The application of dehydration technologies on drying kinetics and physicochemical properties of orange-fleshed sweet potato

By

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Declaration

I Daddy Kgonothi, declare that this dissertation, which I hereby submit for the degree in MSc Food Science at the University of Pretoria, has not previously been submitted by me for a degree at this or any other university or institution of higher education

SIGNATURE: 

DATE: 11 November 2021

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Abstract

Title: The application of dehydration technologies on drying kinetics and physicochemical properties of orange-fleshed sweet potato

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Degree: MSc Food Science

Orange-fleshed sweet potato is a highly researched crop due to its nutritional content and more specifically, its high β-carotene content. Most developing countries around the world have adopted the use of orange-fleshed sweet potato as one of the staple food. The short growth period (3-6 months), low agronomical input, and dual-purpose use are properties to combat food security issues in most sub-Saharan African countries. The β-carotene compound is also a precursor for vitamin A, which is one of the most crucial nutrients, especially in children aged between 0-6 years, and pregnant women. African countries (Sub-Saharan region) are known to have a prevalence of vitamin A deficiency. There are challenges when it comes to the storage of fresh plant-based food such as orange-fleshed sweet potato, which is highly perishable and therefore has a short shelf life. Alternative processing methods such as drying and milling into flour can help to extend the shelf life of the orange-fleshed sweet potato.

Traditional drying methods such as sun drying, solar drying and oven drying have been used for over decades. However, these methods generally destroy heat-sensitive compounds such as the critical β-carotene content, mainly due to exposure of the orange-fleshed sweet potato to oxygen, sunlight and high temperature for longer periods. The exposure of β-carotene to the mentioned factors can result in isomerization and auto-oxidation of β-carotene, which reduce the vitamin A content, thereby producing a product with poor nutritional content. The current study seeks to explore novel drying technology, such as freeze-drying, microwave and infrared drying methods.

Orange-fleshed sweet potato (Bellevue and Orleans cultivar) was dried by application of oven (40°C, 4 hours, air velocity 5.2 m/s), microwave (80 W, 1 hour, air temperature of 40°C, air velocity 4.5 m /s), infrared (250 W, 2 hours, air temperature of 40°C, air velocity 4.5 m/s), microwave-infrared (80 W + 250 W, 45 minutes, air temperature 40°C, air velocity 4.5 m/s) and freeze-drying (-45°C, 100KPa, 5 days) technologies, and milled into flour. The drying kinetics were analysed by different models. The produced flour was analysed for physicochemical properties and nutritional composition. The analysed functional properties include water absorption capacity, swelling capacity, solubility index, bulking density, pasting properties and thermal properties. Proximate composition was also evaluated including total dietary fibre and β-carotene content of the flours.

The oven-drying method was the slowest, due to a slow drying rate. The latter is due to the moisture transfer mechanism, as low temperatures are used during drying. The moisture

transfer is by capillary diffusion which is a slow moisture transfer mechanism. Oven drying took about 4 hours to dehydrate the sweet potato slices to solid content of less than 13%. Infrared drying was the second slowest drying method, while microwave took only 1 hour to completely dry the sweet potato slices. The electromagnetic radiation by microwave and infrared cause a rapid structural collapse, releasing water from cytoplasm and vacuole, thus increasing cell membrane water permeability, which makes it easy for water to be transported out of the plant cell. The drying rate of the microwave-infrared drying method was the fastest (45 minutes). The coefficient of diffusion from the models also showed that the microwave-infrared combination had the highest diffusion rate, as compared to other drying methods which showed a lower coefficient of diffusion. The Page model was the most suitable for the oven drying method, Lewis model for infrared drying, while Henderson and Pabis for infrared and Logarithmic for microwave-infrared combined method.

The pasting and thermal properties of the flours were not significantly affected by the different drying methods. However, infrared and microwave-infrared dried flours have indicated a higher final viscosity when compared to other drying methods. The freeze-dried flour showed a higher enthalpy value (4.29 J/g), as compared to other drying methods. Microwave-infrared drying methods, infrared, and microwave had a higher solubility index, while the oven and freeze-drying methods showed a lower solubility index. The freeze-dried flours exhibited the lowest bulk density as compared to other drying methods.

Microwave-infrared combined drying methods revealed a higher retention of β-carotene (85.06-90.14%) and this seem to be mainly due to the fast drying rate of the combined drying methods. The microwave also had a higher retention of β-carotene, followed by infrared, while oven and freeze-drying method showed a lower retention of β-carotene as a result of longer drying periods, exposure to oxidative and destructive conditions, which can cause the degradation of β-carotene (high drying temperature, endogenous enzymes, and oxidative agents).

The study suggest that a combination of microwave-infrared or microwave alone are energy efficient alternatives to produce dried orange fleshed sweet potato flour, with minimal reduction in β-carotene and change in functional properties.

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CHAPTER 1: Introduction

Malnutrition is one of the major issues affecting the African continent for food and nutrition security. The lack of sufficient nutrients in diets contributes to the increasing number of people affected by the triple burden of malnutrition (coexistence of over nutrition, undernutrition, and micronutrients deficiency) in most Sub-Saharan African countries (Harika et al., 2017). According to the World health organization (WHO) 2019 report, the number of undernourished children raised from 181 million in 2010 to almost 222 million in 2016 within sub-Saharan Africa, while the rate of wasting in children was 13.8 million in 2017 (WHO 2019). Malnutrition is also estimated to contribute to more than one-third of all child deaths in developing countries (Bain et al., 2013). 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 (Harika et al., 2017).

The use of vegetables 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 high content of dietary fibre, vitamins, minerals, β-carotene (pro-vitamin A), and other antioxidant phytochemicals (Neela and Fanta, 2019, Alam et al., 2016). As a result, OFSP has been identified as one of the stable root crops, which can be used to address malnutrition and food security in developing countries. OFSP has to survive adverse growing climatic conditions, a short period of growth (about 4 to 5 months), and low agronomical input (Sajeev et al., 2012). The main challenge with OFSP is its perishability in nature, which is caused by the high moisture content and water activity in its fresh state (Sugri et al., 2017).

Food processing methods such as drying can be used to transform fresh produce (fruits and vegetables) into shelf stable foods. The dried OFSP can be processed into flour, which can be used in food to food fortification, thickener in soups, bakery products, and as a substitute for cereal flour (Amajor et al., 2014). Drying using solar energy has been used for centuries as a method of preserving fresh produce (Sagar and Kumar, 2010), and oven drying is currently used for commercial production of OFSP flour. Drying of fruits and vegetables can negatively impact the nutritional and functional properties of OFSP. For instance, oven drying is known to cause a decrease in β-carotene content and vitamin C of the OFSP (Haruna et al., 2018). Oven drying has also been reported to have a destructive impact on the functional properties

such as water holding capacity, swelling capacity and solubility of the OFSP flour depending on the drying temperature used for dehydration. Freeze-drying methods preserve most of the heat-sensitive nutrients, and many researchers have reported that it improves the functional properties of the dried food products (Jayanthi et al., 2021). Another noted disadvantage relating to oven and freeze-drying methods is their long period of drying, which may imply a higher cost of energy. Freeze drying approximately takes about 3-5 days to completely dry the sample, while oven drying can take 2 to 5 hours to dry the same sample, depending on the sample parameters such as sample type, sample size, and initial moisture content (Touil et al., 2014).

Other dehydration technologies such as infrared and microwave energy can improve the physicochemical properties of OFSP flour and also show higher retention of β-carotene content due to faster dehydration rate (Riadh et al., 2014). Infrared and microwave do not seem to cause any case hardening , which can result in poorly rehydrated products (Thao and Noomhorm 2011). The microwave was also reported to have a faster drying rate by Baysal et al (2003). More so, increased rehydrating capacity, higher β-carotene retention, and does not cause significant loss in the colour of OFSP flour (Ruttarattanamongkol et al., 2016). Faster drying ensures more efficient use of energy. The mode of heat generation and transfer during infrared and microwave dehydration can result in faster dehydration and efficient energy use (Doymaz, 2012, Guo et al., 2017).

Most research investigated the retention of β-carotene OFSP using different drying technologies such as infrared (IR) (Doymaz, 2012), microwave, oven drying, and solar drying (Bechoff et al., 2009). Limited research has reported on functional properties and β-carotene content of OFSP flour (Yan et al., 2013, Ssepuuya et al., 2020). There is also scarce research on the combined use of microwave and infrared energy on the dehydration of OFSP. Detailed functional properties of OFSP flour in terms of swelling power, water absorption capacity, pasting properties, and solubility of OFSP flour are also scarce in the literature. The project will focus on the properties of dehydrated OFSP by a combination of infrared and microwave energy compared to freeze and oven drying.

CHAPTER 2: Literature review

The literature review focuses on the general functional and nutritional properties of OFSP as affected by different dehydration methods. The science and kinetic of food dehydration is critically discussed in detail. The science and technology of the dehydration methods is also reviewed.

2.1. Orange-fleshed sweet potato (OFSP)

Sweet potatoes are classified into different cultivars, which are distinguished by the colour of their pulp, shape, size, the intensity of their sweetness, and precociousness (Ruttarattanamongkol et al., 2016, Christerbel Nicarunu., 2015). Most well-known pulp colours include white, yellow, purple, red and orange-fleshed sweet potatoes (Tong et al., 2019). The latter four are mostly cultivated for their health benefits (Sajeev et al., 2012). The purple and red sweet potato are known for their high levels of phenolic compounds such as acylated water-soluble anthocyanin, which has aromatic acylated glycosyl groups and exhibit relatively high pH tolerance and are thermostable (Wang et al., 2016). Yellow and orange-fleshed sweet potatoes have relatively high content of fat-soluble β-carotene (Wang et al., 2016).

Orange-fleshed sweet potato is a bio-fortified plant crop enriched with β-carotene, which provide nutritional and health benefits (Low et al., 2020). Orange-fleshed sweet potato is the most researched sweet potato in the African continent because of it's dual-purpose, its roots and leaves can be used for consumption, and also the roots are used to address vitamin A deficiency (VAD) (Laurie et al., 2012).

2.2. Nutritional composition of OFSP

Different parts of the sweet potato such as the leaves and the roots have several beneficial nutrient compounds (Nyathi et al., 2019), and research has shown that the root is the main source of starch and sugar (sucrose, maltose, and glucose). The starch composition of sweet potato is 20-34% amylose and 70-80% amylopectin (Tong et al., 2019, Wang et al., 2016). Other than storing starch and sugars, the roots of the sweet potato are also a source of other non-starch polysaccharides (cellulose, hemicellulose, and pectin), and monosaccharides, for instance, rhamnose, arabinose, galactose, glucose, xylose, mannose, and uronic acids (Wang et al., 2016). Sweet potatoes have also been identified as a good source of minerals such as calcium, sodium, potassium, iron, magnesium, and zinc, these minerals are also found in the

roots of the sweet potato (Table 2.1). It is also an excellent source of vitamins such as Vitamin C, Vitamin B, β-carotene (pro-Vita A), and phenolic compound (Ruttarattanamongkol et al., 2016). Table 2.1 higlights that different amounts of nutrients, such as minerals, vitamins, fat, fibre, protein and starch are found in different varieties of OFSP. This can be attributed to the different growing conditions, maturity of the roots and cultivar differences.

Table 2.1. Nutritional value of Orange-Fleshed Sweet Potato by various researchers.

Carbohydrates (%)	Starch (%)	Crude fibre (%)	Protein (%)	Fat (%)	Ash (%)	Reference
90.13	33.66±3.76	2.57±0.14	4.80 ±0.24	0.39±0.03	2.11±0.12	Rodrigues et al (2017)
24.50 ± 0.13	NR	0.40±0.12	2.70± 0.93	0.28 ±0.22	1.17±0.02	Muhammad et al (2016)
88.01 ± 0.04	NR	3.83±0.06	2.48± 0.24	1.12± 0.01	4.33±0.03	Endrias et al (2016)
NR	53.61±0.23	21.78±0.01	1.61± 0.03	0.18± 0.01	1.41±0.01	Ju et al (2017)
	Minerals and vitamin Composition (µg/100 g)					
Magnesium	Zinc	Iron	Calcium	Phosphorus	Pro-vitamin A (β-carotene)	Reference
22.50 ± 1.11	3.23± 0.41	1.12± 0.02	27.35 ± 1.03	44.58±1.68	4183.25±22.51	Alam et al (2020)
280.00±17.00	3.32± 0.34	15.17±0.69	839.00±19.00	592.00±7.00	NR	Tang et al (2010)
5.86 ± 0.11	1.14± 0.01	11.51±0.02	7.42 ± 0.01	19.22±0.01	NR	Endrias et al (2016)
130.00 ± 0.05	NR	NR	510.00±0.26	260.00±0.03	NR	Krochmal-Mraczak et al (2014)

NR (not reported)

Different varieties of sweet potatoes contain varying amounts of β-carotene content (Table 2.2). The fat soluble carotenoids contribute to the amount of the β-carotene present in each cultivar, which also contribute to the pigment of the sweet potato flesh colour. Most of the dark orange-fleshed sweet potatoes are reported to have higher β-carotene content, compared to yellow, pale-orange, purple and white-fleshed sweet potato, which is attributed to various

factors such as absent or low carotenoids content, growing conditions and maturity levels (Khathabwalika et al., 2016).

Table 2.2. The β-carotene content of different sweet potato flesh colours.

Sweet potato flesh colour	β-carotene content (µg/g dw)	Reference
White	90.95 ± 2.05	Kammona et al (2015)
Orange	365.03 ± 11.05	Kammona et al (2015)
Yellow	117.00 ± 3.12	Kammona et al (2015)
Purple	113.86 ± 14.17	Kammona et al (2015)
BV/009 (deep orange)	75.21 ± 18.32	Kathabwalika et al (2016)
LU06/252 (Pale orange)	78.70 ± 25.36	Kathabwalika et al (2016)
LU06/0258 (Yellow)	26.95 ± 19.33	Kathabwalika et al (2016)
LU06/0299 (Yellow)	25.78 ± 15.22	Kathabwalika et al (2016)
Resisto (Dark orange)	207.79	Faber et al (2015)
Orange	382.22 ± 2.18	Hussein et al (2014)
Yellow	122.96 ± 1.54	Hussein et al (2014)
Purple	116.28 ± 1.80	Hussein et al (2014)
White	111.18 ± 0.71	Hussein et al (2014)

Dry basis (dw)

2.3. β-carotene chemistry and health benefits

Carotenoids are known for their properties that give colour to most fruits and vegetables. The red, yellow, and orange pigments are provided by the carotenoids compounds, photosynthetic microorganisms such as algae and cyanobacteria, and some non-photosynthetic bacteria and fungi are also able to produce carotenoids (Mezzomo and Ferreira, 2016). Carotenoids compounds are known for being fat-soluble (Britton, 2020), and there are more than 700 carotenoids compounds, which are mostly hydrocarbons consisting of 40 carbon atoms and 2 terminal rings (Mezzomo and Ferreira, 2016). They are also known as terpenoids, which have 8 units of isoprenoids. The conjugated double bonds structure of carotenoids gives it more chemical reactivity, and therefore it can be modified by either hydrogenation, dehydrogenation, cyclization, or oxidation (Mezzomo and Ferreira, 2016).

There are two classes of carotenoids. These include carotenes (contains only carbon and hydrogen) such as β-carotene, which are mostly linear tetraploids, and have six-carbon rings at one end or both ends of the molecule, while the other group is the oxygenated derivatives of

carotenes known as xanthophyll (≥ 1 Oxygen functionality at the cyclic end group), and this includes lutein, violaxanthin, neoxanthin, and zeaxanthin (Jackson et al., 2008, Mezzomo and Ferreira, 2016, Murillo et al., 2021). According to Jackson et al., (2008), linear *all-trans* isomers are the most prevalent isomers found in nature, and the electron-rich polyene backbone is responsible for many of the physicochemical and biological properties of the carotenoids.

The biosynthesis of carotenoids shows that all of them are derived from the acyclic isoprenoid lycopene by reactions such as cyclization, oxidative functionalization, rearrangements, as well as through oxidative degradations (Jackson et al., 2008). The chemical reactions are summarised in Figure 2.1 below, showing the differences in structures of each carotenoid. With regards to the structures, Jackson et al., (2008) explain that carotenoids which possess an unsubstituted β-ionone ring such as β-carotene are known as vitamin A precursors.

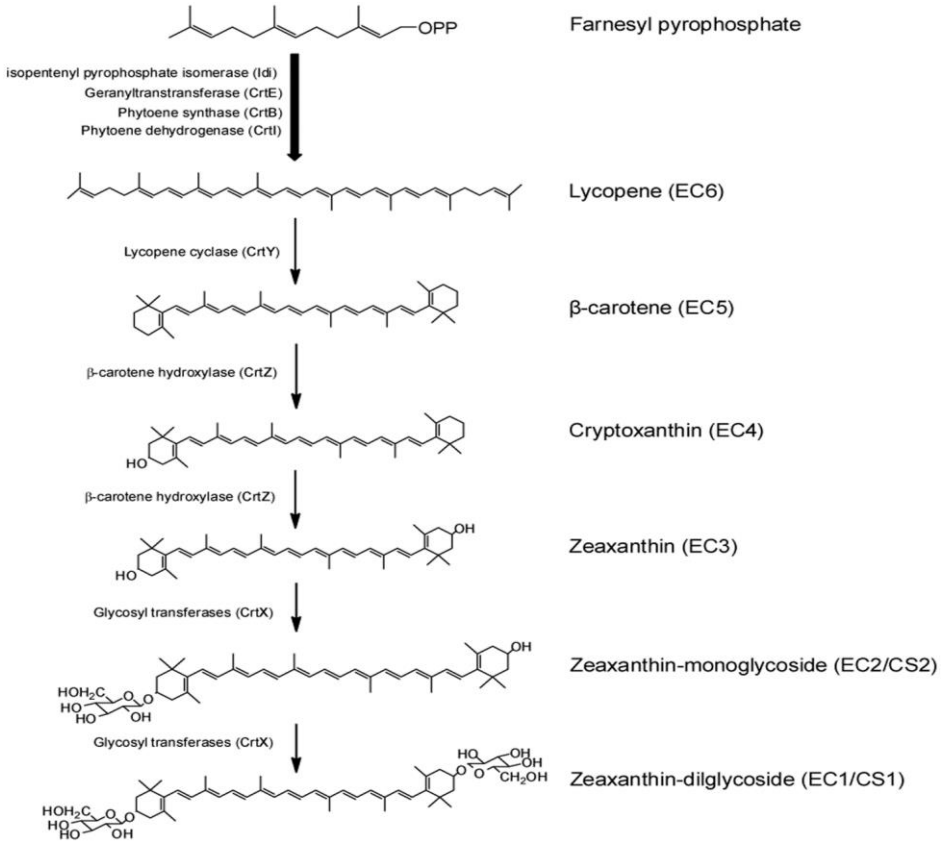


Figure 2.1. Biosynthesis of Carotenoids from lycopene (Zhang et al., 2014)

Carotenoid's chemical and physical properties are mostly determined by their chemical composition, the variation in the end groups and the presence of oxygen functions which also determines the subtle differences in properties of individual carotenoids, specifically in terms of solubility, and molecular interaction (Britton, 2020). Carotenoids are fat-soluble and mostly extracted using an organic solvent. Britton (2020) explains that when carotenoids are in an

aqueous medium, they can form aggregates that are stabilized by dipole interaction, hydrogen bonds, van der Waals interactions, and hydrophobic bonds. The two main known aggregates are the H-aggregates and J-aggregates (Figure 2.2), and the formation of these aggregates is influenced by the presence of anions, temperature, and structure of carotenoids. The formation of the aggregates determines the functional properties of the carotenoids, through energy dissipation, redox properties, and reactions. The aggregates also close a gap between the physics of single molecules and structurally ordered crystals of carotenoids (Britton, 2020).

