxidant phytochemicals that can address the above-mentioned challenges [2]. As a result, OFSP has been identified as one of the staple root crops, which can be used to address malnutrition and food insecurity in developing countries. OFSP has the ability to survive adverse growing climatic conditions such as high weather temperature, and it also has a short period of growth of 4 to 5 months and low agronomical input [3], which makes it easy to be cultivated and used in developing countries.

The main challenge with OFSP is its perishability in nature, which is caused by the high moisture content and water activity [4]. Therefore, there is a need to come up with food processing methods that can convert the fresh OFSP into a more shelf-stable product and diversify its application in different food systems. Food processing technologies such as drying can be used to transform fresh OFSP into shelf-stable products such as flour. The dried OFSP flour can be processed into food ingredients that can be used as a thickener in soups, bakery products, and baby foods and as a

substitute for cereal flour [5]. Furthermore, sweet potato flour can be used to produce products required by health-conscious consumers such as low-calorie, zero-cholesterol, and high-fibre products [6].

Drying has been used to lower the moisture content of the product before being further processed into other types of products such as flour or flakes. The famous drying techniques are thermal drying methods, which in most cases are used at high temperatures. High temperatures have a negative impact on heat-sensitive nutrients such as vitamin C and vitamin A precursor, β-carotene. For example, oven drying can decrease the β-carotene and vitamin C content of OFSP [7] in addition to having a destructive impact on functional properties such as water holding capacity, swelling capacity, and solubility, depending on the drying temperature used [8]. Ruttarattanamongkol et al.'s [9] study reported a β-carotene retention of about 35.05% when using a drum roll drying method at 110°C and 7 rpm; furthermore, their study also showed that at a lower temperature (80°C) and lower rpm (3), the β-carotene retention was even lower (19.76%). Indirect solar drying was used by Omodamiro et al. [10] to dry OFSP, and the β-carotene retention was higher (53.50%) than that of OFSP dried by the oven (26.11%). A fluidized bed drying study by Haile et al. [11] reported a high retention of β-carotene compared to sun drying and solar drying, and they also reported an improvement in the technofunctional properties of OFSP flour dried by the fluidized bed drying. The functional properties of the flour are important, and they need to be preserved, as these determine the industrial application [6]. Therefore, it is necessary to explore lower temperatures and other novel drying technologies to preserve heat-sensitive nutrients and functional properties during the thermal drying of OFSP.

Freeze-drying methods can preserve most of the heat-sensitive nutrients, and it has been reported to improve the dried products' functional properties [12]. Oven and freeze-drying methods are disadvantageous due to their long drying periods which may imply a higher energy cost. Freeze drying takes approximately about 3-5 days to completely dry the sample, while oven drying can take 2-5 hours, depending on the sample parameters such as sample type, size, and initial moisture content [13]. Therefore, it is worth considering alternative drying methods, which are quicker and more energy-efficient when it comes to food dehydration. Microwave drying utilizes less electricity when compared to conventional oven drying technologies [14]. This is because of their different drying mechanisms, as MW focuses its energy directly on water molecules as compared to the oven which needs to heat up the drying chamber to reach saturation temperature before it can initiate drying [15].

The IR and MW can potentially improve the physicochemical properties of OFSP flour as well as show higher retention of β-carotene due to a faster drying rate [16]. Infrared and MW do not seem to cause any case of hardening. The latter has resulted in dehydrated products with inferior functional properties in terms of swelling, water absorption, and pasting properties [17]. The microwave was also reported to have a faster drying rate and result in products with increased rehydrating capacity and higher β-carotene (>80%) retention and did not cause significant colour loss in OFSP flour [18]. The mode of heat generation and transfer during IR and MW dehydration can result in faster drying and efficient use of energy [19, 20].

Haruna et al. [7] dried OFSP under different temperatures (40, 45, 50, 55, and 60°C) using oven drying and showed a lower β-carotene retention at 60°C and higher retention at 40°C. Sebben et al. [21] compared the drying rate of MW with hot air; however, they did not report on the effects of MW drying on the physicochemical properties of the OFSP. Onwude et al.'s [22] study reported on the effects of combining IR with hot air drying on sweet potatoes. Their study focuses on drying kinetics and not on the technofunctional properties of the dried sweet potato. To the best of our knowledge, the combination of MW with IR to dry OFSP has never been reported. Therefore, this research determines the effects of infrared and microwave alone and in combination compared to oven and freeze drying on the drying kinetics, technofunctional properties, and β-carotene of orange-fleshed sweet potato flour.

2. Materials and Methods

2.1. Raw Materials. Fresh OFSPs (Bellevue cultivar) were supplied by Langplaas Boerdery (Brits, North West Province, South Africa). The chemicals used for UFLC analysis were all HPLC grade (≥99.9% inhibitor-free), and these were tetrahydrofuran (THF), acetonitrile, toluene, methanol, and β-carotene standard (EC number 230-636-6) which were all purchased from Sigma-Aldrich (Pty) Ltd. (Cnr Kelly and Ackerman Streets, Unit, 16/17 Lake Site, Industrial Park, Jet Park, 1469). The total dietary fibre kid (K-TDF-200 Assay) was purchased from Megazyme (Ltd.) (Bray Business Park, Bray, Ireland).

2.2. Methods: Preparing and Drying OFSP. Fresh OFSPs were washed, peeled, and sliced into 5 mm thickness. The slice thickness was chosen based on the literature. Kamal et al. [23] studied the effect of slice thickness of sweet potatoes with a thickness of 3, 5, and 7 mm on the drying rate constant using an oven. Abano [24] also studied the effect of different slice thicknesses (3, 6, and 9 mm) of sweet potatoes on the drying kinetics using microwave energy. Furthermore, Doymaz [19] studied different slice thicknesses (3, 5, and 8 mm) of sweet potato on drying kinetic with infrared. Thus, for our study, a 5 mm thickness was used.

The sliced OFSPs were pretreated by following the method by Haruna et al. [7]. About 2 kg of the sweet potato slices were dipped in a 5 l solution of 2.5% sodium metabisulphite (w/v in distilled water) for 30 minutes as a reducing agent to prevent colour change. After 30 minutes, the slices were left to drain off the excess solution before they could be dried. According to the CODEX standard, the permitted level for using sodium metabisulphite as a preservative in dried vegetables is 500 mg/kg [25]. However, metabisulphite is used as a reducing agent to prevent colour loss by the dipping method. Higher levels of sodium metabisulphite have been used to prevent colour loss. About 3% (30 000 ppm) (w/v) of sodium metabisulphite was used by Nguyen et al.

[26] to prevent colour loss in aromatic coconut. Latapi and Barret [27] preserved the colour loss and nutritional and sensory quality of sun-dried tomatoes pretreated with 8% (80,000 ppm) (*w*/*v*) sodium metabisulphite. The pretreated slices were divided into 250 g portions for each drying experiment.

The samples for freeze-drying were frozen at -20°C overnight before freeze-drying at -45°C at a pressure of 100 kPa for a period of 5 days. The sample was frozen at -20°C as a pretreatment for freeze-drying, known as prefrozen. Since freeze-drying is a change in state from the solid phase to the gaseous phase, the material to be freeze-dried must first be adequately prefrozen. It is very important in freeze-drying to prefreeze the product to below the eutectic temperature before beginning the freeze-drying process [28]. The oven samples were dried in a convective oven at 40°C with an air velocity of 4.5 m/s for 4 hrs. In order to determine optimized drying conditions for MW and IR, a series of trials were conducted on different drying power levels for both MW and IR. Power inputs at 120, 100, and 80 W were tested for MW, and 350, 300, and 250 W were tested for IR. The higher power levels for MW and IR were found to charr the sample and had unevenly dried samples even though they were fast. The lower power levels of 80 W for MW and 250 W for IR were found to have an even sample drying and not charring the sample, and therefore were selected for drying the OFSP slices. Hot air at 40°C and an air velocity of 4.5 m/s were applied during both MW and IR drying.

2.3. Analysis

2.3.1. Drying Kinetics. During the thermal drying of the OFSP, samples were taken out at 15 min interval to determine the moisture content and to calculate the drying rate and moisture ratio. The formula below shows the calculation of the moisture ratio [29].

$$\mathrm{MR} = \frac{M_t - M_e}{M_o - M_e}, \tag{1}$$

where MR is the moisture ratio (dimensionless), M_t (g/100 g dry solids) is the moisture content at time t, M_o (g/100 dry solids) is the initial moisture content, and M_e (g/100 g^{-1} dry solids) is the equilibrium moisture content. The drying rate was calculated using the formula below.

$$\mathrm{DR} = \frac{M_o}{M_t x t}, \tag{2}$$

where DR is the drying rate (g water/g dry mass × time), M_o is the initial moisture weight (g), M_t is the weight (g) of the dry solids, and t is the time elapsed (minutes).

The data collected from calculating the moisture ratio was used to select fitting models, and the models were selected on the basis of specific criteria using root mean square error (RMSE), coefficient of determination (R^2), and chi-square (X^2). The selection was based on the highest R^2 and lowest RMSE and X^2. The formulas below were used to calculate R^2, RMSE, and X^2.

$$\mathrm{RMSE} = \left[\frac{1}{N}\sum_{i=1}^{N}\left[\left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2\right]\right]^{1/2},$$
$$X^2 = \frac{\sum_{i=1}^{n}\left[\left(\mathrm{MR}_{\mathrm{pre},i} - \mathrm{MR}_{\mathrm{exp},i}\right)^2\right]}{N-n}, \tag{3}$$

where $\mathrm{MR}_{\mathrm{exp},i}$ is the i^{th} moisture ratio observed from the experimental data, $\mathrm{MR}_{\mathrm{pre},i}$ is the i^{th} predicted moisture ratio, n is the number of drying constants from the model formula, and N is the number of observations.

$$R^2 = 1 - \frac{\mathrm{SSE}}{\mathrm{SST}},$$
$$\mathrm{SSE} = \sum_i \left(\mathrm{MR}_{\mathrm{exp},i-}\mathrm{MR}_{\mathrm{pre\,ava}}\right)^2, \tag{4}$$
$$\mathrm{SST} = \sum_i \left(N - \mathrm{MR}_{\mathrm{pre,ave}}\right)^2,$$

where SSR is the sum of squared regression and SST is the sum of the squared total. $\mathrm{MR}_{\mathrm{exp},i}$ is the i^{th} experimental moisture ratio and $\mathrm{MR}_{\mathrm{pre,ave}}$ is the mean value of the predicted moisture ratio. The drying models used for the studies are listed below.

$$\begin{aligned}
\text{Newton model} \quad & \mathrm{MR} = e^{-kt},\\
\text{Page model} \quad & \mathrm{MR} = e^{-kt^n},\\
\text{Henderson and Pabis model} \quad & \mathrm{MR} = ae^{-kt},\\
\text{Logarithmic model} \quad & \mathrm{MR} = ae^{-kt} + b,
\end{aligned} \tag{5}$$

where a, n, and b are drying constant; t is the drying time (min); and k is the coefficient of diffusion (m^2/s) [29].

It is well known that the drying of agricultural product is affected by different parameters such as thickness, air velocity, temperature, and the agoraphobic nature of the material. However, given that products such as sweet potato roots grow in different shapes and sizes, trying to have a uniform size for effective drying may result in waste as you might have to remove and cut some parts out. Therefore, during this study, the shape and size of the sweet potato were neglected, and we used different sizes and shapes of the sweet potato; however, the thickness was constant.

2.3.2. Estimation of Effective Diffusivity. The effective diffusivity analysis was done by following Arulkumar et al.'s [30] method. Their method follows the proposed Fick's second law equation for the moisture diffusivity of the cube sample, as indicated below.

$$\mathrm{MR} = \left[\frac{8}{\pi^2}\sum_{N=1}^{\infty}\frac{1}{(2n-1)2}\ \exp\left(-\frac{(2n-1)2\pi Dt}{L^2}\right)\right]3, \quad (6)$$

where MR represents the experimental moisture ratio, D represents the effective moisture diffusivity in m^2/s, t is for drying time in min, L represents the slice thickness in m, and n represents the list of positive integers.

For a long drying period, the first term of Equation (6) is considered to find out the effective moisture diffusivity (D), and the rest is negligible. Hence, the slope (k_0) was obtained from the linear line in plotting ln (MR) against time t, as described in Equation (7). The effective moisture diffusivity is calculated using the following equation:

$$\mathrm{MR} = \left(\frac{8}{\pi^2}\right)^3 \exp\left(\frac{\pi^2 Dt}{L^2}\right)^3, \quad (7)$$

$$k_0 = -\frac{3\pi^2 \mathrm{Deff}}{L^2}. \quad (8)$$

2.3.3. Estimation of Activation Energy. The activation energy (E_a) was determined by using the Arrhenius type of equation as shown in Equation (9) below [24]. From the equation, the slope (K_1) of the straight line is found by plotting ln (D) against $1/T$. Then, the activation energy is determined by using the following equation:

$$D = D_0\ \exp\left(-\frac{E_a}{\mathrm{RT}}\right), \quad (9)$$

$$K_1 = \frac{E_a}{R}, \quad (10)$$

where D denotes the effective moisture diffusivity in m^2/s, D_0 denotes the preexponential factor in m^2/s, E_a denotes the activation energy in kJ/mol, R denotes the universal gas constant (8.314 J/mol. K), and T denotes the drying temperature, respectively.

2.3.4. Proximate Analysis of Fresh and Dried OFSP Flour. Proximate compositions were done for the dried sample at the end of the drying process, following the AOAC methods. The moisture content was done following the AOAC (2000) official method of analysis (925.10) with an oven temperature set at 105°C and samples dried for 3 hours. The protein content was determined according to AOAC's (2000) official method of analysis 46.3 using Gerhardt Dumatherm (Konigs Winners, Germany). A conversion factor of $N \times 6.25$ was used to determine the % protein content. The AOAC (2000) method of analysis (923.3) was used to determine ash content. The fat analysis was done following AOAC's (2000) official method of analysis (920.31) using the Soxhlet fat extraction method.

2.3.5. Determination of Soluble and Insoluble Dietary Fibre. The total dietary fibre was done according to the megazyme method using the total dietary fibre megazyme kit (K-TDFE). Orange-fleshed sweet potato flour (about 1 g) was suspended in MES-TRIS buffer and thermostable $\acute{\alpha}$-amylase at 100°C for 30 min. The temperature was reduced to 60°C, and protease was added. The pH was changed to 4.6, and then amyloglucosidase was added. The enzymes were filtered, and the sample was washed with 95% ethanol and acetone. Four volumes of absolute ethanol were added to the filtrate, which was then filtered and washed with 78% ethanol, 95% ethanol, and acetone. Samples were measured for protein and ash [31].

2.3.6. Determination of β-Carotene Content. Extraction of β-carotene was done using tetrahydrofuran, where 2 g of flour and 10 g of fresh orange-fleshed sweet potato were used. The extraction was repeated 3 times for 30 min. The THF was then evaporated, and 10 ml of toluene was added to dissolve the β-carotene. Samples were filtered into amber vials using a 0.45 μm PTFE membrane. The determination of β-carotene was done using ultrafast liquid chromatography (UFLC) (Shimadzu, Tokyo, Japan). Carotenoids were recorded between 200 and 600 nm with the detection of β-carotene at 450 nm. The mobile phase used was 58% acetonitrile, 35% methanol, and 7% THF, with a flow rate of 1 ml/min for 45 min and an injection of 20 μl [10].