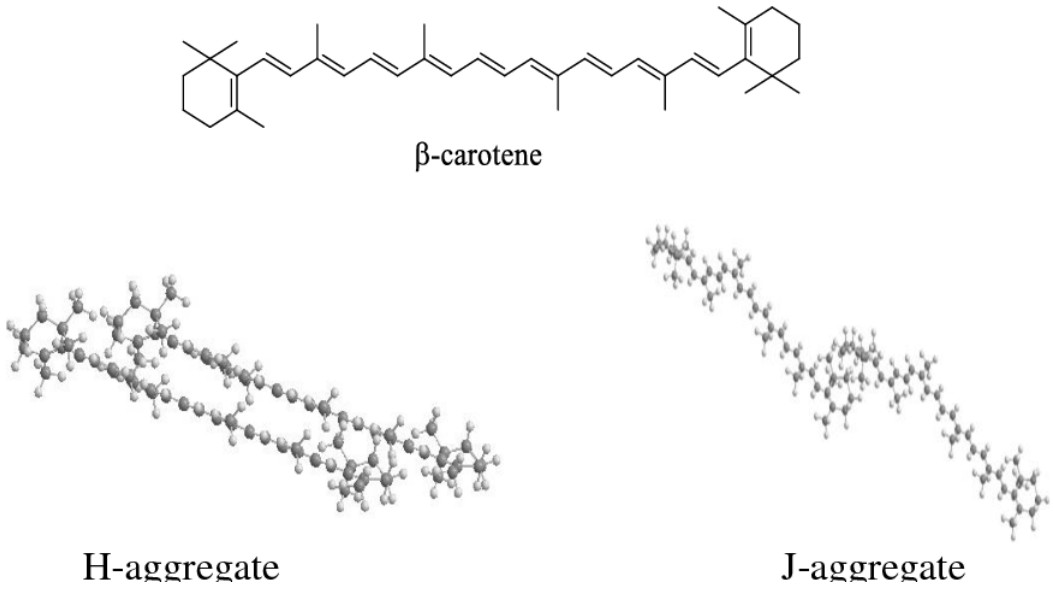


Figure 2.2. Molecular structures of β-carotene, J-, H-aggregates (Alwis et al., 2017)

Carotenoids are known for their antioxidant properties in humans. They function to protect cells from oxidative reactions and take action against the inflammatory process and carcinogenic reactions. Most carotenoids have a positive impact on human health, and this is attributed to their ability to scavenge reactive oxygen species (Coronel et al., 2019). Carotenoid's antioxidant properties can prohibit the adverse effects caused by the free radicals by scavenging them through quenching of singlet oxygen molecules (Ramel et al., 2012, El-Agamey et al., 2004). Han et al (2012) stated that the radical scavenging properties of carotenoids are mostly dependent on the structure of the carotenoids and the type of the radical species, they further explained that the chemical reaction can either be through electron transfer (ET), radical adduct formation (RAF), or through hydrogen atom transfer (HAT). This is summarised by Figure 2.3.

$$Car\ (H) + RO^{\bullet} \longrightarrow Car\ (H)^{\bullet +} + RO^{-} \quad [ET] \quad (1)$$

$$Car\ (H) + RO^{\bullet} \longrightarrow [RO\text{---}Car\ (H)]^{\bullet} \quad [RAF] \quad (2)$$

$$Car\ (H) + RO^{\bullet} \longrightarrow Car^{\bullet} + ROH \quad [HAT] \quad (3)$$

Figure 2.3. Stepwise chemical reaction in radical scavenging by carotenoids (Car)

Carotenoids can exhibit both pro-oxidant and antioxidant properties, through the aforementioned chemical reactions, however, different carotenoids are effective under different conditions. El-Agamey et al (2004) stated that due to their hydrophobic nature they are found in lipophilic regions such as adipose tissues and the interior of the cell membrane. They further noted that β-carotene and lycopene are more able to scavenge singlet radical oxygen molecules under a hydrophilic environment more than zeaxanthin, which can effectively protect against both hydrophilic and lipophilic peroxyl radicals. (Krochmal-Mraczak, et al., 2014)

2.3.1. Conversion of β-carotene to vitamin A and degradation

It is has been reported that β-carotene is not stable due to it's unsaturated nature, therefore, two types of β-carotene can exist, *cis*-β-carotene and *trans*-β-carotene. The latter is the natural form at which β-carotene exists, while the *cis*-β-carotene is due to structural changes, which can be caused by the processing of the food material, thus causes structural changes (Boon et al., 2010). Chaijan et al (2021) explains that other factors such as acidic conditions, singlet oxygen, transition metal, and free radicals can result in the oxidation of β-carotene, and results in the *cis* isomers of *all-trans*-β-carotene as well as other secondary compounds such as epoxides, endo-peroxides, and apocarotenones. Which can also promote auto-oxidation of the remaining *all-trans*-β-carotene. Isomers of *all-trans*-β-carotene include 9-*cis, 11-cis, 13-cis, and 15-cis*-β-carotene, and their structural differences are shown in Figure 2.4 below. Isomerization of *all-trans*-β-carotene to *cis*-β-carotene reduces activity of vitamin A (Chaijan et al., 2021). This is due to change in geometric structure which affects the conversion of β-carotene to vitamin A. The *all-trans*-β-carotene is the one identified to be able to form the provitamin A precursor as it resembles the vitamin A by its structure (Grune et al., 2010).

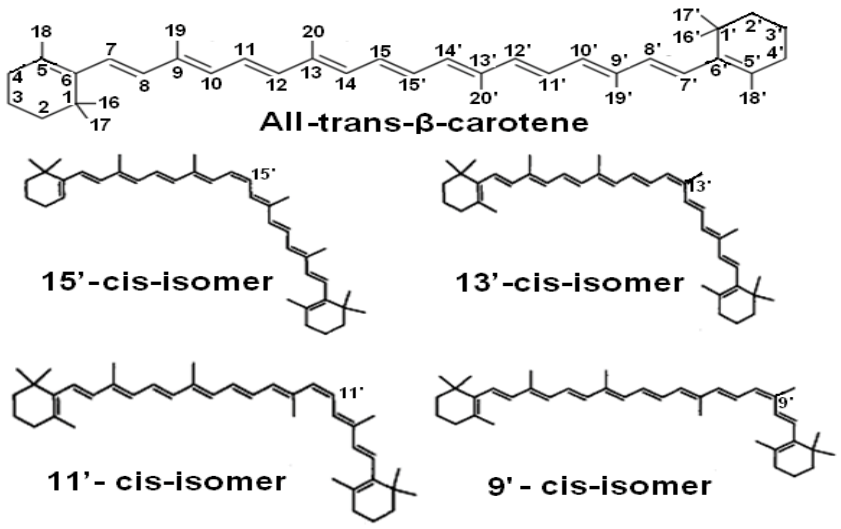


Figure 2.4: Structural isomers of *all-trans-β-carotene, 15-cis,* 13-*cis,* 11-*cis* and 9-*cis*-β-carotene. Extracted from (Jing and Rohrer, 2014)

The phytochemical properties of β-carotene have made it more valuable, especially the link to vitamin A which has more health benefits. Biochemistry of β-carotene has shown that it is a precursor of vitamin A (Figure 2.5), with the presence of the two β-ionic rings, the cleavage of β-carotene chain at –C15 = C15 '- position results in two retinol molecules (Bogacz-Radomska and Harasym, 2018). This conversion of β-carotene to retinol takes place through a passive diffusion within the small intestine. β-carotene dioxygenase enzyme catalyses the breakdown of β-carotene in the walls of the small intestine to form retinal, then retinaldehyde reductase further reduces the retinal aldehyde by addition of hydrogen to form the alcohol retinol, which is also known as Vitamin A (Knockaert et al., 2015, Tang, 2010).

The equivalency ratio of β-carotene to vitamin A has been estimated as 12:1 by weight. Meaning that 12µg of β-carotene is equivalent to 1 µg of retinol (Vitamin A) (Van Loo-Bouwman et al., 2014). The conversion ratio was based on the estimated 17% to 65% absorption of β-carotene, from a mixed diet of plant sources (Haskell, 2012). Some study showed that *all-trans*-β-carotene was the only carotenoid capable of yielding 2 molecules of all-*trans*-retinal (Lemke et al., 2003). There are many studies showing several conversion of vitamin A equivalency of β-carotene, however, those studies revealed that higher consumption of vegetable β-carotene was required to have an adequate amount of vitamin A (Lemke et al., 2003). The absorption of β-carotene is mostly affected by the food matrices and the processing methods. Haskell (2012), reported that the blended spinach juice had a higher β-carotene absorption as compared to whole leaf spinach, and cooked carrots had a higher absorption

compared to raw carrots. The difference in absorption can be due to the fact that processing releases the β-carotene from plant cells and other plant components making it more available for absorption.

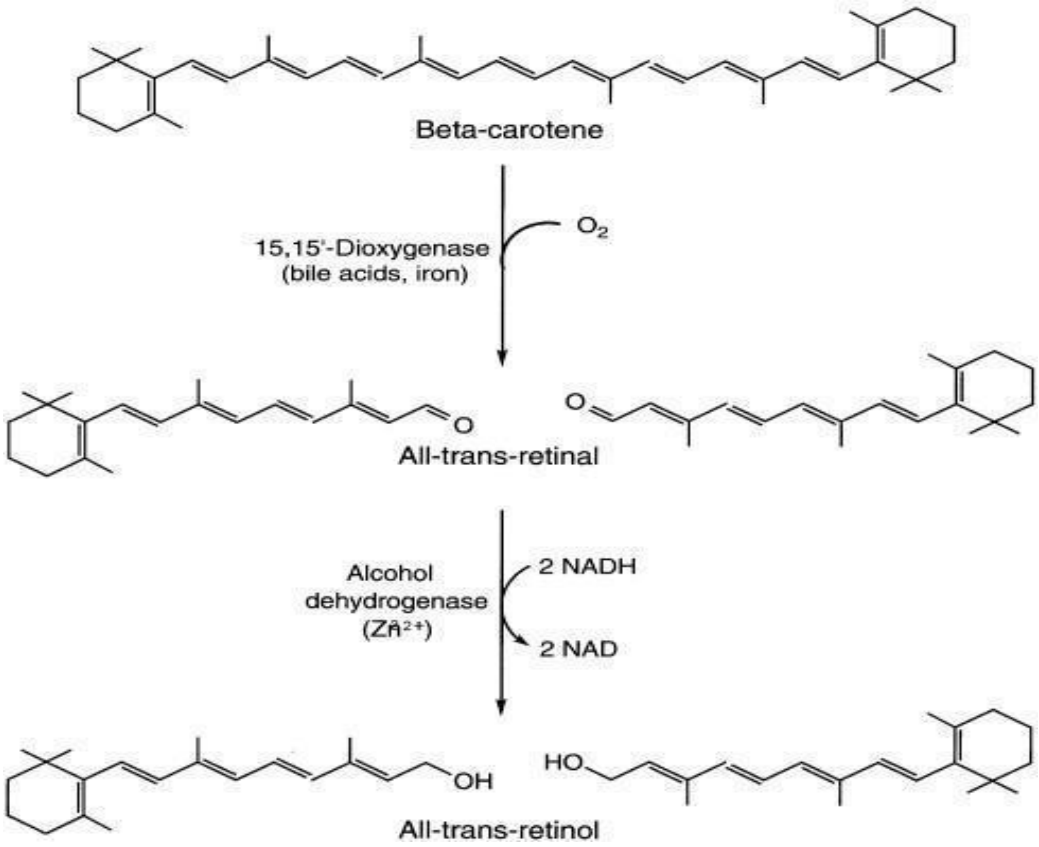


Figure 2.5. Conversion of β-Carotene to vitamin A. Extracted from (Kohlmeier, 2015).

The retention of β-carotene is another challenge, particularly during the processing of food that is known to be rich in β-carotene. The conjugated double bond found on the linear structure of β-carotene makes it vulnerable to be broken by heat, light, and oxidation leading to the production of the *cis*-isomers. The breakdown of β-carotene does not end after processing but also continues during the storage of the food material (Hussein et al., 2014). There is a lack of scientific explanation on how heat results in the isomerization of β-carotene, however, the highly unsaturated structure was reported to be susceptible to auto-oxidation in the presence of heat and light as well as oxygen and oxidizing enzymes (Guiamba and Svanberg, 2016). Guiamba and Svanberg (2016) suggest that during food processing, the breakdown of the food cell matrix occurs for example during milling or cutting may induce auto-oxidation. This can result in the formation of isomers as the size reduction of the food material increases the exposure of β-carotene to oxygen, and endogenous oxidative enzymes, metal ions, light, and co-oxidation with lipid hydroperoxides.

2.4. Carbohydrates of OFSP flour

2.4.1. Orange fleshed sweet potato starch

Starch is one of the molecules which provides nutritional function amongst other carbohydrates. It is also known as the energy reserve of all plants. Starch is partially crystalline and occurs as a granular structure, which is insoluble, but hydratable to some extent in water under room temperature (Kerry et al., 2017). Orange fleshed sweet potato starch has attracted many food processors and its application has been diversified in food processing. In terms of functional properties, it was reported to be close to potato starch (Akintayo et al., 2019). Sweet potato starches are known to have larger granule size, lower pasting temperature, and higher pasting viscosity as compared to those of cereals starches such as maize and wheat (Kitahara et al., 2017). Rodrigues et al (2017) reported that fresh OFSP contained about 65.41±3.17 g/100 g starch dry basis and dried OFSP flour contains about 33.66 ± 3.76 g/100 g dry basis of starch. Sweet potato starch is composed of 20-30% essentially linear amylose and 70-80% branched amylopectin (Tonga et al., 2020).

The heating of starch in the presence of moisture disrupts its crystalline structure, exposing hydroxyl groups of amylose and amylopectin to form hydrogen bonds with water molecules, causing an increase in granule swelling and solubility (Dupuis and Liu, 2019). Starch granule undergoes a phase transition when heated in the presence of water, causes disruption of molecular order within the starch granule, which is accompanied by irreversible changes in properties such as granular swelling, crystalline melting, viscosity development, solubilisation and difference in refractive index. Starch in OFSP flour is the one that gives the desired functional properties of the flour. Gelatinization and retrogradation are the two most important properties of the starch granule (Karim et al., 2007). The importance of gelatinization/pasting is to provide thickening and swelling functions, while retrogradation is related to the stability of the starch paste during storage periods (Tortoe et al., 2017).

2.4.2. Non-starch polysaccharides (NSP) of OFFSP

Many fruits and vegetables are rich in non-starch polysaccharides, and these refer to other complex carbohydrates other than starch. There are different types of non-starch polysaccharides which include cellulose, pectin, glucans, gums, mucilage, inulin, chitin, and lignin, and these molecules form part of total dietary fibre (Gedrovica et al., 2011). Dietary fibre has been identified to be of health benefits, and contribute to the functional properties of

the flour (pasting, viscosity, and rehydration capacity, oil absorption capacity, swelling capacity, and swelling capacity) (Al-Sheraji et al., 2011). Many studies are linking intake of dietary fibre with a reduced risk of cardiovascular diseases, the incidence of type 2 diabetes, and regulation of weight (Kritensen and Jensen, 2011). Non-starch polysaccharides are not digested by the upper gastrointestinal enzymes, due to their molecular structure complexes, they end up in the lower digestive tract, where they improve the digestive system by serving as nutrients (pre-biotics) for probiotics, which help in the prevention of diseases (Brown and Valiere, 2004).

According to Gedrovica et al (2011), dietary fibre is divided into low molecular weight (soluble) and high molecular weight (insoluble). The high molecular weight includes cellulose, galactomannans, xylans, xyloglucans, and lignin, while the low molecular weight includes pectin, arabinogalactans, arabinoxylan, and β—(1,3)(1,4)-D-glucans (β-glucans) (Ozyurt and Otles, 2016). Dietary fibre has been known for its physiochemical properties, which influence the viscosity of the flour (Kritensen and Jensen, 2011). Kristensen and Jensen (2011), explained that most soluble dietary fibre induced thickening when mixed with liquids. Neela and Fanta (2019) indicate that OFSP is a good source of insoluble dietary fibre, they have reported about 3.6% dry basis of dietary fibre. Wang et al (2016) reported 2.7 g /100 g fresh weight from 18 different varieties, of which was composed of 31.2% cellulose, 16.9% lignin, 15.7% pectin, hemicellulose being 11.3%. They also reported monosaccharides dietary fibre from 10 varieties of OFSP which composed of rhamnose (1.4-2.5%), arabinose (2.9-4.3%), mannose (0.5-2.1%), galactose (7.5-14.2%), xylose (2.6-4.1%) and uronic acids (14.8-34.7%) (Galactunoric and glucuronic acids). Other than health benefits, this different dietary fibre contributes to the physicochemical properties of the OFSP flour, such as water absorption capacity, oil absorption capacity, and therefore provides good opportunities for OFSP to be utilized in the food industry as a functional flour.

Sweet potatoes are known for their rich content of soluble sugars, which consist mainly of sucrose, glucose and fructose (Adu-Kwarteng et al., 2013). The sweet taste perceived from sweet potato is mainly attributed to maltose (Sawai et al., 2009).

The soluble sugars can affect the functional properties of the sweet potato flour, such as pasting properties. This can be due to their water solubility nature, which can compete with starch molecules for the available water, resulting in decreased swelling and viscosity, while causing an increase in pasting temperature (Aina et al., 2009). The low pasting viscosities are due to

high sugar content and drying of sweet potato, the starch amylose content is decreased while the sugar content is increased (Olatunde et al., 2016). Olatunde et al (2016) also reported a positive correlation between soluble sugars and water absorption capacity of the flour, they also indicated that pasting temperature also increased with the increased sugar content.

2.5. Dehydration processing

Drying has been defined as the process whereby moisture is vaporized from a material and is swept away from the surface, sometimes under vacuum, but normally employing carrier gas which passes through or over the material (Keey, 2001). Commonly, drying is conceived as the removal of water into a hot airstream, but drying may encompass the removal of liquid that can turn into any heated gas. For drying, so defined, to take place, the moist material must obtain heat from its surroundings by convection, radiation, and/or conduction, or by internal heat generation such as dielectric or inductive heating (Keey, 2001). The mechanism by which heat and mass are transferred in materials depends on the physical structure and chemical composition of that material, and according to its water-binding capacity, such as non-hygroscopic and hygroscopic nature (Srikiatden and Roberts, 2007). Hygroscopic materials contain bound water, while non-hygroscopic materials do not contain bound water (Srikiatden and Roberts, 2007).

Drying can be divided into a constant period and one or more falling rate periods (Figure 2.6) (Touil et al., 2014). Constant drying is defined as the period of drying, where dehydration occurs at the surface by evaporation and the internal moisture transfer is sufficient enough to maintain the saturated surface, hence the rate of evaporation remains constant (Srikiatden and Roberts, 2007). The falling rate is described by the surface of the food not being drenched, and the speed of moisture migration from the interior towards the surface is less than the evaporation rate from the surface. Thus, dehydration in the falling rate period is an inside controlled mechanism. More details about the drying mechanism will be discussed later in the literature.

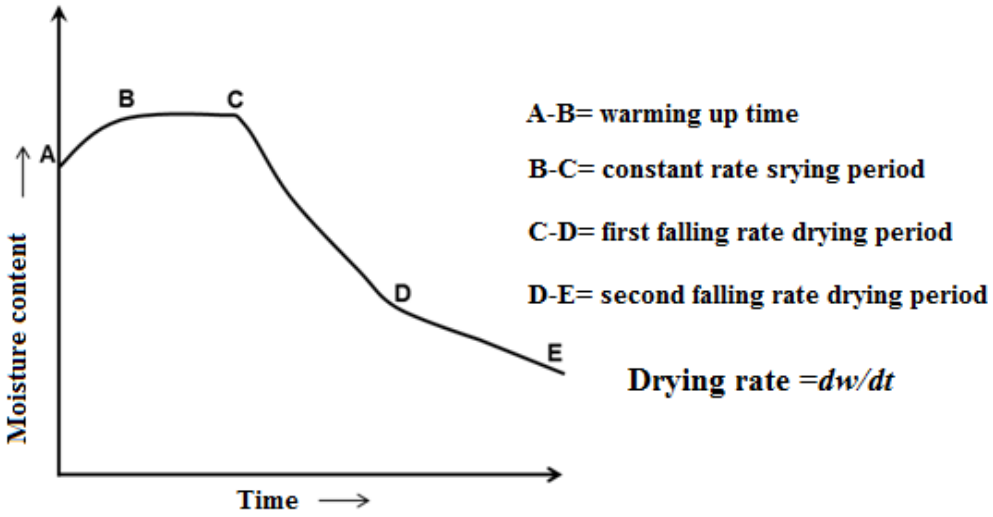


Figure 2.6. A moisture transfer, showing constant drying and falling rate period during drying. Extracted from (Shiksha, 2012).

Drying of fresh produce is one of the oldest methods used to address the issues faced with the post-harvest losses of fresh produce. It has been used as a food preservation technique, due to its ability to reduce moisture content, which inhibits the growth of spoilage microorganisms such as bacteria, yeast, and mould. It is also known to decrease the metabolic enzyme activity, and can produce value-added fresh produce.

Different drying technologies have been applied in the food industry, however, challenges have been faced with each of them, due to thermal energy required for dehydration, energy efficiency, and product quality in terms of nutrients, sensory properties, and functional properties (Sagar and Kumar, 2010). Many convective thermal technologies such as the oven, can result in a product with poor qualities (Adak et al., 2017). This is due to changes in physical properties, such as colour, texture, size as well as chemical changes such as loss of heat-sensitive nutrients, and flavour (Adak et al., 2017).

2.5.1. Drying mechanism

Different drying methods such as freeze dryer, convective dryer, and electromagnetic dryer have different drying mechanisms. The main mechanism of moisture transfer is by diffusion, which it can either be capillary, surface, liquid or vapour diffusion (Onwude et al., 2018). Most dried agricultural products are hygroscopic, and therefore, drying takes place by diffusion on the surface pores, and these products dry at a constant rate and subsequent falling rate and drying stop when the equilibrium is established (Inyang et al., 2018). Moisture transfer from fruits and vegetables is described by a thin layer drying model. Onwude et al (2016) explained

it as a layer of material fully exposed to an airstream during the drying process, this model also assumed the constant temperature of the material during drying, provided that the temperature and relative humidity of the drying chamber are in the same thermodynamic condition during the drying process (Onwude et al., 2018).

Thermal drying of food materials shows different drying periods, this happens because of moisture transfer from different regions of the food, from surface moisture to internal moisture, at some instances involving the critical or bound moisture. A convective oven drying process will have three drying periods including a constant rate period, first falling rate period, and second falling rate period (Onwude et al., 2019). The drying rate period observed are as a result of moisture transfer from different regions of the food material during drying. The surface moisture is the one removed first during drying by hot air, once the surface moisture is removed, the internal moisture is diffused to the surface by osmotic gradient replacing the evaporated surface moisture (Chua et al., 2019). The heat transfer by convection oven drying method is initiated at the surface of the food material, and as moisture is evaporated the heat is gradually transferred to the internal area. The exchange between heat and moisture transfer, where heat is being absorbed by the food material while moisture is released at the same time, could be the reason for the different drying periods (Figure 2.6).

In the case of other drying methods such as microwave and infrared, the constant falling rate period is not observed, and the only observed drying period are the first falling rate period and the second falling rate period, and in some cases, only the second falling rate period can be observed (Onwude et al., 2019). The drying mechanism of microwave and infrared have both the moisture and heat leaving the food material. Microwave and infrared emit electromagnetic radiation. The radiation creates an electric field which causes dipole rotation and vibration of the water molecules (Figure 2.7). The rotation and vibration generates thermal energy, which causes the evaporation of the water molecules, therefore resulting in both heat and moisture transferred out of the food material (Feng et al., 2012).

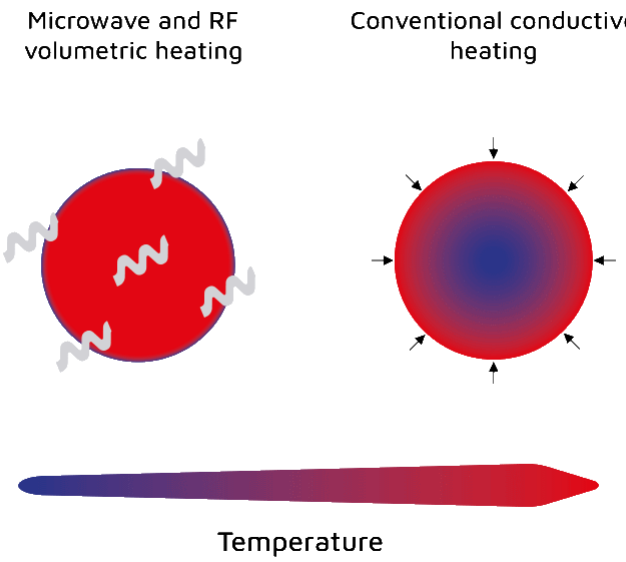


Figure 2.7. The difference of heat transfer between conventional heating and electromagnetic radiation during drying. Source (Sairem 2020)

To clearly understand the mechanism of drying, a curve for drying rate and temperature as a function of time is generally plotted (Figure 2.6). Inyang et al (2018) explains that, "during the constant rate period, the initiation of drying begins, whereby free water is removed from the surface of the food material, and as the equilibrium air temperature is higher than the temperature of the product, during this period the surface moisture will be evaporated, until the product surface attains equilibrium. The initiation of the first falling rate period begins once all the surface and free water is removed from the product and the surface of the product appears to be dry or forming a film. During the first falling rate period, the transport of moisture is controlled by the combination of both external and internal resistance to heat and mass transfer. The first falling rate takes place when the moisture content has decreased to its critical level, as drying continues the second falling rate phenomena will start taking place, where critical moisture is removed from the product and product appears to be in its dry form". Circumstances such as temperature, moisture content, and product structure influence the falling rate periods (Onwude et al., 2018). The change in different drying periods is influenced by the change in product temperature, as drying time increases, the product temperature is also increasing, leading to a change in moisture removal and drying periods.

2.5.2. Drying Kinetics

Drying kinetics help in understanding the drying mechanism of the drying technology and can predict the drying time, energy cost of the drying process, and moisture equilibrium relationship (Chanpet et al., 2020). Other factors such as the nature of the food, drying temperatures, food composition, and initial moisture content, are known to affect the rate of moisture transfer.

Shyam et al (2008) reported that moisture transfer can be in two mechanisms, *viz* liquid water transport, which consists of capillary flow, surface diffusion, and liquid diffusion; as well as water vapour mechanism, which consists of Knudsen diffusion, mutual diffusion, poseuille flow, and condensation water vapour. In food, drying surface diffusion has been reported as a well-known moisture transport, where moisture can be transported to the surface of the products and be evaporated, or evaporated internally at liquid-vapour interface and be transported as vapour to the surface of the food material.

Moisture transport mechanism has many characteristics such as pressure diffusion, thermal diffusion, forced diffusion, and ordinary diffusion. The diffusion mechanism is universally assumed when drying food materials, where the rate of moisture migration is defined by an effective diffusivity value D_{eff}, and this value is derived from Fick's second law of diffusion as shown in formula 1 below.

$$\frac{\partial m}{\partial t} = D_{eff}\,\nabla^2 m \qquad (1)$$

Where m is the local moisture content on a dry basis, t is the time (s), and D_{eff} is the moisture diffusivity. Fick's second law of diffusion assumed that if the food product is unidimensional, it has a uniform initial moisture content, and the internal moisture movement is assumed as the major resistance, with no shrinkage in the product during drying and negligible external and internal heat transfer effect. This does not hold true for all food materials and drying technologies. To have a holistic understanding of the drying kinetics, parameters such as slice thickness, the geometry of the food material need to be considered, and this is resolved by the Crank and Luikov equation as shown in formula 2 below.

$$m* = \frac{m-m_e}{m_o-m_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)}\,exp\left[-(2n+1)^2\frac{\pi^2 D_{eff}t}{L^2}\right] \qquad (2)$$

Where m^* is the dimensionless moisture ratio, m is the average moisture content of the wet material on a dry basis, m_o is the initial moisture on a dry basis (kg/kg), m_e is the equilibrium moisture content on a dry basis (kg/kg), L is the thickness of the slab (mm). There are many other theories relating to the drying mechanism of thin slices showing that there is no single solution towards addressing the drying kinetics problems. Food materials can be dried with different shapes and thicknesses. Therefore, this requires mathematical solutions to accommodate different shapes, Thao and Noomhorm (2011) reported that these parameters can be solved using equation 2 above for infinitive slab, as well as equation 3 below for spherical shape.

$$MR = \frac{6}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{n}exp(-n^2\pi^2\frac{Defft}{R^2}) \quad (3)$$

Where MR is the local moisture ratio, R is the radius of the slice (m), and n is the number of constant. The information is necessary for determining which drying model will be used to determine the effectiveness of the drying method. In this regard, the drying model assists to determine the drying period and also provides some information about the drying mechanism. Further information about the drying models will be discussed.

2.5.3. Modelling for the drying process

To understand the drying mechanism and the period of drying, it is important to come up with models which will help to predict the drying period before it starts (Feng et al., 2012). These models have been used for the different drying processes and different food materials. As much as the models can be used for the same food material and drying technology, different parameters can give different results for each model. Table 2.3 shows different models, which have been used to predict the drying period for the different drying processes.

Table 2.3. Some of the semi theoretical drying models used for determining drying kinetics and modelling during drying.

Model	Analytical expression
Lewis	MR= e^{-kt}
Page	MR= e^{-kt^n}
Henderson and Pabis	MR= a e^{-kt}
Wang and Singh	MR= 1 + at + bt^2
Logarithmic	MR= a e^{kt} + c
Two-term	MR= a $e^{-k_1 t}$ + b $e^{-k_2 t}$
Two-term exponential	MR= a $e^{-k_1 t}$ + (1-a) $e^{-k_2 t}$
Modified Henderson and Pabis	MR= a e^{-kt} + b e^{-gt} + c e^{-ht}
Midilli	MR= a e^{-kt^n} + bt
Approximation of diffusion	MR= a $e^{-k_1 t}$ + (1+a) $e^{-k_2 t}$
Verma *et al*	MR= a $e^{k_1 t}$ + (1-a) $e^{-k_2 t}$

Where MR = (M – Me)/ (Mo – Me), moisture ratio (dimensionless); a, b, c, g, h, k, k_1, k_2 and n = drying constants; t = drying time (hours). Extracted from (Thao and Noomhorm, 2011)

There are many models developed every year by different researchers, some models are old but being modified, this brings questions about the reliability of the old models compared to the newly developed models or modified old models. The models are derived by using a thin-layer drying model, this model is divided into three phases which are: theoretical, semi theoretical, and empirical models (Akpinar, 2006, Inyang et al., 2018). The theoretical models account only for the internal moisture transfer resistance, they are reported to be inadequate, due to errors that are generated from the model. Inyang et al (2018) explain that the theoretical model provides a better understanding of the moisture transfer. However, they make too many assumptions, which creates errors and limits their application in designing the dryers.

The semi theoretical and empirical models are the ones mostly used for modelling than the theoretical model (Ertekin and Firat, 2017), the empirical model neglects the fundamental drying process, resulting in parameters with no physical senses. According to Inyang et al

(2018), the empirical model gives a better fit to the experimental data without any understanding of the transport processes involved. The other limitation of the empirical model is that it neglects the basics of the drying process. It can only explain the drying curve, however, it cannot explain the process which takes place during drying. The empirical models depend largely on experimental data and give limited information about the heat and mass transfer during the dehydration process (Inyang et al., 2018).

For thin-layer drying modelling, semi theoretical models are mostly preferred over the empirical models because it is believed that the semi theoretical models consider both external and internal resistance to moisture transfer (Onwude et al., 2018). The semi theoretical models can be reliable considering that they put into account factors that can influence the drying behaviour, and some can even describe the drying mechanism of other drying methods. Semi theoretical models work perfectly when drying parameters such as temperature, relative humidity, air velocity, and moisture are in the range for which the model is developed (Inyang et al., 2018). These models were derived from a series of Fick's second law and were based on Newton's law of cooling applied to mass transfer. These laws accept that the conditions are isothermal and moisture resistance is restricted to the surface of the food material (Inyang et al., 2018). Even though they can show some reliability, more research still needs to be conducted to test with different drying conditions for drying fruits and vegetables as well as other food materials. This is because food has different components, which show different thermal conductivity properties as well as dielectric properties, and models seem to be neglective of these intrinsic factors.

The drying models work for different drying technologies, however, these are dependent on the source of heat, temperature, and geometry of the dried material. The models provide drying curves that help in understanding the drying mechanism. The drying curves are plotted using moisture ratio against time to show drying rate, rehydration rate, and decrease in moisture ratio over time (Touil et al., 2014). The experimental moisture ratio can be used to determine or predict the drying period. The selection of the drying model is based on the coefficient of determination (R^2), chi-square (X^2), and root mean square error (RMSE). For a model to be considered fitting, the R^2 should be the highest, with the lowest X^2, and lowest RMSE (Srikiatden and Roberts, 2007).

Onwude et al (2019) used IR and hot air drying methods to determine a suitable drying model for drying sweet potato slices, and in their studies, they found that Newton/ Lewis model was

suitable for the IR drying method, and from the drying curve, they managed to describe the different drying phases, showing the mechanism of drying, they also found the Page model to be suitable for hot air drying. Thao and Noomhorm (2011) also informed that the Verma model was suitable for drying sweet potato starch at 55°C using hot air tray drying, while the Page model was more fitting for drying the same sweet potato starch with the same drying method at 65°C. The logarithmic model was reported to be fit for predicting the drying time of sweet potato starch at 65°C. From Thao and Noomhorm (2011) studies, it can be seen that changes in parameters such as temperature, can affect the drying mechanism and therefore will need a new model, it also shows that models only work for specific conditions and not for all the drying conditions, even though the drying method can be the same.

Drying methods such as microwaves are shown to fit in different models such as Parabolic, Lewis, Logarithmic, Page, and Henderson and Pabis models. However, this depends on the power levels of the microwave, and the food material's geometrical shapes. Ernest Abano (2020) looked at the model which was fit for drying a blanched OFSP by microwave at power levels (385 W and 697 W) and hot air at 70°C, and from the study, where Page, Henderson, and Pabis, as well as logarithmic models, were used. It was concluded that the Page model was the best fit to predict drying time for blanched microwave dried OFSP, while Logarithmic was a good fit model for blanch assisted hot air drying at 70°C. The study shows that power levels and temperatures affect selecting a best-fitting model as they influence the moisture diffusion rate from the sample (Abano, 2020, Marzuki et al., 2020). The results obtained by Abano (2020) are comparable to those obtained by Marzuki et al (2020), where they looked at the effects of blanching purple sweet potato and drying it by the microwave-vacuum oven. From their studies, they also found the Page model and Logarithmic model to be fitting models for predicting the drying period.

2.6. Different drying technologies

This part of the review will focus on the use of microwave, infrared, and freeze-drying methods as compared to the traditional convection oven.

2.6.1. Oven drying technology

Oven drying has been used for many years to determine the moisture content of samples, from plant to soil materials. Because parameters such as temperature and drying environment can be controlled, it has attracted the food industry as it offers a much diverse application. Oven drying temperatures need to be carefully selected based on the type of the food being dried to avoid

over dehydrating the food material, which will result in caramelization, tissue rupture, and overall loss of functional properties of the final product due to long drying periods (Guo. et al., 2019). Owing to the lengthy period of dehydration, oven drying is not energy efficient, and it is time-consuming (Thao and Noomhorm 2011). There are different types of oven drying such as vacuum oven, rotary oven, vertical towers, and convection drying oven. In this study, the focus will be on the convective drying oven.

Parikh (2014) asserts that the drying mechanism by the convective oven is done by introducing dry air in the drying chamber, which removes the moisture from the surface of the food material (Figure 2.8). Due to the moisture equilibrium which needs to be sustained by the food material, the inside moisture has to migrate to the outward of the food material, which will eventually be conceded out by the new hot dry air. This progression continues until the food material is finally dry and has no free moisture to shield the surface. This is a heat and mass transfer route, where heat is transmitted to the product to vaporise the moisture, and mass is shifted as a vapour into the surrounding air.

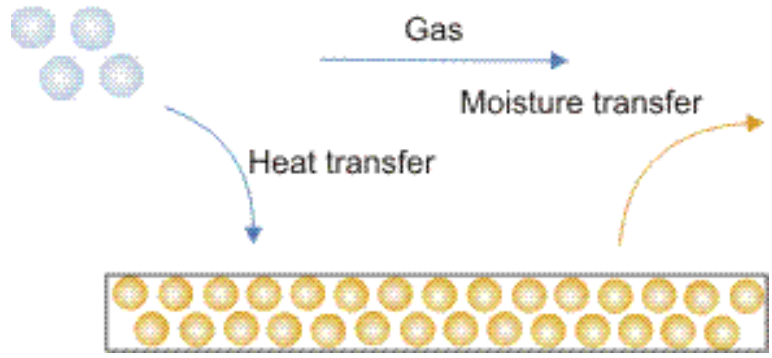


Figure 2.8. Mechanism of moisture transfer by convective drying process. Source: (Ozalp et al., 2011)

The drying of fresh produce by oven has been used for many years. It brings the advantage of the ability to control the temperatures from low to high, enabling the drying of different types of food materials (Wilson et al., 2002). Oven drying has also been used in the processing of fresh produce for either drying, preservation, or moisture analysis (Coklar et al., 2018). The temperature applied during drying affects some of the heat-sensitive nutrients, therefore, it can result in the degradation of those nutrients. Fruits and vegetables are known for their health-promoting factors due to bioactive compounds and phytochemicals such as phenolic compounds, flavonoids, carotenoids, and vitamins, as a result, oven drying can affect those compounds as some of them are heat sensitive (Mbondo et al., 2018). In a research done by Mbondo et al (2018), an eggplant was dried under different drying temperatures (50°C, 60°C,

and 70°C) and drying at 70°C had a higher retention of phenolic compound as compared to drying at 50°C and 60°C (Table 2.4). The high retention is due to the fast drying rate at high temperature, which limits the exposure time of the phenolic to the drying temperature.

Table 2.4. Effects of different drying methods on some of the nutritional content of fresh produce

Raw material	Drying method and condition	Main effect of drying condition	References
African eggplant	Solar, oven at (50, 60, and 70°C), vacuum (50, 60, 70°C and 60 mbar pressure) and freeze-drying (-47°C, 0.055 mbar pressure, for 72 hours)	Oven drying at 70°C retained total phenols at 761.50 mg/100 g as compared to fresh samples which had 813.77 mg/100 g Oven drying at 70°C had the lowest β-carotene retention of 1.53 mg/100 g as compared to 14.75 mg/100 g of fresh sample	(Mbondo et al., 2018)
Hawthorn (crataegus orientalis) fruit	Freeze-drying (-110°C, 2.0 mbar pressure), oven drying (60°C), microwave combined oven dryer (360 W for 5 minutes, oven at 60°C)	Freeze-drying had total phenolic content of 12.64 mg GAE/g, oven had total phenolic of 9.68 mg GAE/g and combined microwave-oven had total phenolic content of 10.45 mg GAE/g as compared to 13.36 mg GAE/g total phenolic content of fresh sample	(Coklar et al., 2018)
Orange-fleshed sweet potato	Oven (65°C, 9 hours), microwave oven (800 W, 50 Hz, 5 minutes), freeze-drying (-50°C, 0.006 mbar, 36 hours)	Freeze-drying had a higher β-carotene content of 55.3 mg/100 g dry basis, microwave reported lower β-carotene of 28.3 mg/100 g dry basis, oven drying reported 30.5 mg/100 g β-carotene content	(Yang et al., 2010)
Raw and ripe papaya (carica papaya l.)	Oven drying (60°C, 24 hours), freeze-drying (-50°C, 0.12 Toor, 24 hours)	Freeze-drying had higher phenolic compound retention of 70.2 ± 2.30 mg GAE/g for raw and 141.7 ± 3.21 mg GAE/G for ripe, while oven had lower retention of 52.40 ± 1.27 mg GAE/g for raw and 21.10 ± 0.32 mg GAE/g for ripe	(Annegowda et al., 2013)

Heat-sensitive nutrients such as β-carotene are some of the most studied nutrients in literature. Studies have shown that the β-carotene is isomerized to *cis-β*-carotene when exposed to heat for a longer period (Knockaert et al., 2015). In some cases when lower temperatures (< 50°C) are used in the oven for drying, it can take a longer time to dehydrate the food materials. The yellow-fleshed sweet potato has been reported to have a 40% β-carotene retention after being dried by oven at a temperature of 80°C, while microwave has been reported to have over 75% β-carotene retention at a power level of 2.0 W/g (wet basis) (Yan et al., 2013). Oven drying can preserve the food material by reducing sufficient water content (thus reduce water activity), however, it comes with the risk of losing heat-sensitive nutrients when high temperatures are used during drying (Onwude et al., 2018). When using an oven to dry fresh produce it is important to consider which drying temperature to use as well as drying period, as these parameters can affect the quality of the product in terms of nutritional content (Hihat, 2017).