2.3.7. Determination of Physicochemical Properties

(1) Water Holding Capacity (WAC), Swelling Capacity (SC), and Soluble Index (SI). A mass of 1 g of OFSP was weighed into a conical graduated centrifuge tube. Distilled water (10 ml) was added to the flour and mixed thoroughly using a whirl mixer for about 30 sec. The mixed sample was allowed to stand for about 30 min at room temperature and then centrifuged at $3400 \times g$ for 30 min. The supernatant was discarded, and the weight of the absorbed water was calculated using the formula below. The value is expressed as a gram of water absorbed per gram of sample [32]. Swelling capacity was determined by weighing 1 g of the flour into a 10 ml centrifuge tube and mixing it with 10 ml of distilled water. The samples were placed in a hot water bath at 80°C for 30 min. The tubes were removed and allowed to cool to room temperature for 10 min. The samples were centrifuged at $3400 \times g$ for 30 min. The supernatant was discarded in a predried evaporation dish and dried at 105°C for 3 hrs in an oven to determine the solubility index. The sediment was used to determine the swelling capacity, as shown by the formula below [33].

$$\mathrm{WAC} = \frac{\text{weight of absorbed water}}{\text{weight of dry sample}} \times 100,$$

$$\mathrm{SC} = \frac{\text{mass of sediment}}{\text{mass of dry sample}} \times (1 - \text{solubility index}), \quad (11)$$

$$\%\mathrm{SI} = \frac{\text{mass of dissolved solids}}{\text{mass of dry sample}} \times 100.$$

(2) Pasting Properties. The pasting properties of the flours were evaluated using the starch cell of a modular compact rheometer (Anton Paar Co. Ltd., Austria). The pasting viscosity of the flours was recorded using a flour suspension (10%, w/w in distilled water; 15 g total weight). A

programmed heating and cooling cycle was used, where the samples were held at 50°C for 1 min, heated to 92°C at 6°C/min, and held at 92°C for 2.7 min, before cooling from 92°C to 50°C at 6°C/min and holding at 50°C for 2 min. Parameters recorded were pasting temperature, peak viscosity, trough viscosity, final viscosity, breakdown viscosity, and setback viscosity.

(3) Determining Thermal Properties of the Flour. The thermal properties of sweet potato flours were evaluated by DSC (DSC1 STARe System, Mettler-Toledo Ltd., Leicester, England). Indium was used for standard and calibration ($T_p = 156.6$, $\Delta H = 28.45$ J/g). The flour sample (10 mg dry basis) was prepared by mixing with 30 μl of distilled water in a 100 μl size aluminium pan. The latter was hermetically sealed and equilibrated for 4 hrs before analysis. The samples were heated from 25°C to 120°C at a scanning rate of 10°C/min with an empty pan as a reference. Nitrogen was used as a purging gas at a 50 ml/min flow rate, and a pressure of 4000 KPa was maintained during the analysis. The onset temperature (T_o), peak temperature (T_p), end-set temperature (T_c), and enthalpy (ΔH) for observed endotherms were then determined.

(4) Colour. The colour of the fresh and dried OFSP flour was instrumentally measured using a Chroma meter CR-400/410 (Konica Minolta Sensing, Inc., Osaka, Japan) model. The results are expressed in the CIE $L*a*b*$. Colour change (ΔE) was also calculated as shown in the formula below [9].

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

where L, b, and a are the chromatic colours of the fresh sample and $L*$, $b*$, and $a*$ are the chromatic colours of the dried samples.

Chroma (C_{ab}) and hue ($h^0{}_{ab}$) angle parameters were calculated per the formula below [34].

$$C_{ab} = \sqrt{a^{*2} + b^{*2}},$$
$$h^0_{ab} = \tan^{-1}\left(\frac{b^*}{a^*}\right). \quad (13)$$

2.4. Microstructure of Dried OFSP Flour

2.4.1. Bright Field Light Microscopy. The dried OFSP flour samples were visualized with a VS3 Series Biological Trinocular Light Microscope (Micromet Scientific, Delhi, India) equipped with a polarising filter lens. The flour samples (10 mg) were suspended in 30% (v/v) glycerol in distilled water. Ungelatinized starch and starch microstructure were observed under the polarising filter and staining with iodine, respectively.

2.4.2. Scanning Electron Microscopy (SEM). Dried OFSP flour was mounted on aluminium stubs with the aid of double-sided carbon tape, followed by a coating with carbon of about 20 nm in thickness. The coated flour was scanned using the Zeiss Crossbeam 540 FE 6 Scanning Electron Microscope (Carl Zeiss Microscopy, 6mbH, Germany) at an accelerating voltage of 5.0 kV.

2.5. Statistical Analysis. The experiments were repeated three times. The least significant differences among the mean values of nutritional, drying kinetics, and physicochemical properties were examined using multivariate analysis (MANOVA) and Tukey's multiple comparison test ($p < 0.05$) with drying technologies as an independent variable.

3. Results and Discussion

3.1. Drying Kinetics of Orange-Fleshed Sweet Potato Chips by IR, MW, and Oven Drying Method. Figures 1, 2, and 3 show the moisture content reduction over time as affected by the different drying methods. Oven drying showed the highest time (180 min) to reach a moisture content of less than 13%, followed by IR (120 min), MW (60 min), and a combination of MW and IR drying methods showing the shortest moisture content over time (45 min). The results obtained from this research for oven drying are comparable to the findings reported by [17], where they compared drying methods such as IR, fluidized bed drying, tray drying, and oven drying under different drying temperatures ranging from 45°C to 65°C. They have reported that oven drying at 45°C was the slowest drying method. In our research, we used 40°C to limit case hardening, as Mahiuddin et al. [34] explained that case hardening phenomena can happen when higher temperatures (>50°C) are applied during drying. Mahiuddin et al. [34] further explained that food material undergoes shrinkage rather than case hardening under lower temperatures (<50°C). This is because when low temperatures are used, the plant cells experience low thermal stress due to the low or absence of cell raptures [34].

The MW and IR used in this study had the fastest drying rates as compared to convective oven drying (Figure 2). During the drying experiment, it is worth noting that hot air at 40°C at a constant velocity of 3.5 m/s was used to assist in removing moisture from the food surface and to maintain a constant drying temperature. The study done by Onwude et al. [22] and Doymaz [19] also showed that IR drying of sweet potato at 1100.4 W/m^2 and 250 W, respectively, was shorter than oven drying. The different drying times are based on the drying mechanism, IR utilizes electromagnetic radiation which causes the vibration of the water molecules, and the kinetic energy is converted to thermal energy which results in moisture removal.

The microwave drying time of OFSP was shorter than that of the oven and IR (Figure 1). Other researchers found a similar drying time of 70 minutes for sweet potato at a power level of 70 W, a dry air temperature of 40°C, and an air velocity of 1 m/s [35]. Askari et al. [36] reported a drying time of 110 minutes when drying apple slices at 200 W using a MW drying method. A combination of the two electromagnetic radiation drying technologies (MW and IR) showed the lowest drying time for OFSP slices. Combining

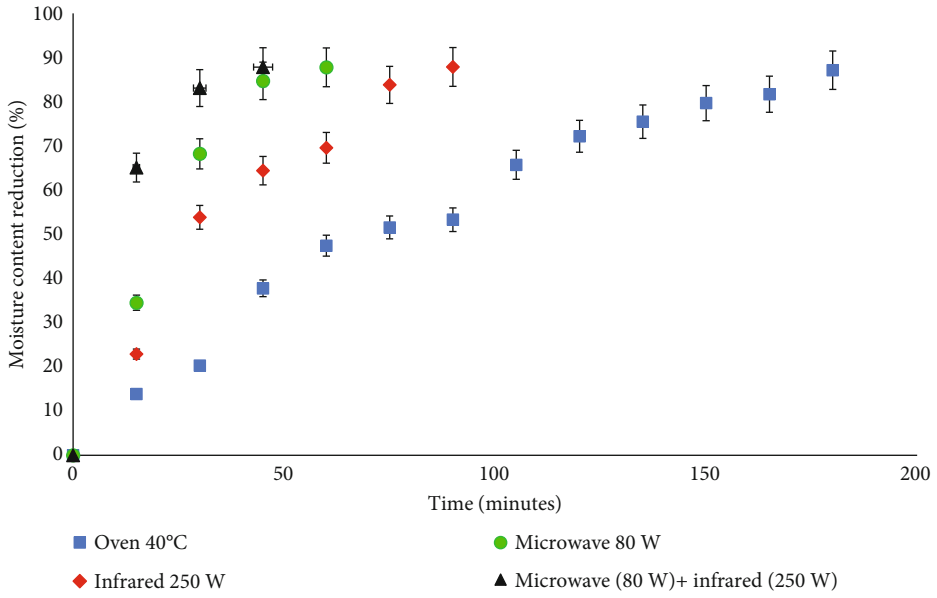

Figure 1: Effect of drying methods on the moisture content of orange-fleshed sweet potato. Error bars are representative of the standard deviation between the mean values ($n = 3$).

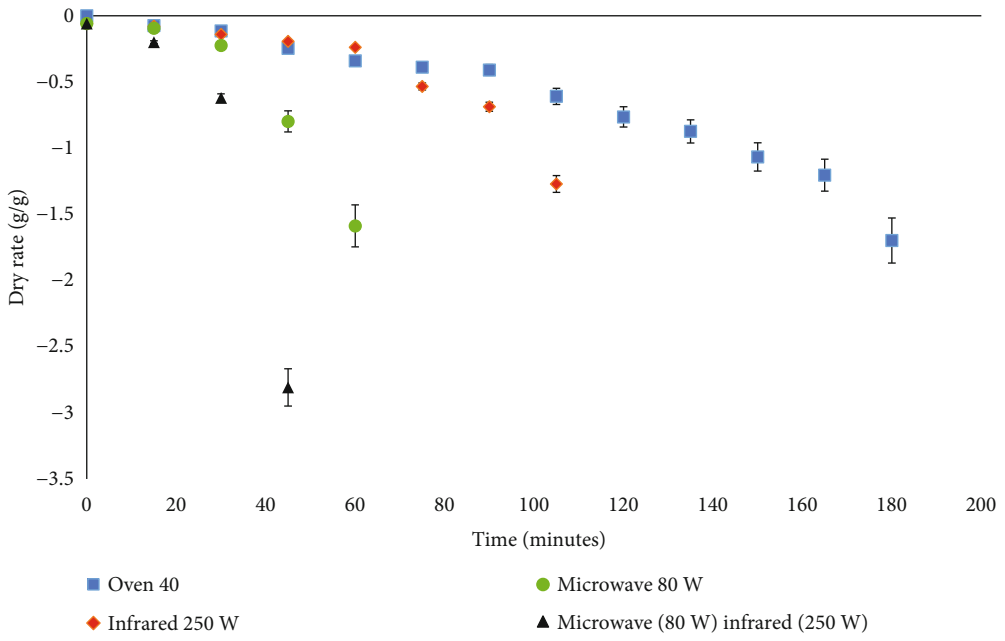

Figure 2: Effect of different drying methods on the drying rate over time of orange-fleshed sweet potato slices. The error bars are representative of the standard deviation between the mean values ($n = 3$).

hot air, MW, and IR reduced the drying time of green pepper by up to 76%, as compared to their convective drying methods [37]. This suggests that the volumetric heating mechanism of MW and surface heating by IR increased the moisture transfer rate [38]. Furthermore, Datta and Ni [38] reported that a combination of MW drying with an IR heating mechanism during drying can remove the excess moisture that can accumulate on the surface of the food material, which can result in a higher coefficient of diffusion and faster moisture transfer and drying rate.

The different drying technologies had an effect on the effective moisture diffusivity and activation energy of OFSP during drying (Table 1). The data on effective moisture diffusivity correlates with that of the coefficient of diffusion in Table 2, where oven drying had lower effective diffusivity and a low coefficient of diffusion; this shows the low rate of moisture removal by the oven drying method. Table 1 further shows that the activation energy of the oven drying method was higher as compared to that of the MW, IR, and MW-IR drying methods. The lower effective diffusivity

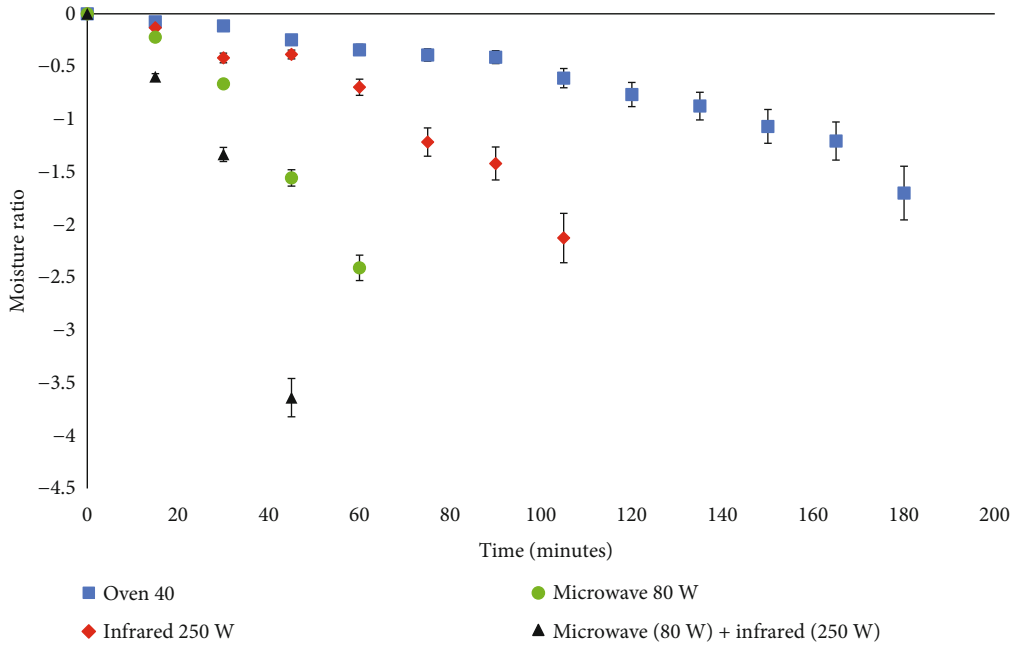

Figure 3: Effect of different drying methods on the moisture ratio over time of the dried orange-fleshed sweet potato slices. The error bars are representative of the standard deviation between the mean values ($n = 3$).

Table 1: Effects of drying methods on effective diffusivity, activation energy, and slope of OFSP slices during drying.

Drying methods	Activation energy (kJ/mol) × 10^3	Effective diffusivity $(m^2/s) \times 10^{-8}$
Oven	0.304	0.055
Infrared	0.251	3.383
Microwave	0.214	21.54
Microwave-infrared	0.188	39.36

values mean that higher activation energy is required before the initiation of drying by the drying method [30]. The study by Ashutosh et al. [39] reported on the effective diffusivity of potato slices dried by MW. The study also revealed an increase in effective diffusivity on MW-treated potato slices. Similar results are reported by Abano [24], who observed an increase in effective diffusivity on OFSP slices dried by MW compared to blanched OFSP slices. Their study shows an increase in effective diffusivity with an increase in MW power level. Abano [24] stated that the increase is a result of MW energy being able to increase the activity of the water molecules. The values obtained from this study lie within the general range of 10^{-12}-10^{-8} m^2/s for drying food materials [24]. The infrared energy reported the second-lowest effective diffusivity after oven drying; however, the activation energy from the IR drying was not significantly different from that of MW drying alone. The study by Onwude et al. [40] on drying sweet potato slices with IR reported that the low effective diffusivity by IR drying can be attributed to shrinkage of the slices during drying; the study also reported low effective diffusivity on IR drying which was increasing with an increase in IR intensity. The combination of MW with IR drying technology shows the highest effective diffusivity (Table 1) and the lowest activation energy. This can be attributed to the synergistic effect of MW and IR combined energy which minimises the shrinkage of the sample and results in instant vaporisation of the water molecule. The data in Table 1 for MW-IR is also in conjunction with the coefficient of diffusion for MW-IR in Table 2.