Drying is known to affect the cell wall polysaccharides, causing irreversible modification and can affect the original structure as well as the physicochemical properties of the dietary fibre. Research done on date fruits by Borchani et al (2011) revealed that when the fruits were dried at higher temperatures (50°C and 60°C), their dietary fibre had lower water holding capacity as compared to the one dried at 40°C using an oven. The higher drying temperatures by the oven caused structural changes of some of the dietary fibre and protein denaturing, which leads to loss of water holding capacity. Not only do non-starch polysaccharide are responsible for physicochemical properties of fresh produce, some studies have shown that starch is one of the components which also partly take in these properties (Horstmann et al., 2017).

Sweet potatoes dried at higher temperatures (70°C) had higher pasting viscosity, for example higher peak viscosity than the ones dried at lower temperatures (60°C) (Ruttarattanamongkol et al, 2016). However, another study done by Haruna et al (2019) shows that the highest peak viscosity was achieved at a temperature of 40°C, which is different from what Ruttarattanamongkol et al (2015) have reported. Ruttarattanamongkol et al (2016) explains that the high viscosity of the flour can be associated with the high pasting temperature, and further intricate that the high pasting temperature is associated with high amylose content, which is resistance towards swelling. The study by Haruna et al (2019) indicates that an oven-dried sweet potato had improved solubility index, water holding capacity, oil absorption capacity as well as an improved swelling capacity when dried at 45°C. The properties can be due to low

drying temperature as such condition did not cause any damage to the flour properties, for example gelatinization of starch.

During convective drying, a rubbery glassy transition (phase transition) of the food material takes place, also known as case hardening (Gulati and Datta, 2015). The formation of case hardening, together with the deformation of the food material due to migration of moisture, plays a major role in determining the final physicochemical properties of the food material. Most researchers have reported that drying of fresh produce by convective process (solar, oven, or hot air) results in the formation of case hardening, which is linked to shrinkage of the food material (Touil et al., 2014, Wilson et al., 2002). Case hardening is argued to occur at high-temperature as the outer part of the fresh produce become hard, and making it difficult for the moisture to escape this, which can result in a poor dehydrated product with moisture trapped inside (Siebert et al., 2018).

The poorly dehydrated product results in poor functional properties of the final product. A study done by Vishwanathan et al (2010) where oven and infrared (both at 80°C) were used for drying carrots and potatoes have reported that the infrared dried samples had a higher rehydration ratio of 7.21 ± 0.03 for potato and 7.57 ± 0.06 as compared to oven samples which reported 7.03 ± 0.04 for potato and 7.23 ± 0.02 for carrots. Vishwanathan et al (2010) also conveyed that the microstructure of the oven-dried sample was more damaged and flattened as compared to the intact and porous infrared dried samples. Oven drying does have its effect when looking at physicochemical properties of the fresh produce, the temperature is one parameter that should be considered as the higher temperature can result in case hardening on certain types of fresh produce. Therefore considering what type of fresh produce you are drying is of utmost importance, as it can also help give an idea of which temperature to consider, and other parameters such as lice thickness which can affect the drying rate.

2.6.2. Microwave drying

Microwave is an electromagnetic drying technology, with a frequency range of between 300 MHz and 300 GHz (Feng et al., 2012). The heat from the microwave is generated by electromagnetic radiation (Figure 2.7), when there is an interaction between the microwave and the medium by which part of the electromagnetic energy is dissipated volumetrically in the form of heat (Feng et al., 2012). The electromagnetic heat energy of the microwave generates vapour inside the food material, which then spreads through an internal pressure gradient (Cui et al., 2008). The dielectric properties of the food materials are the ones that enable them to

convert electromagnetic energy into heat energy (Guo et al., 2017). During drying by microwave, the radiation frequency causes the dipoles in water to align themselves to the electric field, but due to the high frequency produced by the electromagnetic radiation, it creates oscillation (Yan et al., 2013). The oscillation causes a change in the electric field from positive to negative and vice versa, and as the dipoles follow this oscillation, frictional heat is generated, which results in heating of the water molecules and ions in the food sample to produce heat until the water evaporates (Si et al., 2016).

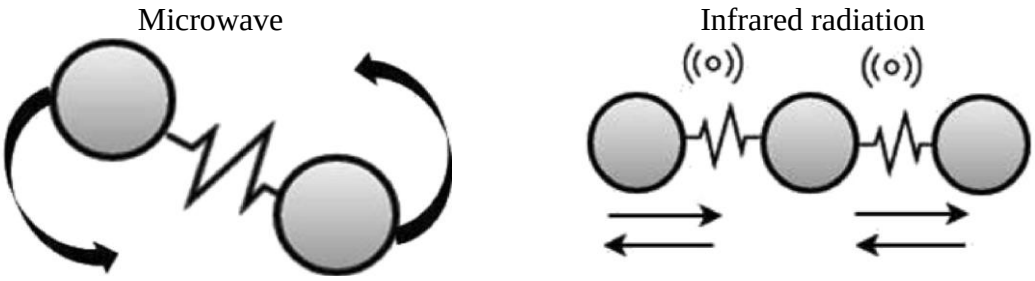


Figure 2.9. Mechanism of energy absorption by electromagnetic radiation (Sakare et al., 2020)

The rapid drying by microwave has great benefits such as being energy efficient, producing a product with lower shrinkage (Figure 2.12), higher bulk density, and higher rehydration ratio (Guo et al., 2017). Dehydration of fresh produce using a microwave can also help in retaining high levels of bioactive compound, colour, decrease anti-nutritional factors, increase in-vitro digestibility of proteins and retain antioxidant activities of bioactive compounds, such as phenolic acids, anthocyanin, and carotenoids (Asioli et al., 2019). There are different types of microwave drying such as vacuum-microwave drying, hot-air-microwave drying, microwave-far infrared combination, microwave convective drying, and microwave-freeze drying (Guo et al., 2017). The combination of a microwave with other drying methods came as a result of improving the product quality, drying rate, as well as avoiding overheating and scorching of the product, which can result in leaching of nutrients and poor product quality (Parit and Prabhu, 2017).

Microwave is acknowledged for its effective drying rate as well as producing high-quality products. By high-quality product, it can be assumed that it also covers the nutritional part, bioactive compound, and phenolic compound form part of the nutrients. Drying of fruits is known to concentrate phenolic compounds and other bioactive compounds, which can increase their antioxidant activity, as well as the fibre content (Ozcan et al., 2020). The dried kiwi and Pepino fruits, in a study done by Ozcan et al (2020) showed that the microwave dried fruits

had higher phenolic content than the ones dried by an oven. A vacuum-microwave dryer was used for drying sour cherries by Wojdylo et al (2013). In their study, phenolic compounds were being analysed, and they also found that the phenolic compounds were significantly higher, when compared to the lower values they obtained by drying with an oven.

Table 2.5. Effects of oven and microwave drying methods on phenolic content, β-carotene and colour properties of some fruits and vegetables

Dried sample	Drying conditions and method	β-carotene content (µg/g)	Phenolic content (mg/100 g)	*L**	*a**	*b**
Kiwi fruits[a]	Oven drying (70°C, 20 h)	N/A	1034.23 ± 0.003	N/A	N/A	N/A
Kiwi fruits[a]	Microwave (720 W, 5 min)	N/A	1117.32 ± 0.009	N/A	N/A	N/A
Carrots[b]	Oven drying (60°C, 6 h)	371.40 ± 15.09	N/A	38.58 ± 0.68	11.11 ± 0.65	12.48 ± 0.53
Carrots[b]	Microwave (175 W, 4 h 30 min)	388.34 ± 26.56	N/A	39.96 ± 0.08	11.14 ± 0.28	13.20 ± 0.08
Purple-fleshed sweet potato[c]	Oven (70°C, 500 min)	N/A	200.3 ± 0.32	52.96 ± 1.29	12.90 ± 0.19	1.48 ± 0.49
Purple-fleshed sweet potato[c]	Microwave (450 W, 12 min)	N/A	340.12 ± 0.36	48.79 ± 1.47	22.16 ± 0.34	-10.69 ± 0.83

Sources: (Marzuki et al., 2020[a], Özcan et al., 2019[b], Zhao et al., 2014[c]), N/A (not available), W (Watts), GAE (Gallic acid estimation)

Siani et al (2014) reported higher ascorbic acid and carotenoids from Moringa leaves dried with microwave, than those dried by the oven and solar. Microwave drying can also result in the isomerization of β-carotene due to its heat-generating effect during drying, and this can result in a loss of *all-trans-β*-carotene (Zhao et al., 2014). However, the loss is not as high as those which result from drying by convective drying method. This was demonstrated by Zhao et al (2014) when carrots slices were dried using an oven and microwave, the results show that there was a higher reduction of β-carotene from samples dried by the oven as compared to the microwave dried samples.

In a study done by Sebben et al (2017), orange-fleshed sweet potato was dried by oven and microwave. The microwave samples had a higher crude protein (5.75%) dry basis, crude fibre (3.46%) dry basis, and ash content (4.10%) dry basis as compared to the oven-dried samples. The deep penetration of electromagnetic radiation into the food material can result in structural changes of the dried samples, which can end up affecting the texture of the final product (Askari et al., 2016). The deep penetration of electromagnetic radiation can cause inter-cellular gaps and this was reported by Askari et al (2016) where apples were dried by an oven. They showed that the apples had a softer and less firm texture due to the effects of the microwave. A study by Aamir and Boonsupthip (2017) where okra was dried by the microwave showed that the texture of the dried sample increased at different microwave power, which became firmer and formed a crust-like texture. The flavour of the okra at a microwave power level of 800 W was reported to be significantly better than other power levels (Aamir and Boonsupthip, 2017).

Microwave prevent case hardening during drying (Giri and Prasad, 2009). The microwave radiation can directly cause water evaporation from the inside of the food material, which prevents condensing of water molecules within the plant cell (Figure 2.10), decreasing drying time and preventing crusting (Ibrahim et al., 2012). The drying of mushrooms by Giri and Prasad (2009) by oven and microwave, showed that the mushrooms dried by microwave were less hard compared to the oven-dried samples. The authors (Giri and Prasad, 2009) also did a consumer preference study as part of the sensory study for the mushroom, and they reported that microwave samples received a significantly higher ratings than oven products for colour, texture and overall acceptability.

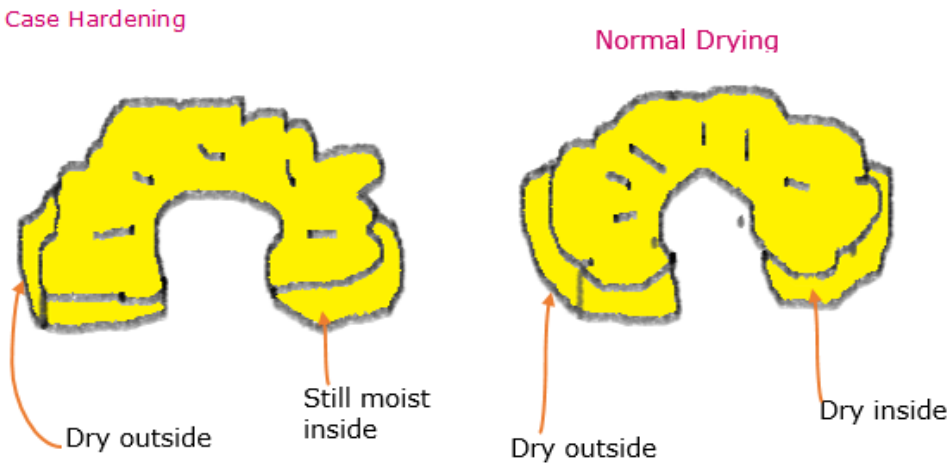


Figure 2.10. Formation of case hardening during convective drying compared to normal drying. Extracted from (Athukorala, 2019)

Microwave drying causes changes in the microstructure of the product, which can alter the physicochemical properties (Zhao et al., 2014). The drying mechanism of the microwave has been reported to result in a product with improved functional properties such as high rehydration ratio, high oil absorption capacity, and improved rheological properties of the orange-fleshed sweet potato flour by Haruna et al (2019). The volumetric heating caused by microwave, which dehydrates the food material from inside out, and produces a more porous structure cause the physicochemical properties of the final product to be improved (Guo et al., 2017). Yan et al (2013) described that drying of orange-fleshed sweet potato by microwave-vacuum and the microwave-spouted bed had a higher rehydration ratio, compared to the air-dried sample. The authors suggested that the rapid evaporation of moisture during the microwave-vacuum and microwave-spouted bed drying process has induced the formation of a porous structure, which then favours rapid rehydration of the product. Giri and Prasad (2009) also reported a higher rehydration ratio of the mushroom, which was dried by oven and microwave.

Microwave drying offers many benefits, it is one of the novel technologies, which can be used to improve the physicochemical properties of dried fresh produce, more especially when used in combination with other drying technologies. There is a lack of study in terms of the rheological properties of the dried samples, most researchers focus on the rehydration capacity of the dried sample when doing their physicochemical property analysis. Therefore, a thorough study still needs to be done to understand holistically the effect of microwave drying on rheological properties of the dried samples.

2.6.3. Infrared (IR) drying

Infrared is one of the electromagnetic radiation between the visible region and the microwave (Aboud et al., 2019). Infrared has three types of rays, which are Near-IR, mid-IR, and far-IR, these rays differ according to their wavelength (Figure 2.11), and therefore they produce different amounts of energy (Doymaz, 2012). The near-IR is commonly used in the dehydrating of food materials because the conversion of IR radiation through water is at the near-IR, which has a shorter wavelength, while at the far-IR it is absorbed on the surface (Riadh et al., 2014). The shorter wavelength IR is reported to dry thicker food materials better than the longer wavelength IR (Si et al., 2016). Infrared drying uses energy from electromagnetic radiation emitted by a hot object, to directly heat the bulk materials of the polymer. The electromagnetic radiation causes internal heating and molecular vibration (Figure 2.9). Therefore heats the bulk material and removes internal moisture. A stream of cooler ambient air surrounds the granule and the internal heat drives the moisture out into the cooler air stream that removes it from the food surface (Kent, 2019).

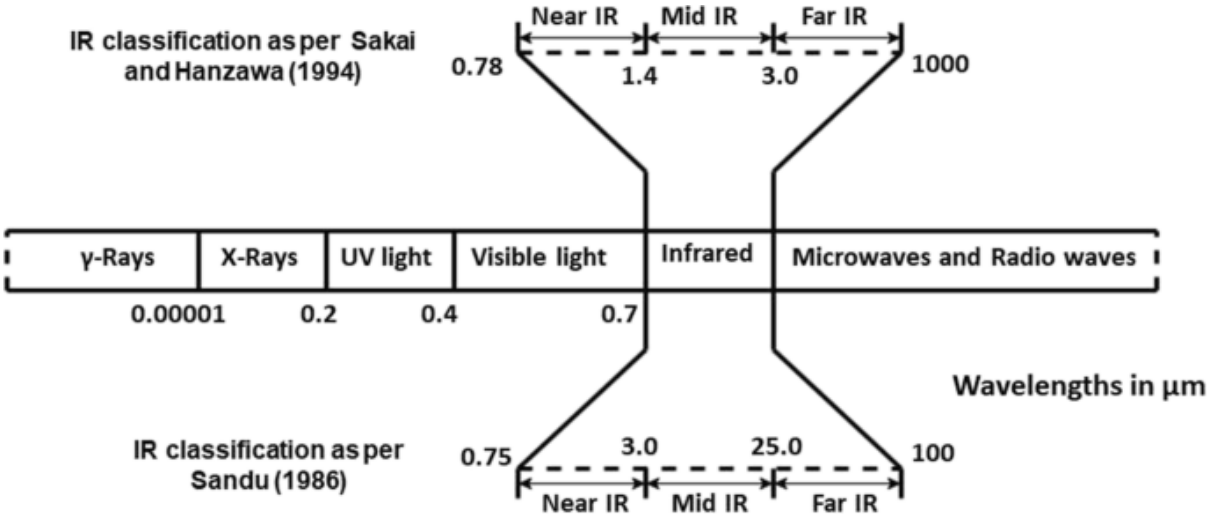


Figure *2*.11. Classification of electromagnetic waves (Sakare et al., 2020).

Infrared drying appealed to the food industry because it offers great advantages over convective drying technologies. These advantages include that it is energy efficient due to its fast drying rate, it has a great heat sink, gives the product improved sensory and physicochemical properties, and does not cause great loss of heat-sensitive nutrients. (Aboud et al., 2019, Si et al., 2016, Riadh et al., 2014). Infrared drying has been used in many studies of fresh produce such as onion, apple, sweet potato, strawberries, and cherries to understand how it affects the quality of the final product.

Infrared drying is known for its properties of evenly distributing the radiation to the centre of the food material materials as well as being able to maintain and retain natural active compounds (Zeng et al., 2019). Bioactive compounds such as phenolic compounds have been reported to be unaffected by infrared radiation. Drying strawberries by infrared has been reported to have a significant increase in the total phenolic content of the samples, which can be linked to an increase in infrared power (Adak et al., 2017). Increasing the power of the infrared also increases the temperature during drying and the temperature affects the browning index, which is caused by reactivity between sugars and amino acids (Adak et al., 2017). The rapid drying facilitated by infrared has been reported to retain the Vitamin C content of dried Kiwi fruits by Zeng et al (2019). The authors reported that an increase in infrared temperature from 120°C to 160°C caused an increase in Vitamin C content from 117.14 ± 6.54-129.95 ± 7.49 mg/100 g.

Kocabiyik et al (2014) in their study of drying tomatoes with infrared have looked at how the β-carotene, vitamin C, and lycopene content was affected by the drying method at different intensity power. The authors reported that there was a substantial increase of lycopene by 29-364% when compared to the lycopene content of fresh samples. This was attributed to the ability of the infrared radiation to release lycopene from the plant matrix, through weakening the cell wall bond forces by radiation energy. They also reported a reduction of β-carotene content by 51-5% when compared to the fresh tomatoes due to the heat isomerization of *All-trans*-βcarotene to *cis-β*-carotene by thermal energy. The reduction was increasing with increasing infrared intensity (Kocabiyik et al., 2014). The vitamin C content of the dried tomatoes was also reported to be lower than the vitamin C of the fresh samples by Kocabiyik et al (2014).

The rapid heat generation by infrared provides many benefits such as retention of the bioactive compound, heat-sensitive vitamins, and minerals. Nonetheless, other nutrients such as Vitamin C and β-carotene are highly sensitive to heat and have been reported to decrease during drying, even when the drying time is shortened by infrared. Most nutrients such as lipids, carbohydrates, and proteins have not been researched thoroughly to fully understand how they are impacted by infrared.

The infrared dried product can result in changed sensory properties, mostly in terms of colour and texture. Bi et al (2014) showed that drying of jujube fruits to produce jujube flour changed the colour of the flour. The authors informed that the high sugar content of the fruits could have

been reacted in a Maillard reaction, which generated the dark compounds by sugar and amino acids. Zhan et al (2020) noted a colour change when drying sponge gourd fruit with infrared. It was found that samples dried at 50 to 60°C have a greater colour change than samples dried at 65°C. The author suggests that samples dried at lower temperatures might have changed colour due to an increase in the enzymatic browning as a result of the presence of polyphenol oxidase and peroxidase, while samples dried at a higher temperature might have colour change due to shorter drying time. The same results were recorded by Zeng et al (2019) when they were drying kiwi fruits by infrared. There was an increase in the browning index of the kiwi fruits, which was related to an increase in the drying temperature and in turn increased the mailer reaction between the sugars and amino acids of kiwi fruits. Adak et al (2017) indicated a reduction of chroma values (*L*, a*, and b*),* after drying strawberries using infrared on different power levels. It was noted that as the infrared power increased, there was more reduction in the chroma values.