The drying curves were fitted to various models from the literature. The Page model has the highest R^2 value and lowest RMSE and chi-square values for MW and MW-IR combined drying methods, while the Henderson and Pabis model shows a high R^2 for the IR drying method (Table 2). Table 2 also shows different values of the coefficient of diffusion (k m^2/s) for all drying methods. The combination of MW and IR drying methods shows a higher coefficient of diffusion for all the models except for the Page model (Table 2). Semitheoretical models are used to predict the suitable drying time and moisture content for different types of food under the selected drying parameters (temperature, air velocity, slice thickness, and the type of food). Based on the results (Table 2), most of the models fitted the data from different drying methods.

Marzuki et al. [41] modelled the drying kinetics of purple-fleshed sweet potato, which was dried by hot air (70°C); the tested models for their study included Lewis, Page, Peleg, Logarithmic, and Henderson and Pabis. All the tested drying models reported higher coefficients of determination, ranging from 0.970 to 0.998. Compared to

Table 2: Effects of drying methods on the models describing the drying kinetic of OFSP.

Drying method	Model	Formula	R^2	RMSE	X^2	K (k m^2/s)	a	n	c
Oven	Page	$MR = e^{-kt^n}$	0.9879	0.0338	0.0014	0.0047		1.2372	
	Lewis	$MR = e^{-kt}$	0.4221	0.3211	0.1219	0.0045			
	Henderson and Pabis	$MR = ae^{-kt}$	0.9779	0.04561	0.00246	0.0049	1.2478		
	Logarithmic	$MR = ae^{-kt} + b$	0.9779	0.04557	0.00245	0.0051	1.0458	0.002	
IR	Page	$MR = e^{-kt^n}$	0.9873	0.00196	0.002247	0.2470		0.1228	
	Lewis	$MR = e^{-kt}$	0.9873	0.00198	0.002241	0.0496			
	Henderson and Pabis	$MR = ae^{-kt}$	0.9885	0.00177	0.00203	0.05045	1.03408		
	Logarithmic	$MR = ae^{-kt} + b$	0.9884	0.00178	0.0203	0.0504	1.0341		0.0012
MW	Page	$MR = e^{-kt}$	0.9080	0.4273	0.0273	0.0481		1.3578	
	Lewis	$MR = e^{-kt}$	0.9932	0.00476	0.0271				
	Henderson and Pabis	$MR = ae^{-kt}$	0.9938	0.06843	0.02720	0.0469	1.0407	0.1256	
	Logarithmic	$MR = ae^{-kt} + b$	0.9939	0.06769	0.02726	0.04882	1.0495		0.0028
MW-IR	Page	$MR = e^{-kt^n}$	0.9991	0.00537	0.000153	0.02974			
	Lewis	$MR = e^{-kt}$	0.9991	0.00534	0.000150	0.09410			
	Henderson and Pabis	$MR = ae^{-kt}$	0.9991	0.00534	0.000152	0.09412	1.0010		
	Logarithmic	$MR = ae^{-kt} + b$	0.9981	0.00548	0.000157	0.09408	1.002	0.0032	

R^2: coefficient of determination; RMSE: root means square error; X^2: chi-square; k m^2/s: coefficient of diffusion; a, n, c: drying constant; MR: moisture ratio; t: time (minute); IR: infrared; MW: microwave.

this study, the Lewis model reported a lower coefficient of determination for oven drying. However, this can be due to the lower temperature used (40°C), which resulted in lower moisture diffusion and drying rate. Microwave drying for sweet potato slices at 180 W was also studied by Junqueira et al. [42]. In their study, they have reported two terms as a fitting model for the drying parameter. Other models such as the Logarithmic, Page, and Newton models were studied, which reported higher coefficient of determination. From these studies, it has been observed that a Logarithmic model was fit for MW drying at 80 W. However, other models such as Midilli and Kucuk, Wang and Singh, Parabolic, and Weibull distribution have been reported to be fitting for MW drying at 350 and 180 W [42]. For the combined MW-IR method, the three models (Page, Lewis, and Henderson and Pabis) have shown a higher coefficient of determination (Table 2). The combined drying methods also show a higher coefficient of diffusion due to the effect of the rapid heating of MW and IR radiations, which might have caused rapid cell rapture and instant release and evaporation of moisture [19, 20, 42, 43].

3.2. Physicochemical Properties of Orange-Fleshed Sweet Potato Flour. The drying methods significantly ($p < 0.05$) affected the pasting properties of orange-fleshed sweet potato flour (Figure 4). The IR-dried flour showed a higher peak viscosity and final viscosity as compared to other drying methods (Figure 4). However, there was no significant difference ($p > 0.05$) in the peak viscosity and final viscosity between IR- and MW-IR-dried flour (Figure 4). The MW-, oven-, and freeze-dried flours did not show any significant difference ($p > 0.05$) in the breakdown viscosity. The viscosity properties can be influenced by the highly soluble dietary fibre of the flour (Table 3) and, most importantly, the starch content. Soluble dietary fibre and starch content possess viscous properties. Other physicochemical properties such as swelling capacity and water absorption capacity can influence the pasting properties of the flour. Water absorption and swelling capacity indicate the ability of the biomolecules in the flour, specifically starch granules, to absorb water. As indicated in Table 2, the freeze-drying method has a low water absorption capacity which correlates with the low viscosity in Figure 4.

Compared to Moreno et al. [14], who have studied the pasting properties of orange-fleshed sweet potato flour dried at 80°C and 50°C, the values reported in this study are not the same as their studies. Their study has shown that dried OFSP flour has a higher peak viscosity of about 600 mPa.s and a final viscosity of about 1200 mPa.s. The variation in their viscosity is because of the flour's chemical composition, particle size, and drying temperature. The flour dried at a higher temperature (80°C) and showed a higher viscosity when compared to the one dried at 50°C. The authors argued that the higher drying temperatures (80°C) broke the granular structure of the starch which improved the water permeability of the starch granule and thus decreased the thermal stability of the starch supramolecular structure [14]. In our study, the OFSP was dried under low temperatures in an oven, MW, and freeze-drying (<50°C); this can be the reason why the mentioned drying method shows

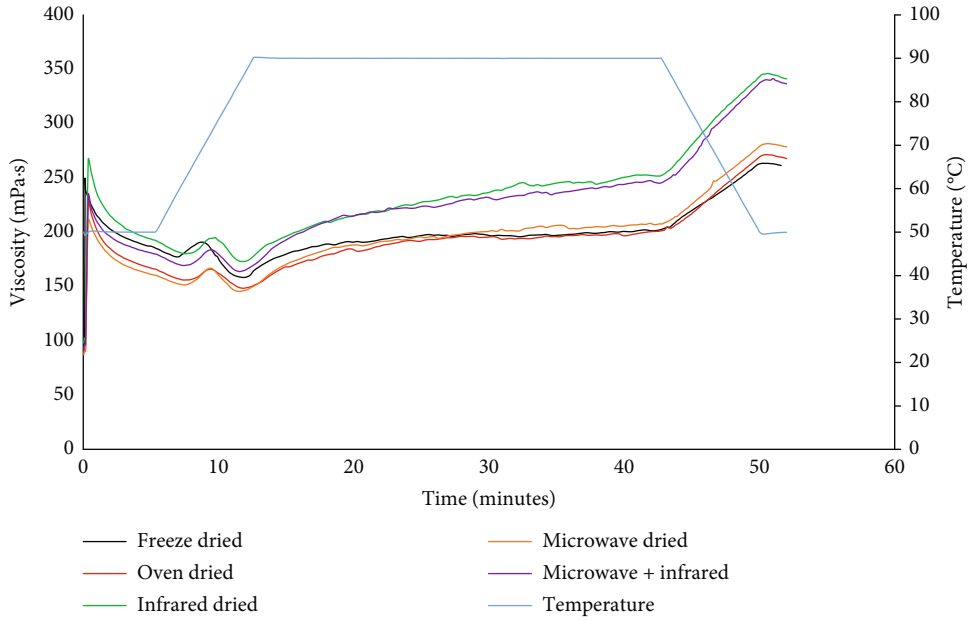

Figure 4: Effect of drying methods on the pasting properties of dried orange-fleshed sweet potato flour.

low pasting viscosity when compared to the IR drying method. The drying temperature of IR could have been higher than 50°C, which then caused some damage to the starch molecule and therefore resulted in a higher pasting viscosity when compared to the other drying methods. Furthermore, sweet potatoes have amylolytic enzymes which can hydrolyze starch and therefore affect the viscosity of the sweet potato flour [44]. The high temperature of IR drying can deactivate the amylolytic hydrolyzing enzyme, preventing it from hydrolyzing the starch and resulting in a high pasting viscosity. The low drying temperatures by the oven, MW, and freeze drying could not deactivate the amylolytic enzyme activity, which made the condition conducive for the enzyme to hydrolyse the starch, and this can be the reason why the mentioned drying technologies had a lower pasting viscosity when compared with IR and a combination of IR with MW drying.

The commercial OFSP flour viscosity studied by Moreno et al. [14] showed that OFSP has a low pasting viscosity and low water absorption capacity in its nature. The low pasting and water absorption are a result of the low amount of starch content found in the OFSP [45]. The low viscosity of the OFSP makes it suitable to be used in infant formulation, as stated by [45, 46]. Amagloh et al. [45] showed that OFSP was higher in simple sugars during extrusion than in starch when compared to maize, and they also showed that the apparent viscosity of the OFSP-based infant food was 20 times lower compared to maize-based infant food. Makame et al. [46] have managed to show the low apparent viscosity of the orange-fleshed sweet potato, making it easy for an infant to orally process the complementary porridge. The porridge can be made up to about 23% solid and is below the required 3000 mPa.s.

The solubility index significantly increased ($p < 0.05$) for MW and MW-IR compared to oven-dried OFSP. Oven- and IR-dried flour showed a lower solubility index than MW, freeze-drying, and MW-IR drying methods (Table 3). The solubility index values obtained from this study ranged from 39.37% to 46.78%, and these values are comparable to those reported by [12], where they reported the solubility index of the freeze-dried and air-dried flours of sweet potatoes to be around 48.8% and 51.1%, respectively. The change in the microstructure of the orange-fleshed sweet potato chips during drying can be attributed to the increase in the solubility index of MW-IR-, MW-, and freeze-dried flours. The loose structure of the flour allows for more soluble materials to be accessed by water, thus increasing the solubility index of the flour.

The bulk density for the freeze-drying method showed to be significantly lower ($p < 0.05$) than oven, IR, MW, and MW-IR drying methods. Drying methods influence the bulk density, more especially if there is a change in the macrostructure of the food material caused by the moisture transfer mechanism which also affects the particle size, particle size distribution, and the number of contact positions of the particles [47, 48]. Freeze-drying can have significant changes on the structure and volume of materials due to the ice sublimation moisture transfer mechanism [49]. The drying technique of freeze-drying creates a porous product which decreases the bulking density. The bulk density decreases when the structure becomes more porous and increases when the structure is less porous [50]. The high bulk density from thermally treated flour (oven, MW, and IR) in this study can be due to changes in microstructure as well as macrostructure (shrinkage) [50]. Figure 5 shows the different particle sizes of the flour after drying under a scanning electron microscope. From the mentioned figure, it can be seen that the particle sizes of the freeze-dried flour are larger and aggregated as compared to other drying methods, which influenced the differences in the bulking density.

The OFSP flour had a water absorption capacity ranging between 2.03 ml/g and 3.41 ml/g. The MW-IR method shows a higher water absorption and swelling capacity as compared

Table 3: Effects of drying methods on physicochemical properties of dried orange-fleshed sweet potato flour.

Drying method	Solubility index (g/100 g)	Bulk density (ml/g)	Swelling capacity (ml/g)	Water absorption capacity (ml/g)	Insoluble dietary fibre (g/100 g)	Soluble dietary fibre (g/100 g)	Total dietary fibre (g/100 g)	Caloric value of TDF (kcal/g)
Freeze	41.81 ± 2.72^{c}	0.33 ± 0.01^{a}	13.83 ± 0.21^{a}	2.03 ± 0.21^{a}	14.43 ± 0.33^{a}	3.48 ± 0.37^{a}	17.91 ± 0.70^{a}	35.82
Oven	40.59 ± 3.15^{b}	0.44 ± 0.01^{b}	15.19 ± 0.96^{b}	3.09 ± 0.13^{b}	14.44 ± 0.35^{a}	3.58 ± 0.43^{a}	18.02 ± 0.78^{b}	36.04
IR	39.68 ± 2.22^{a}	0.46 ± 0.01^{b}	15.50 ± 0.28^{b}	3.11 ± 0.15^{b}	14.41 ± 0.31^{a}	4.43 ± 0.69^{b}	18.84 ± 1.00^{b}	37.68
MW	42.25 ± 3.63^{d}	0.44 ± 0.01^{b}	15.16 ± 0.92^{b}	3.02 ± 0.21^{b}	14.51 ± 0.30^{a}	4.52 ± 0.47^{b}	19.03 ± 0.77^{c}	38.06
MW-IR	44.53 ± 1.02^{e}	0.44 ± 0.01^{b}	15.43 ± 0.34^{b}	3.41 ± 0.22^{b}	14.49 ± 0.30^{a}	4.53 ± 0.32^{b}	19.02 ± 0.62^{c}	38.04

The data is representative of mean values and standard deviations ($n = 3$). Values with the same superscripts in the column are not significantly different ($p < 0.05$). IR: infrared; MW: microwave.

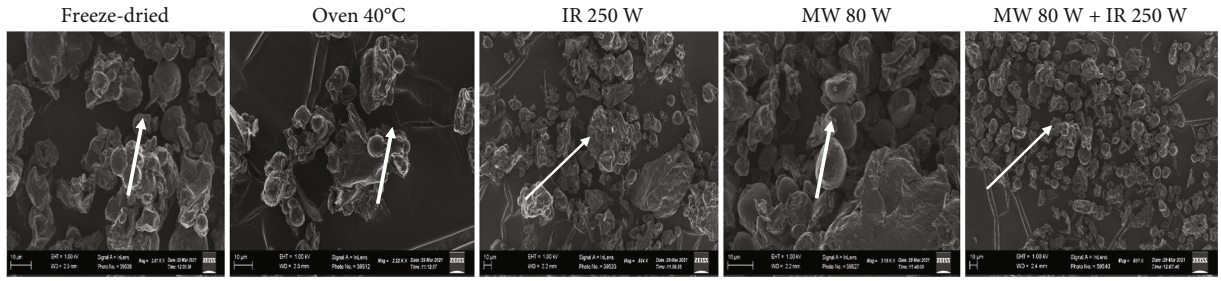

Figure 5: Effects of different drying methods on the scanning electron microscope of dried orange-fleshed sweet potato flour. Scale bar of 10 μm.