Infrared drying technology has the benefits of improving the texture properties of the dried product, due to its ability to heat the product from inside, while improving the porosity of the final product (Antal and Kerekes, 2016). The change in the cell wall structure by infrared radiation improves the texture firmness of the product. Wu et al (2018) dried potato chips using infrared to determine their crispness and found that the potato chips' hardness increased by 0.96-fold, with an increase in thickness from 0.6 to 1.3 mm. More so that the sample with less thickness was crispier than the thick samples, this was attributed to the deep penetration of infrared on thin samples, which made them more porous and lost more moisture much quicker. Antal and Kerekes (2016) reported an increase in firmness of apple slices that were dried by freeze dried-infrared.

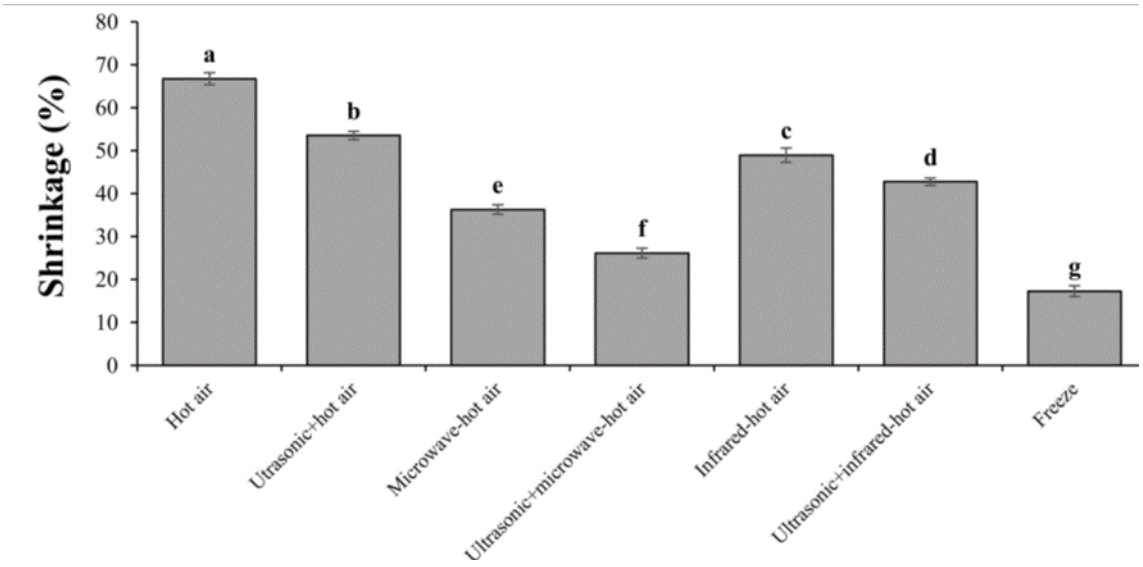


Figure 2.12. Shrinkage of dried hawthorns affected by different drying methods. Bars with different letters differ significantly from each other at $p < 0.05$ as determined by the LSD test. Source (Abbaspour-Gilandeh et al., 2021).

Some of the dehydrated food products are normally hydrated before being consumed, therefore, it is important to understand the rehydration capacity of the dried product. The rehydration ratio helps in understanding physical and chemical changes, which happened during the drying of the product (Briki et al., 2019). A comparative study which was conducted by Briki et al (2019) of comparing convective drying and infrared drying effects on rehydration capacity of arils revealed that the infrared dried arils had a higher rehydration capacity than convective dried arils, mainly at 60°C than at 50 and 70°C. The authors suggest that structural changes causing a loss of hydrophilic character were more extensive than these latter two temperatures such as an increase Maillard browning and thermal denaturation at 70°C and increase formation of polyphenol-based precipitate at 50°C.

Antal and Kerekes (2016) specified an increase in the rehydration capacity of apple slices dried by infrared-assisted freeze-drying and that the rapid heating with infrared and quicker diffusion of water vapour within the sample might be facilitating the material to retain its porous structure, and therefore increases its ability to absorb more water during rehydration. The other study where carrots and potato were dried by two different methods, which is Hot air, infrared, and a combination of the two methods, done by Vishwanathan et al (2010) exhibited that the rehydration ratio of hot air-dried samples was lower than those of infrared dried and combined drying methods. The combination of infrared and hot air resulted in a higher rehydration ratio than infrared alone, the rapid and uniform heating by infrared radiation, and the absence of case hardening might have been responsible for the result.

Table 2.6. Effects of different drying methods on some functional properties of sweet potato leaves and purple-fleshed sweet potato flour: extracted from (Sui et al., 2019, Qiu et al., 2019)

Drying method and condition and sample	Swelling capacity (g/g)	Water absorption capacity (g/g)	Oil absorption capacity (g/g)	Solubility (g/g)
Oven drying (60°C, 12 h). Sweet potato leaves	11.40 ± 0.20	4.29 ± 0.00	1.66 ± 0.03	4.29 ± .20
Microwave-vacuum (350 W, -0.95 mpa pressure, 120 min) sweet potato leaves	14.92 ± 0.71	5.68 ± 0.07	3.86 ± 0.03	7.14 ± 0.50
Vacuum freeze dryer (-56°C, 72 h, 10 Pa pressure) sweet potato leaves	9.08 ± 0.42	5.43 ± 0.04	2.02 ± 0.11	5.71 ± 0.35
Infrared-hot air (65°C 0.8m/s, 500 W). Purple-fleshed sweet potato	14.70 ± 0.30	7.80 ± 0.20	N/A	20.50 ± 0.60

The effects of ultrasound-assisted infrared drying and oven drying on hydrocolloids extracted from okra fruits were studied by Baeghbali et al (2020). From their study, it has been found that the apparent viscosity of samples dried by oven was lower than that of the samples dried by infrared. The authors concluded that the application of ultrasound and infrared has improved or at least preserved the rheological properties of okra hydrocolloids. Yao et al (2020) reported that there was less deformation and a smoother surface appearance with few scattered starch grains and little gelatinization on mango slices which were dried by infrared. Thao and Noomhorm (2011) dried sweet potato using infrared, and established that the infrared had slightly affected the functional properties of the starch in terms of gel texture, swelling power, solubility, and pasting properties.

2.6.4. Freeze-drying method

Freeze-drying, also known as lyophilisation or cryodesiccation, is a low-temperature drying process, which involves freezing the food material, lowering pressure, and removing the ice by sublimation (Bhatta et al., 2020). The usage of the freeze-drying method is mostly recommended for preserving heat-sensitive nutrients, and other components, which are prone to oxidation as it provides a free oxygen environment during drying and it is normally used as a standard for referencing in most experiments (Lan et al., 2020). Bhatta et al (2020) further explain that freeze-drying methods have been generally used to produce high valued products, and products with improved functionality, such as bulking density, rehydration capacity, flow properties, and better retention of volatile compounds. Freeze drying methods are expensive as they take longer periods to dehydrate the food materials, this can range between 24 to 72 hours or more depending on the type of food material being dried and some can take up to 5 days to completely dry. This appears not feasible as it will increase the cost of production to the food processors due to energy consumption and low productivity of this drying method. Therefore, alternative methods have to be explored which will produce and retain the same product quality as compared to the freeze-drying method.

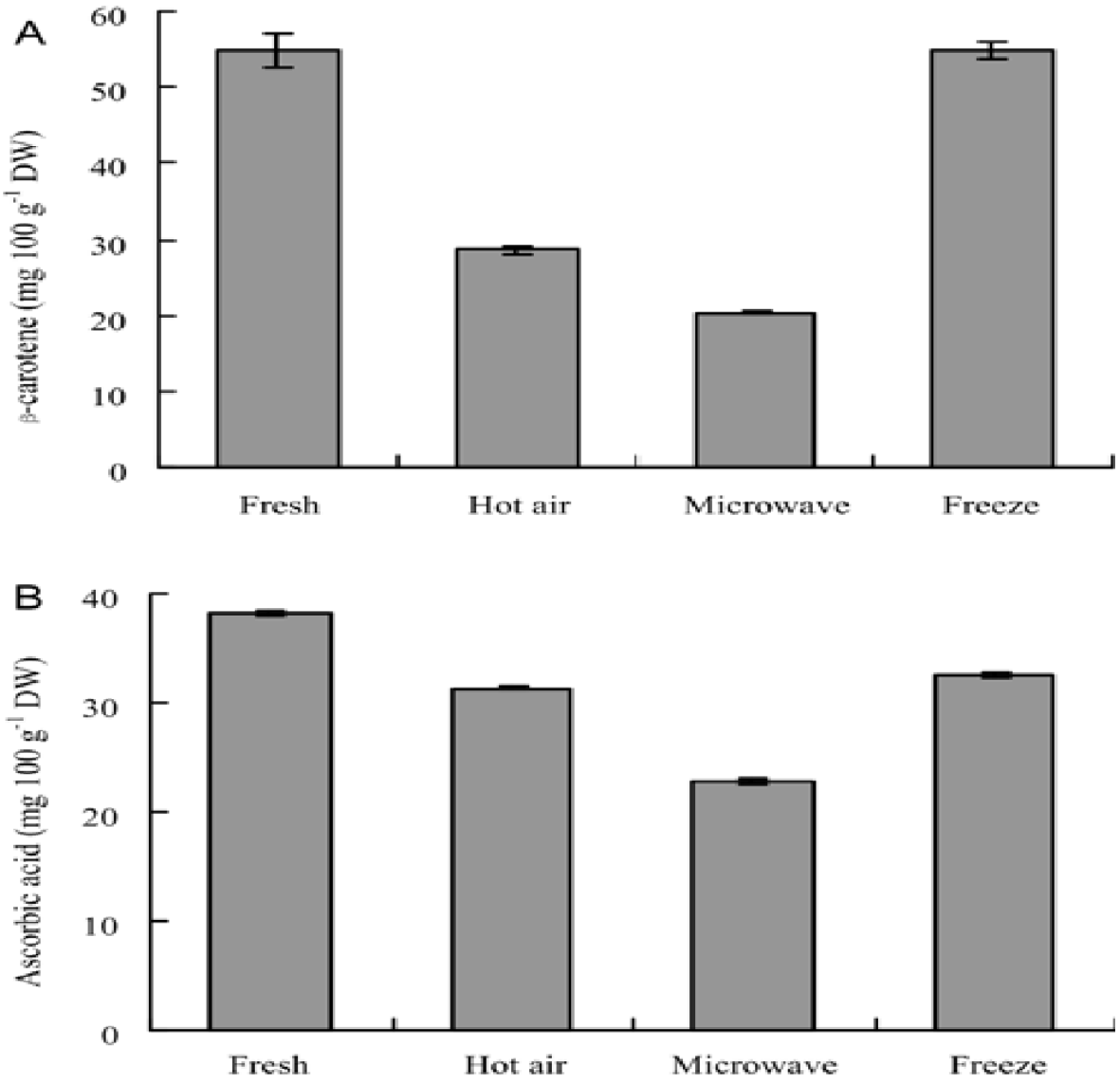


Figure 2.13. Contents of β-carotene (A) and ascorbic acid (B) in fresh, hot-air, microwave, and vacuum-freeze dried orange-fleshed sweet potatoes. Source (Yang et al., 2010).

Several research studies have been conducted on the application of freeze-drying, where most fruits and vegetables were used. Specifically in determining its effects on retaining the heat-sensitive nutrients, such as β-carotene, vitamin C, phenolic compounds, which are susceptible to heat treatment, and polyphenol oxidase. Other physicochemical properties such as colour, texture, and functional properties have been studied using freeze-drying method (Caglar et al., 2021). According to Liu et al (2020), freeze-drying can retain higher nutritional value, flavour, colour and creates a more porous structure of the dried product, which can give the desired attributes of the final products. Liu et al (2020) carried a research study where they used freeze drying, microwave, and infrared. They reported that a combination of freeze-drying with infrared produced mushroom soup with a higher viscosity than freeze-drying alone. They

further indicated lower rehydration capacity of freeze-dried mushrooms, as compared to a combination of freeze-drying with infrared. Although freeze-drying can preserve volatile compounds and heat-sensitive nutrients, some freeze-dried products have been reported to collapse when the product temperature exceeds the collapse temperature and this can also affect the viscosity of the food material (Yamamoto et al., 2021).

Phenolic compounds, as well as anthocyanins, are known to be heat sensitive among other compounds such as β-carotene. Chomorro et al (2021) assert that freeze-drying could preserve the loss of phenolic compounds, anthocyanins, as well as β-carotene from purple-fleshed sweet potato as compared to spray drying, which use high drying temperatures and it can cause degradation of the heat-sensitive compounds. Wang et al (2011) also revealed higher retention of phenolic compounds from a purple-fleshed sweet potato, using freeze-drying, as compared to using hot air drying and drying using the addition of maltodextrin to the sample. In addition, lower rehydration capacity of the sweet potato dried by freeze-drying, as compared to those dried by conventional oven drying. The freeze-drying method can lead to cellular breakdown or the loss of shape in the solute matrix if the temperature is greater than the glass transition temperature (T_g), and therefore results in lower rehydration capacity (Wang et al., 2011). Most literature that is available focuses on the utilization of freeze-drying technologies and how it preserves the nutritional properties of the dried food material. There is a lack of studies in terms of how freeze-drying affects the functional properties of the dried food material. This study will explore the effects of freeze-drying on the functional properties of orange-fleshed sweet potato flour.

2.7. Other drying technology

The science of drying has evolved over time, and this is because of a need to improve the drying technologies. There have been many drying methods, which have been developed to improve the drying of fruits and vegetables. Some of these developed drying technologies include bed dryer, drum dryer, spray dryer, solar dryers (direct and indirect), radio frequency, vacuum oven, microwave-vacuum, infrared-vacuum, and other combined thermal hybrid drying technologies (Riadh et al., 2014, Sakare et al., 2020). The different drying models have different effects on the functional properties, and nutritional properties of the dried food materials. This is attributed to the difference in drying mechanism, as some of the drying methods have ability to improve the functional properties and retain sensory and nutritional content (Roratto et al., 2021).

Mostly the hybrid combined drying methods, have been conveyed to retain sensory properties of the dried food samples, Rorrato et al (2021) expound that using the hybrid combined drying methods can result in improved quality product. Chen et al (2016) conducted an experiment using a combination of infrared and microwave-vacuum to look at the effects of the quality of raspberry and they found that the rehydration ratio of the product improved, and also reported a higher retention of anthocyanin by using the mentioned drying method. Sebben et al (2015) also reported that drying of orange-fleshed sweet potato using a combination of microwave and hot air drying, results in a faster drying rate, retention of colour and β-carotene as compared to drying by oven.

Table 2.7. Some of the hybrid combined thermal drying technologies used in the food industry

Drying method	Dried food sample	Processing parameters	Effects of the processing parameters	References
Microwave and hot-air	Orange-fleshed sweet potato	Microwave at 820 W, hot air at 60°C	Faster drying rate, 80% retention of β-carotene by microwave drying	(Sebben et al., 2017)
Far-infrared assisted heat-pump drying,	Purple-fleshed sweet potato	Infrared (500 W) oven (65°C, air velocity at 0.8 m/s)	Low energy consumption, higher viscosity, colour retention, and improved functional properties by infrared drying	(Qiu et al., 2019)
Combined infrared and hot air	Orange-fleshed sweet potato	Air velocity at 1.2 m/s, IR at 1100 W/m^2, RH 45%, hot air 60-70°C	Low slice shrinkage (69.12%), higher colour retention, faster drying rate (120 min), low energy consumption (48.36 KWh/kg), retention of phenolic compounds	(Onwude et al., 2019)
Microwave-vacuum	Purple-fleshed sweet potato	Power at 450-850 W, vacuum at 160 mm Hg	Improved WAI, WSI and SC, retention of phenolic content, and antioxidant properties and anthocyanin	(Marzuki et al., 2020)
Combination of microwave-Infrared	Paprika	10 W/g, 150-390°C, 120 s heating time, 8 cm IR distance	Increasing power levels degraded carotenoids, increase in browning index, higher temperature retained ascorbic acid	(Shankarrao Shirkole et al., 2021)
Infrared-hot air	Hawthorn fruits	Infrared at 500 W, hot air at 60°C	Loss of colour, reduced sample shrinkage, increased sample RR, retains TPC	(Abbaspour-Gilandeh et al., 2021)
Ultrasonic microwave-hot-air	Hawthorn fruits	Sonic frequency at 37 kHz, power at 70 W, microwave power at 450 W, and hot air at 60°C	Shorter drying time, low energy consumption, retain colour, increased sample RR, reduced sample shrinkage, higher retention of TPC	(Abbaspour-Gilandeh et al., 2021)
Convective + microwave + infrared	Green pepper	Oven at 65°C, IR AT 250 W, MW AT 62	Drying time reduced by 69.32%, 42.97% vitamin C retention, total colour change of 9.41%	(Łechtańska et al., 2015)

Where WSI is water solubility index, SC is swelling capacity, WAI is water absorption index, RR is rehydration ratio, TPC is total phenolic content, and W refers to wat (Kj)

The combination of drying mechanisms by the drying technologies is fundamental in drying the food material. The mechanism have the ability to assist each other, which results in

reduction of energy consumption. Shankarrao Shirkol et al (2021) reported that infrared has the ability to heat the surface, but does not have deep heat penetration as compared to microwave. Hence, the combination of volumetric heating capacity of microwave and surface heating of infrared, can accelerate moisture transfer during drying, which will increase the drying rate. The convective drying method technologies are surface focused, meaning they can only transfer moisture if they are diffused to the surface. This can lead to increased surface shrinkage as described by Onwude et al (2018). They used a combination of microwave and infrared, described that the dried chips were less shrinked as related to the ones dehydrated by hot air.

2.8. Concluding remarks

- Orange fleshed sweet potato can grow under stressful climatic conditions, it is a good source of β-carotene and is used as a staple source of energy.
- Drying can affect important nutrients such as β-carotene, as the latter is sensitive to heat, endogenous oxidative enzymes, light and oxygen. Drying can also affect the functional properties of the flour. High temperatures can cause gelatinization of starch, affect the colour, and sensory properties due to case hardening.
- Alternative drying methods apart from oven drying, such as microwave and infrared, are promising methods for retaining β-carotene content of OFSP, and improve the functional properties of the flour, as they have a shorter drying time.
- Drying models are important in determining drying kinetics of the different drying models, however they only work for the designed parameters such as product slice, temperature and initial moisture content of the specific product. As one model might not fit for different products even under the same parameters.

Chapter 3: Hypothesis and objective

3.1. Hypothesis

1. Dehydration of OFSP using microwave and infrared drying technologies alone and in combination will have higher rehydration ratio, swelling capacity, and pasting viscosity compared to using an oven. Microwave and Infrared drying mechanisms can easily penetrate the food material, without heating the surrounding environment, which can partially prevent the collapse or shrinkage of the tissue material and thus prevent loss of functional properties (Sebben et al., 2017). The electromagnetic energy used by MW and IR cause high heat density and deep penetration of heat, which increases the rate of moisture migration to the surface (Si et al., 2016). The increased rate of moisture migration will limit the exposure of starch granules to the heat, and prevent excess leaching of amylose molecules and improves functional properties of OFSP flour (Viswanathan. et al., 2010). Oven is a slow drying process, which requires a long exposure of the product to the heat, and thus results in inefficient and slow dehydration rate (Thao and Noomhorm, 2011). The slow drying by the oven, enables an extended continued heat transfer, and result in undesirable irreversible changes such as case hardening of the slices (Markus Schirmer, 2015).