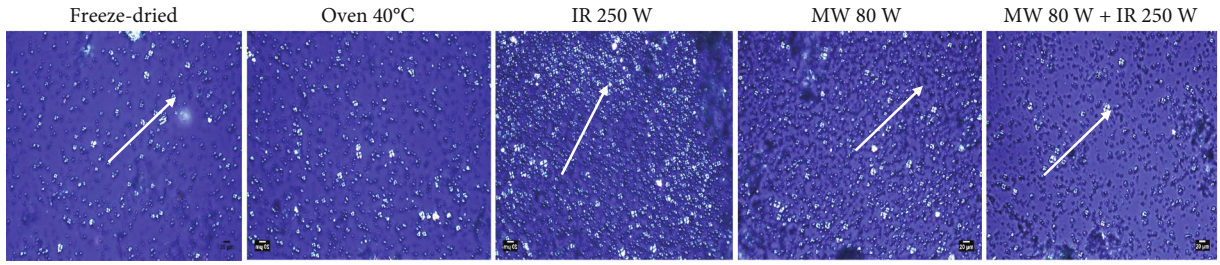

Figure 6: Effects of different drying methods on the polarized light microscope of dried orange-fleshed sweet potato flour. Scale bar of 20 μm.

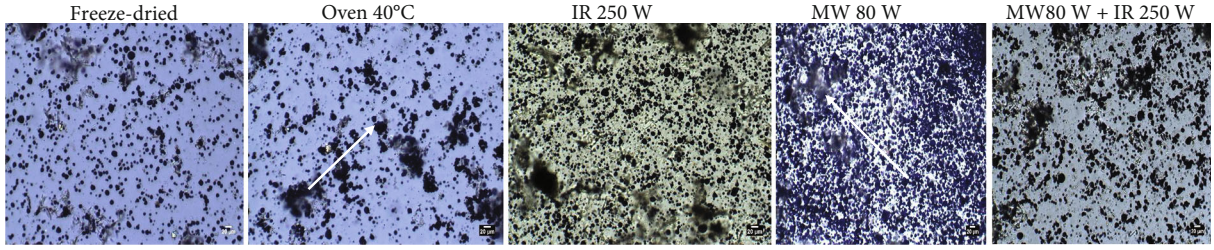

Figure 7: Effects of different drying methods on the iodine-stained light microscope images of orange-fleshed sweet potato flour viewed under a polarized lens. Starch was stained with blue/violet iodine solution. Scale bar of 20 μm.

to other drying methods (Table 3). Microwave, infrared, and oven drying methods did not show significant differences ($p > 0.05$). The high water absorption and swelling capacity reported from thermal drying methods can be due to the partial gelatinization of some starch granules [41]. During starch gelatinization, some structural changes of the starch such as granule swelling, loss of crystallinity, and amylose leaching can expose more hydrophilic side chains which can result in higher water absorption capacity as well as swelling capacity [41]. Marzuki et al.'s [41] study reported a similar range of values from this study, where they used MW to dry sweet potatoes. The values reported ranged between 2.96 g/g and 4.79 g/g for MW power levels at 450 W. The MW-IR-dried flours also reported higher swelling capacity and water absorption capacity values as compared to those of freeze-dried flours. This can be due to higher temperatures generated during drying which can partially gelatinize the starch granules and cause damage and changes in the starch and nonstarch polysaccharides [51]. Furthermore, the polarized microscope images (Figure 6) show that there is partial starch gelatinization for MW-IR drying methods, which is depicted by less birefringent and the Maltese crosses of the starch granules for the MW- and IR-dried OFSP compared to freeze-drying. The iodine-stained microscopic images also show nonstained nonstarch polymers (proteins, sugars, and dietary fibre) which can contribute to water absorption capacity and swelling capacity (Figure 7).

The high enthalpy values are associated with the amount of energy required to gelatinize the starch granule [52], meaning that the starch is resistant and still strongly associated with its native structure. This is further supported by Ngoma et al. [33], who explain that high enthalpy values are expected from a high degree of crystallinity, which makes starch granules more resistant to gelatinization. Low enthalpy values show that the starch molecules have partially lost their crystallinity due to partial gelatinization during drying. The drying conditions used in this study were shown to have effects on the thermal properties of the orange-fleshed sweet potato flour, more especially the thermal drying methods (Table 4). The enthalpy of freeze-dried flour is double that of oven-, MW-, and IR-dried flour (Table 4).

Table 4: Effect of different drying methods on the thermal properties of orange-fleshed sweet potato flour.

Drying method	T_0 (°C)	T_p (°C)	T_C (°C)	ΔH (J/G)
Freeze	72.84 ± 1.35^{c}	80.48 ± 0.69^{c}	85.96 ± 1.97^{c}	4.29 ± 1.38^{c}
Oven	63.85 ± 1.01^{b}	65.92 ± 1.37^{a}	73.66 ± 1.22^{b}	2.27 ± 0.61^{b}
IR	62.16 ± 0.69^{a}	66.49 ± 0.78^{a}	72.42 ± 0.96^{a}	1.63 ± 0.05^{a}
MW	62.67 ± 0.87^{a}	67.49 ± 0.69^{b}	73.47 ± 0.56^{b}	2.25 ± 0.09^{b}
MW-IR	61.56 ± 1.02^{a}	67.85 ± 0.99^{b}	72.96 ± 0.94^{a}	2.01 ± 0.07^{b}

Values are representatives of mean data and standard deviation ($n = 3$). Values with the same superscripts in the column are not significantly different ($p > 0.05$). IR: infrared; MW: microwave; T_o: onset temperature; T_P: peak temperature; T_C: conclusion temperature; ΔH: heat flow.

Table 5: Effect of different drying methods on the β-carotene and proximate composition of OFSP flour.

Drying methods	Moisture (g/100 g)	Ash (g/100 g)	Protein (g/100 g)	Fat (g/100 g)	β-Carotene (μg/g)	β-Carotene retention (%)
Fresh	87.6 ± 0.23^{e}	5.33 ± 0.67^{a}	6.88 ± 0.05^{a}	1.22 ± 0.15^{a}	2343.23 ± 17.11^{f}	—
Freeze	11.23 ± 0.85^{d}	5.71 ± 0.45^{a}	6.03 ± 0.24^{a}	1.26 ± 0.24^{a}	1010.84 ± 9.08^{b}	43.13 ± 0.11^{b}
Oven	7.56 ± 1.64^{b}	5.43 ± 0.32^{a}	6.48 ± 0.07^{a}	1.28 ± 0.32^{b}	553.34 ± 6.02^{a}	23.61 ± 0.57^{a}
IR	8.56 ± 0.99^{c}	5.30 ± 0.72^{a}	6.82 ± 0.02^{a}	1.24 ± 0.20^{a}	1547.51 ± 47.91^{c}	66.04 ± 0.22^{c}
MW	6.42 ± 0.66^{a}	5.31 ± 0.26^{a}	6.66 ± 0.96^{a}	1.24 ± 0.22^{a}	1880.34 ± 52.64^{d}	80.46 ± 0.36^{d}
MW-IR	7.67 ± 0.49^{b}	5.33 ± 0.34^{a}	6.64 ± 0.15^{a}	1.25 ± 0.15^{a}	1993.05 ± 8.05^{e}	85.06 ± 0.87^{e}

The data is representative of mean values and standard deviations ($n = 3$) on a dry basis. Values with the same superscripts in the column are not significantly different ($p < 0.05$). IR: infrared; MW: microwave.

This shows that the drying method might have partially pregelatinized the starch granule, therefore lowering the amount of energy required to gelatinize the starch (Figure 6). Compared to IR-dried flour, the other thermal drying method resulted in a higher enthalpy value, this includes MW-, oven-, and MW+IR-dried flour.

The different drying methods had a significant difference ($p < 0.05$) in the β-carotene content (Table 5). Oven drying showed the least retention of less than 30% β-carotene. The combination of MW and IR showed the highest β-carotene retention as compared to other drying methods (Table 5). Surprisingly, freeze-dried OFSP only showed less than 50% β-carotene retention. The high number of conjugate double bonds on the β-carotene structure has made it susceptible to autooxidation, leading to the degradation of the β-carotene. Factors such as light, high temperature, oxygen, transitional metals, and free radicals formed by lipid peroxidation can accelerate the degradation of β-carotene. The degradation of β-carotene in the presence of heat is temperature-dependent. Qiu et al. [53] observed that all-*trans*-β-carotene was isomerized during high-temperature treatment, and these temperatures ranged from 40°C to 140°C. High temperatures in the presence of oxygen can result in the transformation of all-*trans*-β-carotene to mainly 9-*cis* and 13-*cis*-β-carotene and, consequently, other isomers such as 15-*cis* and 13, 15-di-*cis*-β-carotene. The *cis* isomers can become radicals and react with molecular oxygen, leading to further degradation of the total β-carotene content. The low retention of β-carotene by freeze-drying could be due to the autooxidation caused by oxygen and light or by enzymes such as lipoxygenase in the presence of oxygen. The freeze-drying mechanism creates a more porous structure, which increases the flow of oxygen into the product and therefore activates the enzymatic oxidation of β-carotene. On the other hand, the faster drying method exposed the β-carotene molecule to heat and light for a short period of time, therefore resulting in higher retention of β-carotene.

As reported in Table 5, the oven drying method has lower β-carotene retention (23.61%), and this is the lowest compared to all drying methods. As already described about the factors that can affect the degradation of β-carotene, the same factors might have played a role during oven drying, more especially given that oven drying was the slowest thermal drying method. The study by Idah et al. [54] on the effects of drying time and temperature on the β-carotene content of tomatoes revealed that the β-carotene content of the tomato dried at 30°C for 1 hour was higher than that dried at 30°C for 6 hours. The authors concluded that both temperature and time had an effect on the β-carotene content of the tomato. Similar to our study, the faster thermal drying method had higher β-carotene retention.

The values obtained are different from other studies due to differences in cultivars, growing conditions, and nutrient compositions [32, 55]. Our results can be compared to those obtained by Yan et al. [56], who reported that drying orange sweet potatoes by MW had the highest β-carotene retention (about 80%) as compared to that of hot air drying which had only 40% β-carotene retention. It is evident that the convective drying method has low retention of β-carotene. Ruttarattanamongkol et al.'s [9] study reported a β-carotene retention of about 35.05% when using a drum roll drying method at 110°C and 7 rpm; furthermore, their study also showed that at lower temperatures (80°C) and lower rpm (3), the β-carotene retention was even lower (19.76%). On the other hand, when indirect solar drying was used by

Table 6: Effects of different drying methods on chroma values and colour of the OFSP flour.

Treatment	$L*$	$a*$	$b*$	ΔE	C_{ab}	h^0_{ab}
Fresh	87.39 ± 1.30^c	35.54 ± 1.02^d	50.04 ± 1.90^c	—	61.38^e	54.61^e
Freeze	79.75 ± 0.32^a	18.63 ± 0.39^a	21.02 ± 0.31^a	34.45^b	28.09^a	48.45^d
Oven	78.61 ± 0.44^a	21.60 ± 0.67^b	20.02 ± 1.04^a	34.24^b	29.45^b	42.83^a
IR	80.58 ± 0.20^b	25.18 ± 0.04^c	27.80 ± 0.16^b	25.46^a	37.51^c	47.83^c
MW	79.58 ± 0.53^a	25.89 ± 0.5^c	27.95 ± 0.89^b	25.34^a	38.10^d	47.19^c
MW-IR	79.55 ± 0.53^a	26.01 ± 0.39^c	27.18 ± 0.96^b	25.98^a	37.62^c	46.26^b

The data is representative of mean values and standard deviations ($n = 3$) on a dry basis. Values with the same superscripts in the column are not significantly different ($p < 0.05$). IR: infrared; MW: microwave; C_{ab}: chroma; h^0_{ab}: hue angle.

Table 7: β-Carotene correlation to chroma values ($L*$, $a*$, and $b*$) and colour change (ΔE).

Chroma values	β-Carotene	$L*$	$a*$	$b*$	ΔE
Correlation to β-carotene	1	0.520493	0.810784	0.932001	-0.91227

Omodamiro et al. [10] to dry OFSP, the β-carotene retention was higher (53.50%) than that of OFSP dried in an oven (26.11%).

The reduction in the β-carotene content could imply the low vitamin A activity of the product. When β-carotene is cleaved on the C_{15}, it yields two molecules of retinal which are metabolised to retinol (vitamin A) and retinoic acid. Therefore, the isomerization or reduction of the β-carotene molecule can inhibit the activity of β-carotene 15,15′-oxygenase to cleave the molecule at the C_{15} which will result in a low metabolisation or production of retinol.

The different drying methods resulted in the colour change (Table 6). The oven and freeze-drying methods showed a higher colour change as compared to other drying methods. The IR-dried flour was significantly different ($p < 0.05$) from other drying methods on the $L*$ value but did not show any significant difference ($p > 0.05$) for the $b*$ value between drying methods. The redness colour ($a*$) was greatly reduced by the oven and freeze-drying methods as compared to other drying methods (Table 6). The yellowness colour indicated by $b*$ values was mostly reduced and showed a high significant difference ($p < 0.05$) between the different drying methods (Table 6). There was no significant difference in colour change between MW-, IR-, and MW-IR-dried flour. The most important colours of orange-fleshed sweet potato are represented by redness ($a*$) and yellowness ($b*$), and there is a significant reduction in these colours for all drying methods (Table 5). The change in chroma values ($L*$, $a*$, and $b*$) is associated with the loss of colour pigments during drying [57]. This can be associated with a loss of β-carotene pigment which contributes to the red and orange colour of the flour. Malavi et al. [58] suggested that the chroma values obtained from $a*$, $b*$, and $L*$ can be used to predict the amount of β-carotene in processed products with OFSP as a natural colorant. The correlation data obtained from this study between β-carotene and the chroma values shows that there was a positive correlation between β-carotene and the $L*$ ($r = 0.520493$), $a*$ ($r = 0.810784$), and $b*$ ($r = 0.932001$), and there was a negative correlation between β-carotene and ΔE ($r = -0.91227$) (Table 7). It has also been stated that a longer drying method can result in a higher decrease in colour values, and this is what has been observed from the oven and freeze-drying methods, while the faster drying methods such as MW, IR, and MW-IR had a lower reduction in colour values.

4. Conclusions

A combination of MW and IR as an energy-efficient technology has the potential to produce dried orange-fleshed sweet potato flour. The combined use of MW- and IR-produced flour had the highest retention of about 85.06% of β-carotene. This is because of the relatively high drying rate and short time exposure to heat which can limit the destruction of β-carotene. The heat transfer mechanism by molecular vibration as well as the depth of the radiation energy increase the drying rate and reduce the drying time of MW and MW-IR drying methods. Models such as Page, Lewis, Henderson and Pabis, and Logarithmic can be used to predict drying kinetics for all thermal drying methods. The low pasting viscosity suggests that orange-fleshed sweet potato flour is a good candidate for complementary foods.

The study has some drawbacks; for instance, energy consumption analysis for the drying technologies and other flour functional properties such as oil absorption capacity as well as the flour shelf life were not determined. The study is realistic for countries with enough electricity supply and access to resources such as microwave and infrared; therefore, it targets mostly industrial producers of OFSP flour. In our research, the technoeconomic analysis, which gives a clear cost of production and rate of return for setting up a system, was not analysed. All the mentioned drawbacks could be addressed in future studies. However, the study still has a potential application within the food industry, where it can be used to produce food products with high dietary fibre, low viscous products, and high β-carotene content. The study also offers a novel way of drying OFSP and maintaining the functional properties of the flour.

Data Availability

The underlying data of the results supporting the study are stored at the University of Pretoria database.

Conflicts of Interest

The authors declare that there was no conflict of interest.

Authors' Contributions

D. Kgonothi was responsible for the conceptualization, experimental design, data analysis, and final manuscript writeup. M. Naushad Emmambux was responsible for the supervision, resource acquisition, funding, and review of the final manuscripts. N. Nwabisa Mehlomakulu was responsible for the supervision and review of the final manuscript.

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