2. Drying of OFSP by microwave, infrared and combination of microwave-infrared, will have a higher retention of β-carotene, as compared to convection oven. The β-carotene is an unstable compound, which is susceptible to light, oxygen, high temperature and endogenous enzymes (Tumuhimbise et al., 2009). When it is exposed to this variables over a long period of time, β-carotene can degrade to its cis-isomers in the presence of heat or degrade to epoxy-β-carotene when exposed to light, oxygen and inactivated enzymes. The electromagnetic drying method has a fast drying rate, which will reduce the exposure of OFSP to oxygen, light and high temperature as compared to oven drying method. The freeze-drying method can change the microstructure of the OFSP, making it more porous and increasing the exposure of β-carotene to oxygen during milling, causing oxidative degradation and loss of β-carotene (Harnkarnsujarit and Charoenrein, 2011).

3.2. Objectives

1. To determine the effects of convective oven drying, microwave, infrared, and the combination of microwave-infrared drying methods, on the drying kinetics, the functional properties of the OFSP flour and retention of β-carotene of OFSP flour, with the aim of producing a flour with improved functional properties (swelling capacity, thermal properties, pasting properties, water holding capacity, swelling capacity and bulking density) and high β-carotene content.

Chapter 4: Materials and methods

4.1. Experimental

The experimental design for the research on the different drying technologies on properties of dried OFSP (orange fleshed sweet potato) is shown in Figure 4.1.

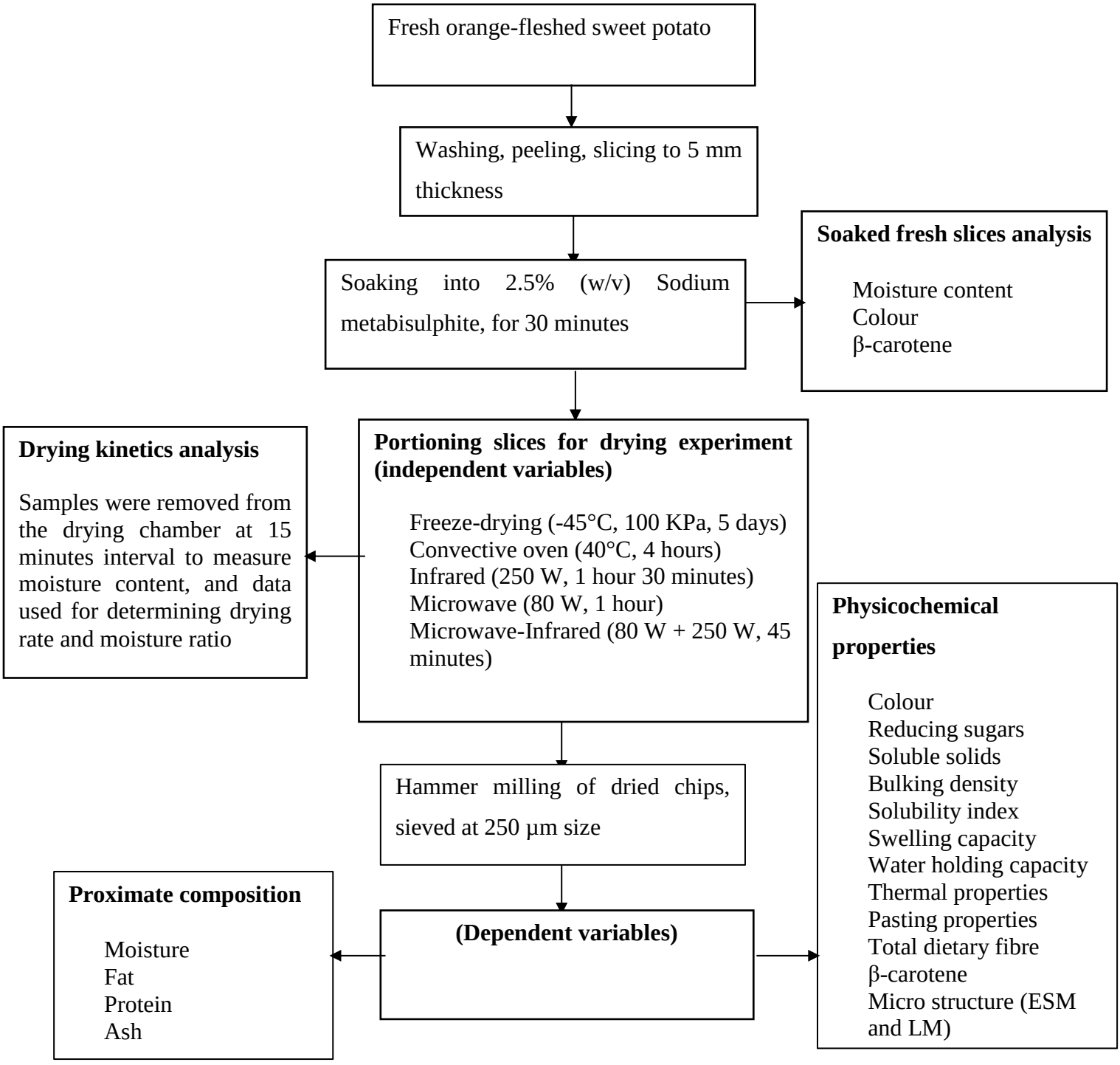


Figure 4.1 Experimental design of the project showing the treatments and analyses

4.2. Raw materials

Fresh OFSP (Bellevue and Orleans cultivars) were supplied by Langplaas Boerdery, situated in Brits, North West province, South Africa. The chemicals used for HPLC analysis were all HPLC grade (≥99.9% inhibitor free), and these are: tetrahydrofuran (EC number 203-726-8), acetonitrile (EC number 200-662-2), toluene (EC number 203-625-9), methanol (EC number 200-659-6), 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, Southern Cross Rd, Bray, Co. Wicklow, A98 YV29, Ireland).

4.3 Methods: Preparing and drying OFSP

Fresh OFSP were washed, peeled and sliced into 5 mm thickness. The sliced OFSP were pre-treated by soaking them into 2.5% Sodium Metabisulphite (w/v in distilled water) for 30 minutes. The soaked slices were left to drain off excess solution before they were dried. The pre-treated 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 and pressure of 100 KPa for a period of 5 days. The oven dried samples were dried at 40°C, with air velocity of 5.2 m/s for 4 hours.

For microwave and infrared drying experiments, the trial run to find suitable power levels for drying OFSP slices indicated that the suitable power levels at which the slices were not charred and completely drying were 80 W for microwave and 250 W for infrared drying methods. The trial power levels were 120 W and 100 W for microwave, and power levels tested for Infrared were 350 W and 300 W. The tested power level (Microwave 120 and 100 W, Infrared 350 W and 300 W were found to have faster drying, however, the samples were charred, with uneven drying distribution, most of the samples were not dried, while some were only drying at the edges.

Microwave drying experiment was done at a power level of 80 W, with air temperature of 40°C and air velocity of 4.5 m/s. Infrared drying power was set to 250 W, air temperature of 40°C and air velocity of 4.5 m/s. The combination of microwave and infrared drying experiment was performed at the same parameters of microwave and infrared as mentioned above.

4.4 Analysis

4.4.1. Drying kinetics

During drying of the OFSP, samples were taken out on a 15 minutes interval to determine the moisture content, and to calculate the drying rate and moisture ratio. The formula below shows the calculation of moisture ratio and drying rate (Onwude et al., 2019).

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (1)$$

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.

$$DR = \frac{M_o}{M_t x t} \quad (2)$$

Where DR is the drying rate (g water/ g dry mass x 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 moisture ratio was used to select fitting models, 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.

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2\right]^{1/2} \quad (3)$$

$$X^2 = \frac{\sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2}{N - n} \quad (4)$$

Where $MR_{exp,i}$ is the i^{th} moisture ratio observed from the experimental data, $MR_{pre,i}$ is the i^{th} predicted moisture ratio, n is the number of drying constants from the model formula, N is the number of observations.

$$R^2 = 1 - \frac{SSE}{SST} \quad (5)$$

$$SSE = \sum_i (MR_{exp,i} - MR_{pre\ ava})^2 \quad (6)$$

$$SST = \sum_i (N - MR_{pre,ave})^2 \quad (7)$$

Where SSR is the sum of squared regression and SST is the sum of squared total. $MR_{exp,\ i}$ is the i^{th} experimental moisture ratio, $MR_{pre,\ ave}$ is the mean value of the predicted moisture ratio. Drying models used for the studies are as listed below.

Newton model $MR = e^{-kt}$

Page model $MR = e^{-kt^n}$

Henderson and Pabis model $MR = ae^{-kt}$

Logarithmic model $MR = ae^{-kt} + b$

Where a, n and b are drying constant, t is the drying time (minutes) and k is the coefficient of diffusion (m^2/s) (Onwude et al., 2018).

4.4.2. 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 an 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 (2000) official method of analysis 46.3 using Gerhardt Dumatherm (Konigs Winners, Germany). A conversion factor of N x 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 (2000) official method of analysis 920.31 using Soxhlet fat extraction method.

4.4.3. Determination of soluble and insoluble dietary fibre

Dietary fibre of OFSP flour was determined according to AOAC (2000) official method of analysis 991.43 using the total dietary fibre Megazyme kit (K-TDFE). Orange-fleshed sweet

potato flour (about 1 g) was suspended into 40 mL of MES-TRIS buffer (0.05M, pH 8.2) solution and 50 µL of thermostable α-amylase (3000 U/mL of cerealpha reagent at pH 6.5 and 40°C, EC number 3.2.11) was added to hydrolyze starch to dextrin at 100° C. Protease (100 µL) with an activity of 350 tyrosine U/ml (E-BSPRT) (EC number 3.4.21.62) was added to solubilize the protein. Amyloglucosidase (EC number 3.2.13) (200 µl), with an activity of 3300 U/ml (E-BLAAM) was added to hydrolyse starch to glucose. The enzyme mixtures were filtered and the residues were washed with acetone and 95% ethanol to obtain the insoluble dietary fibre portion (IDF). Four volumes of ethanol at 60°C, were added to the filtrate and left to stand for 60 min to form soluble dietary fibre (SDF) precipitate after which it was filtered. The SDF residues were washed with 78% ethanol, 95% ethanol and acetone. The IDF and SDF residues were dried overnight at 103°C. One part of SDF and IDF was used to determine protein, and the other part to determine ash, which were used for the final calculation of SDF and IDF values.

4.4.4. Determination of β-carotene content

β-Carotene was extracted from 2 g of OFSP flours and 10 g fresh samples with 10 mL tetrahydrofuran (THF) in a small beaker by magnetic stirring for 30 minutes. The mixture was centrifuged at 1149 *x g* for 10 min and the supernatant set aside. The extraction was repeated three times, with a fresh 10 ml THF aliquot and separation of the supernatant after centrifugation until the flour residue was colourless. The THF was evaporated using a rotary evaporator at 27ºC. The crude carotene extracts were dissolved in 10 mL toluene. The carotene extracts in toluene were filtered using 0.45 µm PTFE membrane filters directly into amber vials in preparation for chromatography. Chromatographic analysis of β-carotene content were done using a Prominence ultra-fast liquid chromatography (UFLC) (Shimadzu, Tokyo, Japan) equipped with a SIL-20A Prominence autosampler, a DGU-20A3 Prominence degasser, a CTO-10AS VP Shimadzu column oven and an SPD-M20A Prominence diode array detector. UV/Vis spectra of carotenoids were recorded between 200 to 600 nm, with the detection of β-carotene at 450 nm. The separation of carotenoids were performed at 30ºC on a C18 Waters Nova-Pak carotenoid column (300 x 3.9 mm, 4 µm particle size) by isocratic elution with acetonitrile (58%), HPLC grade methanol (35%) and THF (7%) as mobile phase, at a flow rate of 1.0 ml/min for 45 min and the injection volume of 20 µl. The quantification of β-carotene was done by using a calibration curve of β-carotene standard and the peak area of the sample (Tiwari et al., 2019).

4.4.5. Determination of physicochemical properties

4.4.5.1. Rehydration capacity/ water holding capacity (WAC)

Orange-fleshed sweet potato flour (1 g) 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 seconds. The mixed sample was allowed to stand for about 30 min at room temperature and then centrifuged at 3400 *x 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 (Olatunde et al., 2016).

$$WAC = \frac{Weight\ of\ absorbed\ water}{weight\ of\ dry\ sample}\ x\ 100 \qquad (9)$$

4.4.5.2. Swelling capacity (SC) and solubility index (SI)

Swelling capacity was determined by weighing 1g of the flour into a 10 ml centrifuge tube and mixed with 10 ml of distilled water. The samples were placed in a hot water bath at 80°C for 30 minutes. The tubes were removed and allowed to cool to room temperature for 10 minutes. The samples were centrifuged at 3400 *x g* for 30 minutes. The supernatant was discarded in a pre-dried evaporation dish and dried at 105°C for 3 hours for determining the solubility index. The sediment was used to determine the swelling capacity as shown by the formula below (Ngoma et al., 2019).

$$SC = \frac{mass\ of\ sediment}{mass\ of\ dry\ sample}\ x\ (1 - solubility\ index) \qquad (10)$$

$$\%SI = \frac{Mass\ of\ dissolved\ solids}{Mass\ of\ dry\ sample}\ x\ 100 \qquad (11)$$

4.4.5.3 Pasting properties

The pasting properties of the flours were evaluated using the starch cell of a modular compact rheometer (Model 52, Anton Paar Co. Ltd., Austria). Pasting viscosity of the flours were 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, 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 (Kaur and Singh, 2015).

4.4.5.4 Determining thermal properties of the flour

Thermal properties of sweet potato flours were evaluated by DSC (model DSC1 STARe System, Mettler-Toledo Ltd., Beaumont Leys Leicester, England). Indium was used for standard and calibration (T_p=156.6, ΔH=28.45 J/g). 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 h before analysis. The samples were heated from 25°C to 120°C at a scanning rate of 10°C/min for a total time of 20 minutes with an empty pan as a reference. Nitrogen was used as a purging gas at 50 mL/min flow rate and pressure of 4000 KPa was maintained during the analysis. The results were analysed using STARe software (Mettler Toledo) to get onset temperature (T_o), peak temperature (T_p), end set temperature (T_c) and enthalpy (ΔH) for observed endotherms (Schick, 2009).

4.4.5.5. Determination of reducing sugars

Reducing sugars were determined by the method of Miller (1959) and this method was recently used by Macias et al (2001). Reducing sugars were extracted from 1g of the OFSP flour by solubilising in 100 ml distilled water for 2 hr at 60°C. The suspended materials were separated using filter paper. The total reducing sugars in the filtrate were determined by 3,5-dinitrosalicylic acid (DNS). The filtrate (about l mL) was added into 2 ml of DNS, the samples were mixed by vortex, and then 7 mL of distilled water was added. The samples were placed in a hot water bath at 90°C for 5 minutes. After boiling, +the samples were cooled to room temperature. The extracts were read for absorption using a refractometer at 540 nm against the blank.

4.4.5.6. 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. A fresh cut slice of OFSP and milled dried flour were used to evaluate the colour and compare colour changes to the fresh slice. The results are expressed in the CIE *L*a*b**. The value *L** (100=white. 0=black) is an indication of lightness, *a** measures chromaticity, with positive values indicating redness and negative values indicating greenness. The *b** value also measures chromaticity, with positive values indicating yellowness and negative values indicating blueness. Calibration measurements were done on a plain whiteboard. Readings were taken for each sample in triplicates. Colour change (ΔE*) was* also calculated as shown in the formula below (Zhao et al., 2014).

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

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

4.5. MICROSTRUCTURE OF DRIED OFSP FLOUR

4.5.1. Bright field Light microscopy

The dried OFSP flour samples were visualized with a VS3 Series Biological Trinocular Light Microscope from Micromet Scientific with a Biowizard Image Analysis Software (Delhi, India) equipped with a Polarising filter lens. The flour samples (10 mg) were suspended in 30 % (v/v) glycerol in distilled water. One drop of the suspension was placed onto the specimen glass slide and covered with a glass cover slip. The structural integrity was analysed with a polarising filter. To stain starch, iodine solution was added. Images were taken with 20 *x* magnification and evaluated with the ImageJ® software.

4.5.2. Scanning Electron Microscopy (SEM)

Scanning electron microscopy of the dried OFSP flour was done by taking small fractions of the dried flour and were mounted on aluminium stubs with the aid of double-sided carbon tape, followed by 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.

4.6. STATISTICAL ANALYSIS

The experiments were repeated three times and the results are shown as mean ± standard deviations (n=3). The least significant differences among the mean values of nutritional, and physicochemical properties were examined using one-way analysis of variance (ANOVA) and the Tukey's Multiple Comparison Test ($p < 0.05$) with the drying technologies as independent variable.

CHAPTER 5: Results

5.1. Drying kinetics for orange-fleshed sweet potato chips, by infrared, microwave and oven drying method.

Figure 5.1 shows the moisture content reduction overtime, as affected by the different drying methods. Oven drying had the slowest moisture removal with time. Followed by infrared, microwave, with a combination of microwave and infrared drying method showing the shortest drying time for both OFSP cultivars. Drying rate (Figure 5.2) and moisture ratio (Figure 5.3) also shows that the oven drying had the lowest moisture ratio overtime, followed by infrared, microwave, with a combination of microwave and infrared drying being the shortest. Oven drying had the longest drying time, followed by infrared, microwave and the combination of microwave-infrared being the shortest (Figure 5.1).

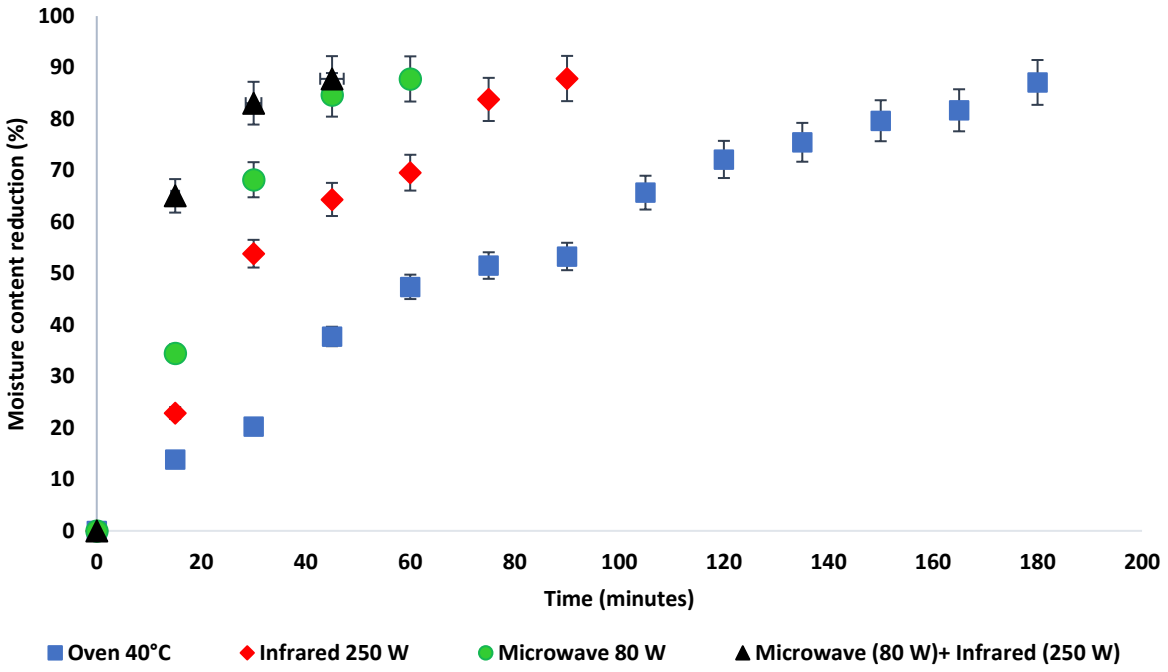


Figure 5.1 Effects of drying methods on the moisture content reduction of orange-fleshed sweet potato

Error bars are representative of standard deviation between the mean values (n=3)

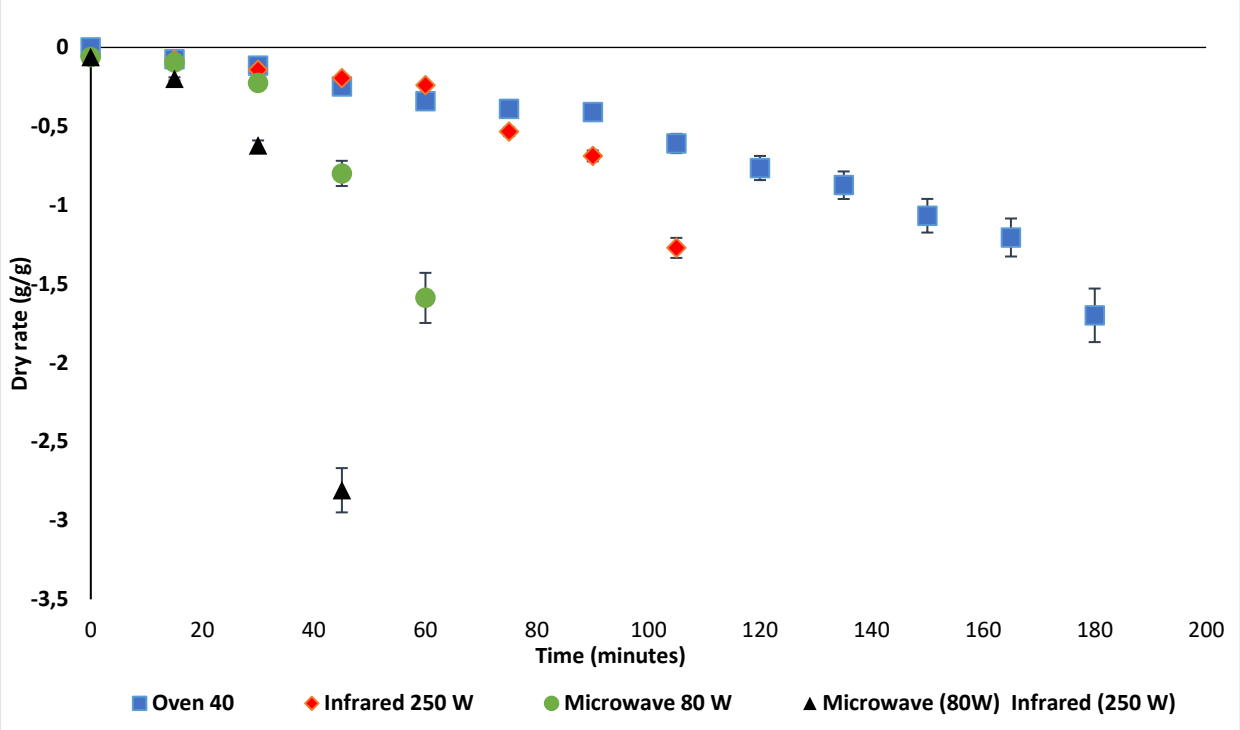


Figure 5.2. Effects of different drying methods on the drying rate over time of orange-fleshed sweet potato slices

The error bars are representative of standard deviation between the mean values (n=3)

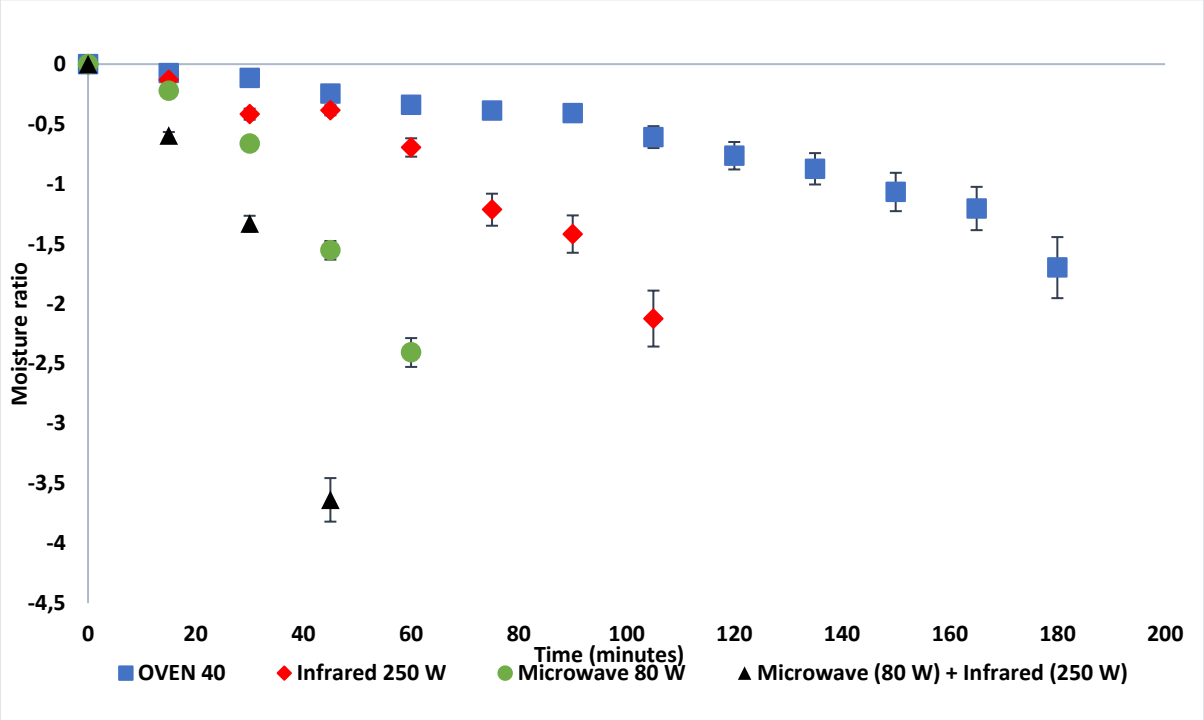


Figure 5.3. Effects of different drying methods on the moisture ratio over time of the dried orange-fleshed sweet potato slices

The error bars are representative of standard deviation between the mean values (n = 3)

Page model seems to be the suitable fit for the oven drying method, as it showed highest R^2 value, lowest RMSE and chi-square values (Table 5.1). Although Lewis, Logarithmic and Henderson and Pabis models showed higher R^2 values, it seems Lewis model presented the best fit for microwave drying, while Henderson and Pabis model is fitting for infrared drying method (Table 5.1). For the combination of microwave and infrared drying method, Page, Lewis, and Henderson and Pabis model exhibited a good fit. Table 5.1 also shows the different values of coefficient of diffusion (k m^2/s) for all drying methods. The combination of microwave and infrared drying method revealed a higher coefficient of diffusion for all the models than Page model (Table 5.1).

Table 5.1. Effects of drying methods on the Models describing the drying kinetic of OFSP

Drying methods	Models	Formulas	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=a$e^{-kt} + b$	0.9779	0.04557	0.00245	0.0051	1.0458	0.002	
Infrared	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
Microwave	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
Microwave-Infrared	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

Coefficient of determination (R^2), root means square error (RMSE), chi-square (X^2), coefficient of diffusion (K m^2/s), drying constant (a, n, c). Moisture ratio (MR), Time (t minutes)

5.2. Proximate composition of Bellevue and Orleans orange-fleshed sweet potato flour

The different drying methods have reported a shelf stable moisture content of less than 12% (Table 5.2). There was no significant difference (P>0.05) on the fat content of Bellevue cultivar for the different drying methods. The same was found for Orleans cultivars (Table 5.2). However, Orleans reports higher fat content than that of Bellevue cultivar. Bellevue reported a higher protein (6.03-6.64 g/100g) content than Orleans cultivar (5.33-5.81 g/100g). Nonetheless, there was no significant difference (P>0.05) between the different drying methods. The ash content [about 5.3-5.8 g/100g) of the cultivars did not show significant difference (P>0.05) between the different drying methods (Table 5.2).

Table 5.2. Effects of drying methods on proximate composition of Bellevue and Orleans orange fleshed sweet potato flour

Cultivars	Drying methods	Moisture (g/100g)	Ash (g/100g)	Protein (g/100g)	Fat (g/100g)
Bellevue	Freeze	11.23 ± 0.85^{d}	5.71 ± 0.45^{b}	6.03 ± 0.24^{b}	1.26 ± 0.24^{a}
	Oven	7.56 ± 1.64^{b}	5.43 ± 0.32^{b}	6.48 ± 0.07^{b}	1.28 ± 0.32^{b}
	IR	8.56 ± 0.99^{c}	5.30 ± 0.72^{b}	6.82 ± 0.02^{b}	1.24 ± 0.20^{a}
	MW	6.42 ± 0.66^{a}	5.31 ± 0.26^{b}	6.66 ± 0.96^{b}	1.24 ± 0.22^{a}
	MW+IR	7.67 ± 0.49^{b}	5.33 ± 0.43^{b}	6.64 ± 0.15^{b}	1.25 ± 0.15^{a}
Orleans	Freeze	6.55 ± 0.51^{a}	5.98 ± 0.10^{b}	5.81 ± 0.10^{a}	1.64 ± 0.25^{b}
	Oven	7.93 ± 0.64^{b}	5.90 ± 0.14^{b}	5.37 ± 0.15^{a}	1.60 ± 0.32^{b}
	IR	8.54 ± 0.51^{c}	5.56 ± 0.33^{b}	5.33 ± 0.24^{a}	1.62 ± 0.22^{b}
	MW	8.55 ± 0.55^{c}	5.66 ± 0.45^{a}	5.45 ± 0.75^{a}	1.67 ± 0.16^{b}
	MW+IR	6.77 ± 0.52^{a}	5.79 ± 0.15^{b}	5.49 ± 0.083^{a}	1.65 ± 0.18^{b}

Values are representative of mean data and standard deviation (n=3) on a dry basis. Values with the same superscripts in column are not significantly different ($p < 0.05$).
Infrared (IR), Microwave (MW)

The reduced sugar content (about 3.5 mg/g) of dried OFSP between the two cultivars and drying methods was not significantly (p>0.05) different (Table 5.3). The total dietary fibre of Bellevue cultivars (about 18-19 g/100g) was higher than that of Orleans cultivar (Table 5.3). The drying methods did not significantly (p> 0, 05) affect the soluble dietary fibre for Orleans cultivar. The Bellevue OFSP flour dried by microwave, infrared and microwave-infrared indicated significantly higher soluble fibre (p<0.05) compared to oven and freeze-drying (Table 5.3).

Table 5.3. Effects of drying methods on soluble, insoluble dietary fibre and reducing sugars of dried orange fleshed sweet potato flour

Cultivars	Drying methods	IDF (g/100g)	SDF (g/100g)	TDF (g/100 g)	Reducing sugars (mg/g)
Bellevue	Freeze	14.43 ± 0.33^{a}	3.48 ± 0.37^{b}	17.91 ± 0.70^{b}	3.58 ± 0.32^{a}
	Oven	14.44 ± 0.35^{a}	3.58 ± 0.43^{b}	18.02 ± 0.78^{c}	3.47 ± 0.23^{a}
	IR	14.41 ± 0.31^{a}	4.43 ± 0.69^{c}	18.84 ± 1.00^{c}	3.57 ± 0.07^{a}
	MW	14.51 ± 0.30^{a}	4.52 ± 0.47^{c}	19.03 ± 0.77^{d}	3.50 ± 0.11^{a}
	MW + IR	14.49 ± 0.30^{a}	4.53 ± 0.32^{c}	19.02 ± 0.62^{d}	3.48 ± 0.13^{a}
Orleans	Freeze	14.31 ± 0.13^{a}	2.55 ± 0.11^{a}	16.86 ± 0.24^{a}	3.50 ± 0.89^{a}
	Oven	14.36 ± 0.33^{a}	2.41 ± 0.15^{a}	16.77 ± 0.48^{a}	3.50 ± 0.25^{a}
	IR	14.30 ± 0.45^{a}	2.53 ± 0.19^{a}	16.83 ± 0.64^{a}	3.51 ± 0.65^{a}
	MW	14.35 ± 0.56^{a}	2.54 ± 0.15^{a}	16.89 ± 0.71^{a}	3.55 ± 0.77^{a}
	MW + IR	14.47 ± 0.87^{a}	2.38 ± 0.19^{a}	16.85 ± 1.06^{a}	3.40 ± 0.63^{a}

Values are representative of mean data and standard deviation (=3) on a dry basis. Values with the same superscript in column are not significantly different ($p < 0.05$).
IR (Infrared), MW (Microwave), IDF (Insoluble dietary fiber), SDF (Soluble dietary fiber).

5.3. Physicochemical properties of Bellevue and Orleans orange-fleshed sweet potato flour

The solubility index notably increased ($p<0.05$) for microwave, and microwave- infrared compared to oven dried for both OFSP cultivars. The soluble solids from the two OFSP cultivars were less affected by the different drying methods (Table 5.4). The bulking density of the both cultivars for the freeze-drying method were lower ($p<0.05$) from oven, infrared, microwave and microwave-infrared drying methods. The swelling capacity (15.16 g/ml to 15.50 g/ml) of Bellevue was remarkably ($P<0.05$) higher for all the thermal drying methods compared to Bellevue. The swelling capacity for freeze-dried, oven, and microwave-infrared Orleans dried flours were lower than those dried by infrared and microwave (Table 5.4).

Table 5.4. Effects of drying methods on the physicochemical properties of Bellevue and Orleans orange fleshed sweet potato flour

Cultivars	Drying methods	Solubility index (g/100g)	Soluble solids (%Brix)	Bulking density (g/ ml)	Swelling capacity (g/ml)
Bellevue	Freeze	41.81 ± 2.72^{c}	3.20 ± 0.06^{a}	0.33 ± 0.01^{a}	13.83 ± 0.21^{a}
	Oven	40.59 ± 3.15^{b}	3.27 ± 0.21^{a}	0.44 ± 0.01^{b}	15.19 ± 0.96^{c}
	IR	39.68 ± 2.22^{a}	3.20 ± 0.12^{a}	0.46 ± 0.01^{b}	15.50 ± 0.28^{c}
	MW	42.25 ± 3.63^{d}	3.30 ± 0.17^{a}	0.44 ± 0.01^{b}	15.16 ± 0.92^{c}
	MW + IR	44.53 ± 1.02^{f}	3.30 ± 0.19^{a}	0.44 ± 0.01^{b}	15.43 ± 0.34^{c}
Orleans	Freeze	46.78 ± 4.22^{h}	3.21 ± 0.10^{a}	0.31 ± 0.01^{a}	13.01 ± 0.58^{a}
	Oven	39.77 ± 3.60^{a}	3.24 ± 0.15^{a}	0.42 ± 0.01^{b}	13.65 ± 0.87^{a}
	IR	39.37 ± 1.66^{a}	3.20 ± 0.10^{a}	0.43 ± 0.01^{b}	15.59 ± 1.01^{c}
	MW	43.09 ± 3.09^{e}	3.30 ± 0.16^{a}	0.43 ± 0.02^{b}	14.12 ± 0.57^{b}
	MW + IR	45.33 ± 4.78^{g}	3.20 ± 0.12^{a}	0.40 ± 0.01^{b}	14.45 ± 1.40^{b}

Values are representatives of mean data and standard deviation (n=3).
Values with the same superscripts in column are not significantly different (p>0.05). Infrared (IR), Microwave (MW)

The OFSP flour had water absorption capacity ranging between 2.03 ml/g and 3.41 ml/g. Bellevue flours dried by microwave-infrared methods revealed a higher water absorption capacity as compared to other drying methods (Figure 5.4). Microwave and infrared drying methods did not show significant difference (p>0.05) between Bellevue and Orleans OFSP flours. The freeze-dried Bellevue flour had the lowest water absorption capacity of 2.03 ml/g (Figure 5.4).

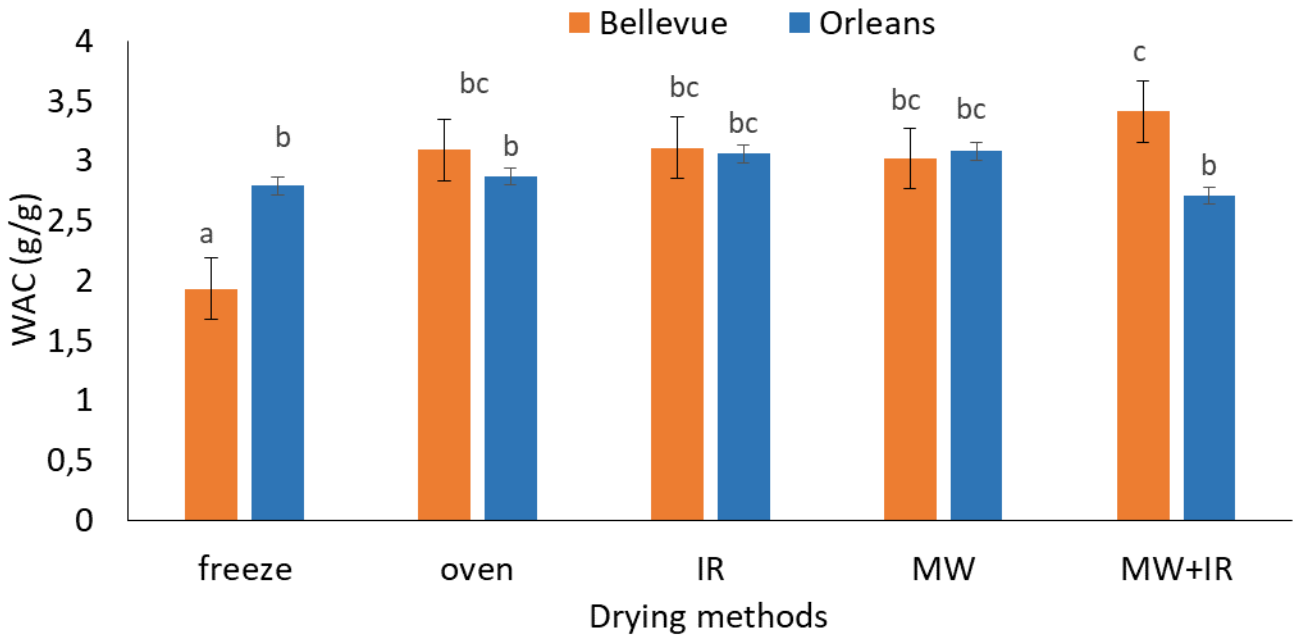


Figure 5.4. Effects of drying methods on water absorption capacity (WAC), of the dried orange fleshed sweet potato flour, Bellevue and Orleans

The error bars are representative of standard deviation between the mean values (n=3). Values with the same superscripts are not significantly different ($p>0.05$)**.** Infrared (IR), Microwave (MW), and combination of microwave and infrared (MW+IR).

5.4. Pasting properties of bellevue and orleans ofsp flour

Flour from Bellevue OFSP had higher viscosity compared to Orleans. The drying methods significantly ($P<0.05$) affected the pasting properties of the orange-fleshed sweet potato flours (Figure 5.5 & 5.6). The Bellevue infrared dried flour exhibited a higher peak viscosity and final viscosity as compared to other drying methods (Table 5.5). However, there was less difference ($p>0.05$) on the peak viscosity and final viscosity between infrared and microwave-infrared dried flour (Figure 5.5). The microwave, oven and freeze dried Bellevue flours did not have any significant difference ($p>0.05$) on the breakdown viscosity.

The Orleans freeze dried flour has been found to have a higher peak viscosity of 147 mPa•s, followed by infrared dried flour with a peak viscosity of 134 mPa•s. There was no significant difference ($p>0.05$) between the peak viscosity of oven, microwave and microwave-infrared dried flour (Table 5.6). Infrared dried flour for Orleans cultivar recorded a higher final viscosity, followed by freeze-drying method (Figure 5.6).

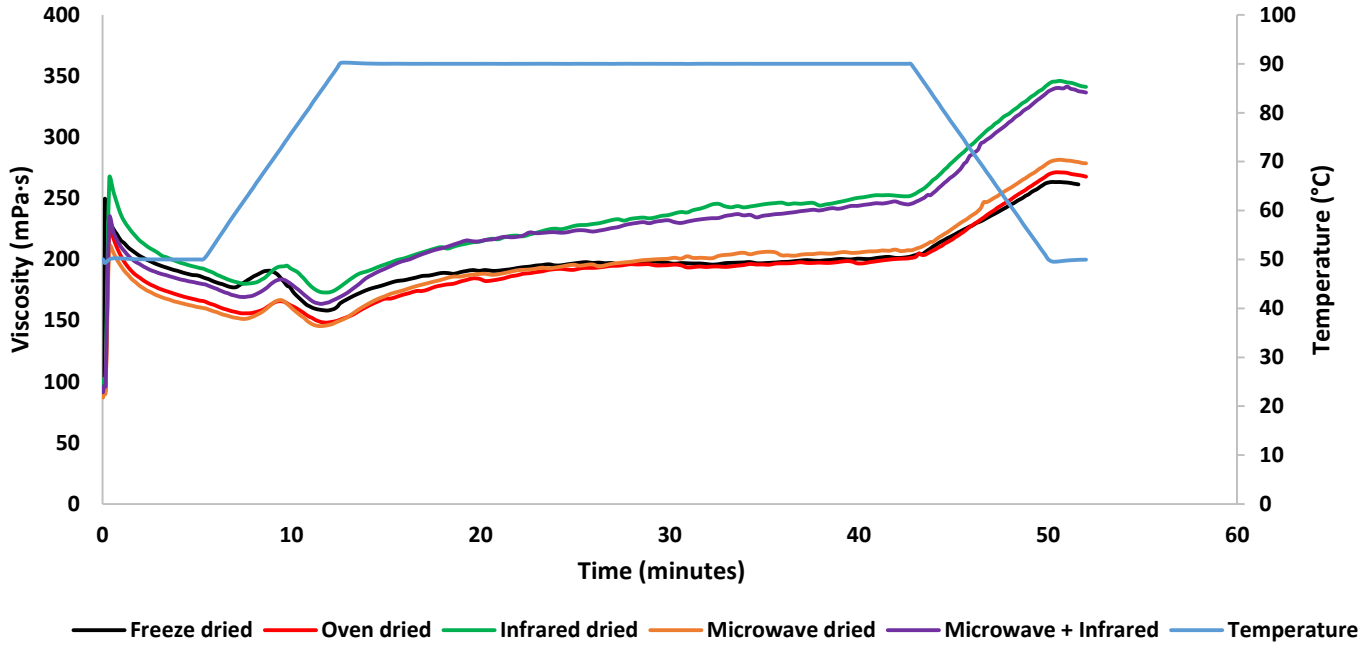


Figure 5.5. Effects of drying methods on the pasting properties of dried Bellevue orange fleshed sweet potato flour

Table 5.5. Effects of different drying methods on the pasting properties of Bellevue orange fleshed sweet potato flour.

Treatments	Peak viscosity (mPa•s)	Set viscosity (mPa•s)	Break viscosity (mPa•s)	Final viscosity (mPa•s)
Freeze	181.37 ± 13.41^{c}	247.93 ± 16.11^{b}	95.30 ± 3.34^{a}	261.37 ± 22.44^{a}
Oven	165.33 ± 8.60^{a}	201.53 ± 19.72^{a}	95.67 ± 5.10^{a}	267.70 ± 26.64^{a}
Infrared	194.26 ± 3.69^{d}	255.73 ± 17.66^{c}	109.25 ± 25.75^{b}	341.13 ± 21.31^{c}
Microwave	165.50 ± 17.22^{a}	209.57 ± 25.54^{a}	95.98 ± 11.72^{a}	287.60 ± 30.66^{b}
Microwave + infrared	177.03 ± 5.40^{b}	246.10 ± 35.76^{b}	102.84 ± 4.84^{b}	336.50 ± 47.29^{c}

The data is a representative of mean values and standard deviations (n=3). Values with same superscripts in column are not significantly different ($p < 0.05$)

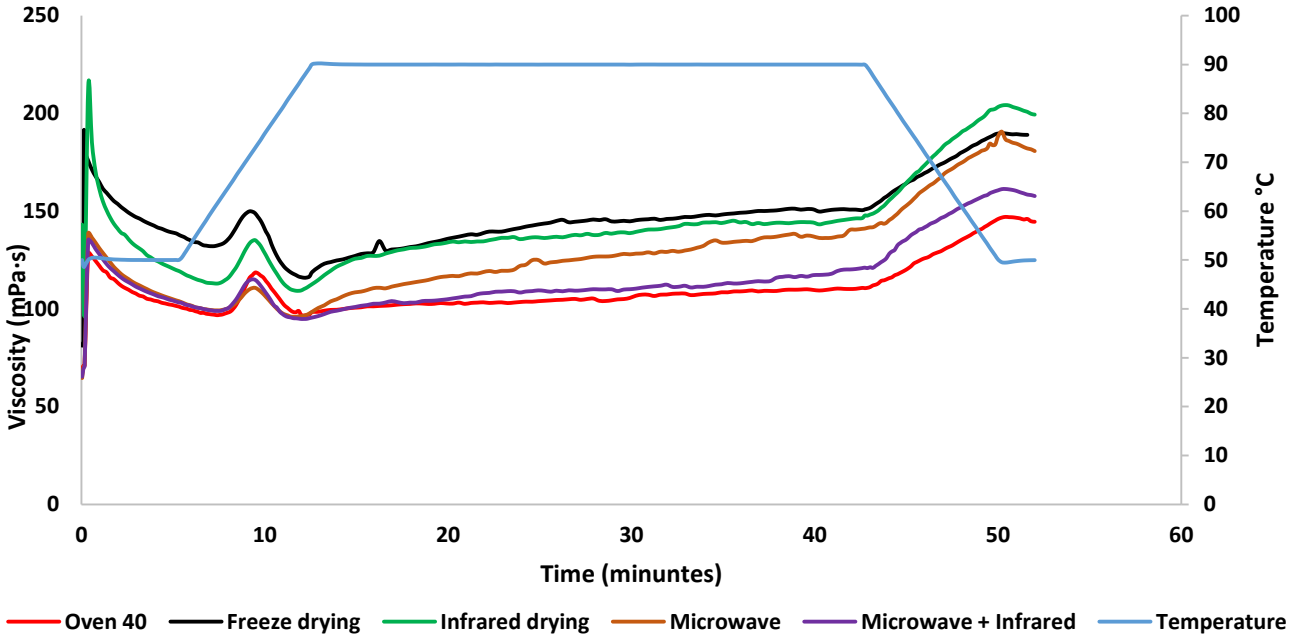


Figure 5.6. Effects of drying methods on the pasting properties of dried Orleans orange fleshed sweet potato flour

Table 5.6. Effects of different drying methods on the pasting properties of Orleans orange fleshed sweet potato flour

Treatment	Peak viscosity (mPa•s)	Set viscosity (mPa•s)	Break viscosity (mPa•s)	Final viscosity (mPa•s)
Freeze	147.30 ± 4.12^{c}	150.47 ± 15.53^{d}	185.90 ± 7.79^{c}	189.03 ± 9.38^{d}
Oven	114.87 ± 4.84^{a}	111.17 ± 10.02^{a}	143.57 ± 9.88^{a}	144.57 ± 8.81^{a}
Infrared	133.98 ± 32.75^{b}	146.41 ± 42.99^{c}	198.67 ± 67.78^{d}	199.40 ± 65.36^{e}
Microwave	110.07 ± 14.40^{a}	141.77 ± 30.25^{c}	182.23 ± 44.92^{c}	180.73 ± 44.66^{c}
Microwave + infrared	111.93 ± 3.85^{a}	120.97 ± 5.09^{b}	158.23 ± 3.84^{b}	157.73 ± 3.84^{b}

The data is a representative of mean values and standard deviations (n=3). Values with same superscripts in column are not significantly different ($p < 0.05$)

5.5. The β-carotene content of Bellevue and Orleans orange-fleshed sweet potato flour

Figure 5.7 and figure 5.8 shows the chromatograms of β-carotene, with the peak elution retention time of about 20 to 23 minutes. The Bellevue cultivar had higher β-carotene content of 2343.23 µg/g on a dry basis than that of Orleans cultivar, which is found to be 1989.95 µg/g (dry basis). The different drying methods had substantial differences ($p<0.05$) on the β-carotene content of the two cultivars (Table 5.7). For both cultivars, Oven drying showed the least retention of less than 30% β-carotene. The combination of microwave and infrared showed the highest β-carotene retention as compared to other drying methods (Table 5.7). However, Freeze-dried OFSP only showed less than 50% β-carotene retention.

Table 5.7. Effects of different drying methods on the β-carotene content of dried Bellevue and Orleans-orange fleshed sweet potato flours

Cultivars	Drying methods	β-carotene (µg/g)	β-carotene retention (%)
Bellevue	Fresh	2343.23 ± 17.11^{i}	-
	Freeze-dried	1010.84 ± 9.08^{c}	43.13 ± 0.11^{b}
	Oven	553.34 ± 6.02^{a}	23.61 ± 0.57^{a}
	IR	1547.51 ± 47.91^{f}	66.04 ± 0.22^{e}
	MW	1880.34 ± 52.64^{g}	80.46 ± 0.36^{f}
	MW+IR	1993.05 ± 8.05^{h}	85.06 ± 0.87^{f}
Orleans	Fresh	1989.95 ± 28.09^{h}	-
	Freeze-dried	954.55 ± 29.10^{b}	47.97 ± 0.54^{c}
	Oven	574.91 ± 20.95^{a}	28.89 ± 0.36^{a}
	IR	1147.09 ± 10.46^{d}	57.64 ± 0.65^{d}
	MW	1356.89 ± 12.01^{e}	68.19 ± 0.56^{e}
	MW+IR	1793.72 ± 28.05^{g}	90.14 ± 0.23^{g}

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

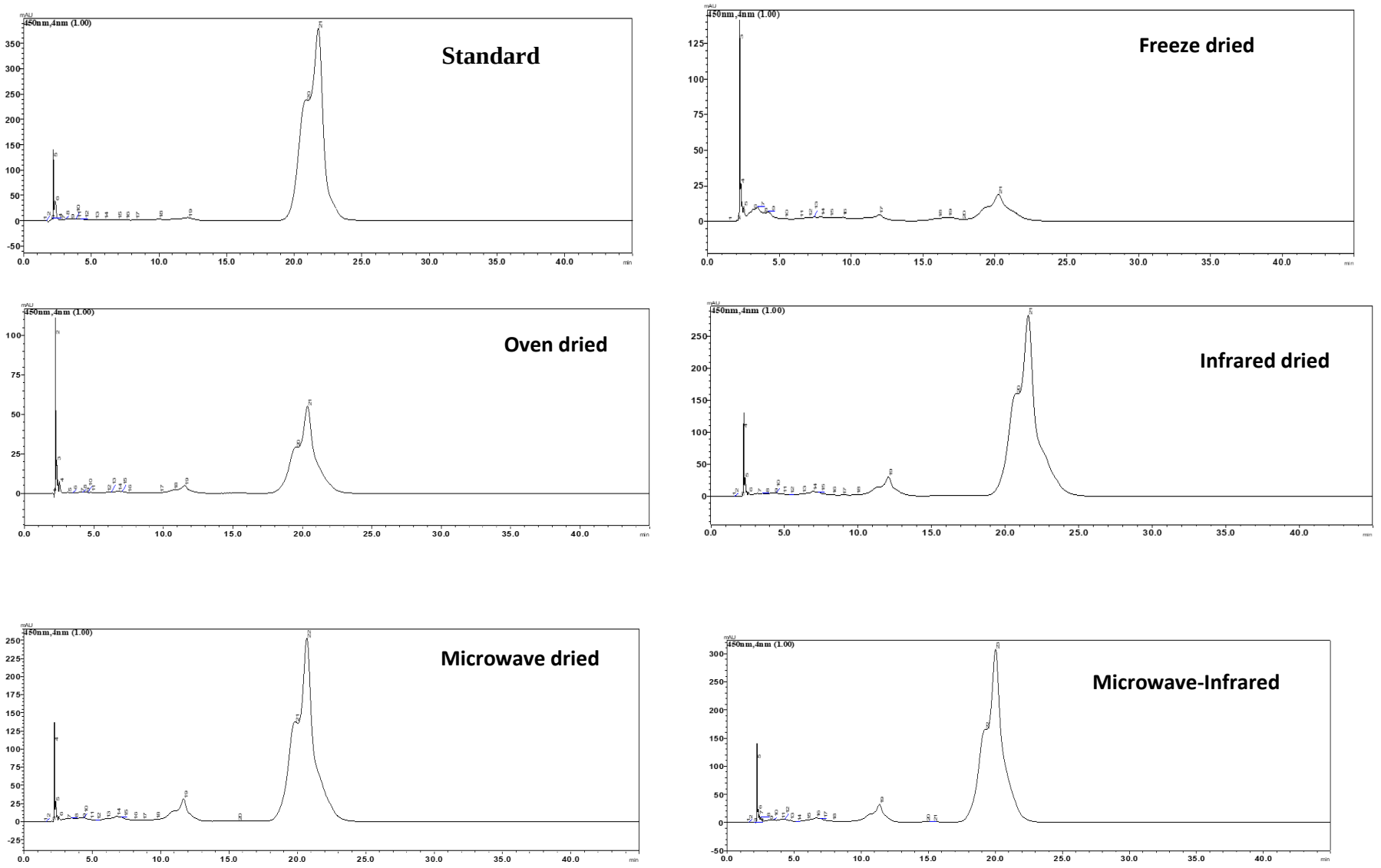


Figure 5.7. HPLC Chromatogram of β-carotene extract from Bellevue orange fleshed sweet potato flour, dried by different methods

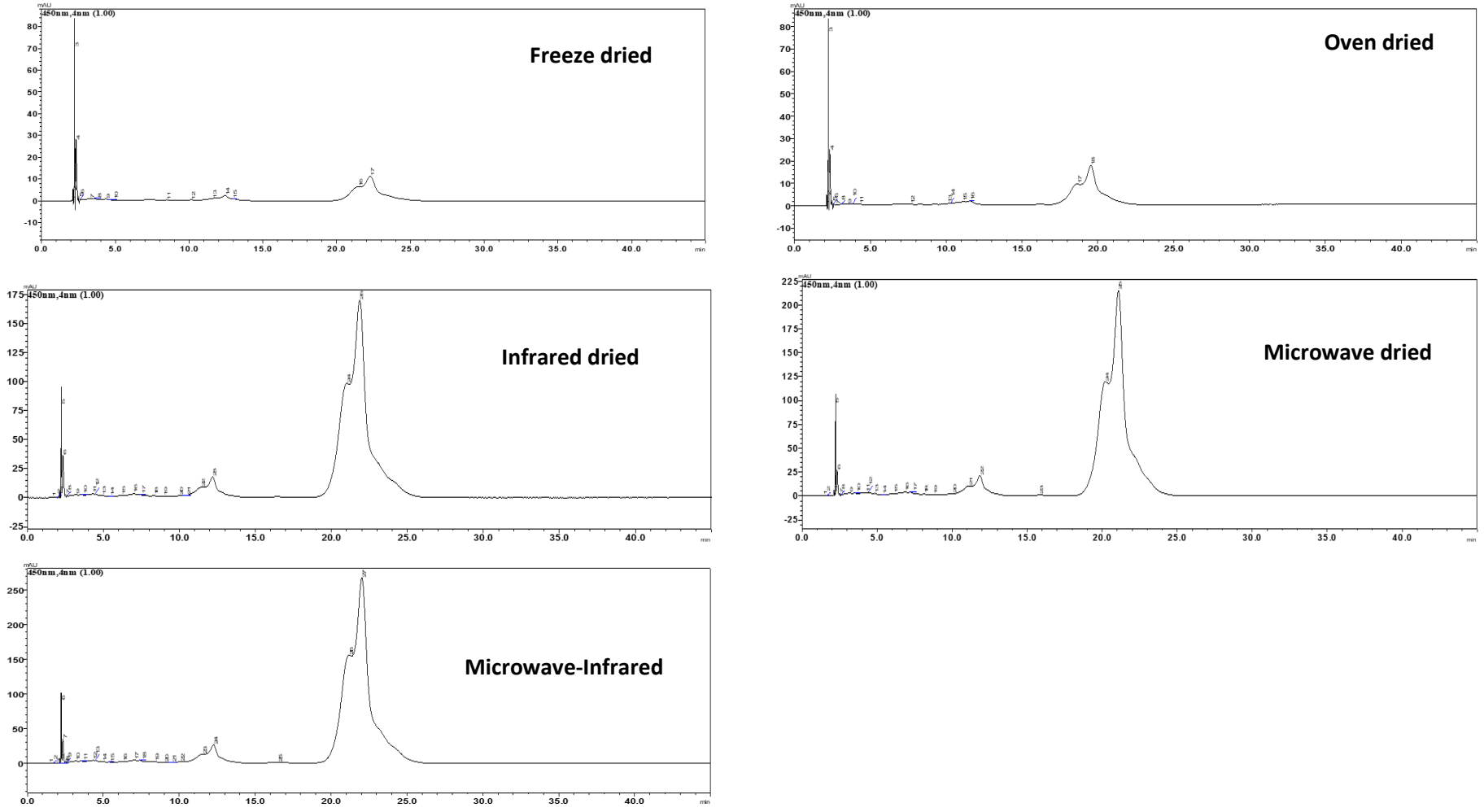


Figure 5.8. HPLC Chromatogram of β-carotene extract from Orleans orange fleshed sweet potato flour, dried by different methods

5.6. Colour values of orange-fleshed sweet potato

The different drying methods resulted in the colour change of both Bellevue and Orleans cultivars (Table 5.8). The oven and freeze-drying method had a higher colour change as compared to other drying methods. The infrared Bellevue dried flour was significantly different ($p<0.05$) from other drying methods on the L* value, but did not show any substantial difference (>0.05) for the b* value between drying methods (Table 5.8).

The L* values which indicate the whiteness, was not significantly different ($p > 0.05$), between microwave, infrared and combination of microwave and infrared dried flour (Table 5.8). The redness colour (a*) was greatly reduced by oven and freeze drying methods as compared to other drying methods (Table 5.8). The yellowness colour indicated by (b*) values were mostly reduced and showed a high significant difference ($p<0.05$) between the different drying methods (Table 5.8).

Table 5.8. Effects of different drying methods on the colour properties of Bellevue and Orleans orange-fleshed sweet potato flour

Cultivars	Drying methods	L*	a*	b*	ΔE
Bellevue	Freeze	79.75 ± 0.32^{a}	18.63 ± 0.39^{b}	21.02 ± 0.31^{a}	34.45
	Oven	78.61 ± 0.44^{a}	21.60 ± 0.67^{c}	20.02 ± 1.04^{a}	34.24
	IR	80.58 ± 0.20^{b}	25.18 ± 0.04^{d}	27.80 ± 0.16^{b}	25.46
	MW	79.58 ± 0.53^{a}	25.89 ± 0.5^{d}	27.95 ± 0.89^{b}	25.34
	MW+IR	79.55 ± 0.53^{a}	26.01 ± 0.39^{d}	27.18 ± 0.96^{b}	25.98
Orleans	Freeze	81.72 ± 0.09^{b}	18.94 ± 0.21^{b}	21.66 ± 0.23^{a}	32.03
	Oven	79.78 ± 0.58^{a}	17.60 ± 1.00^{a}	21.24 ± 1.11^{a}	33.25
	IR	82.30 ± 1.48^{b}	24.53 ± 3.55^{d}	26.34 ± 2.33^{b}	25.42
	MW	80.04 ± 0.19^{ab}	25.87 ± 1.11^{d}	27.15 ± 0.58^{b}	24.64
	MW+IR	80.28 ± 0.38^{ab}	26.82 ± 0.16^{d}	27.74 ± 0.37^{d}	23.77

The data is a representative of mean values and standard deviations (n=3). Values with same superscripts in column are not significantly different ($p > 0.05$)
Infrared (IR), microwave (MW)

5.7. Thermal properties of orange-fleshed sweet potato flour

The peaks for the endothermic energy are shown in Figure 5.9 and Figure 5.10 for Bellevue and Orleans respectively. Bellevue cultivars dried flour shows a higher endothermic energy as compared to that of Orleans cultivar (Table 5.9). The freeze dried Bellevue flour recorded a higher endothermic energy of 4.59 J/g, while the infrared dried Bellevue recorded the lowest value of 1.63 J/g. The oven, microwave, and microwave infrared dried Bellevue flour did not show any significant difference ($p>0.05$) on the endothermic energy (Table 5.9). There was no significant difference ($p>0.05$) on the endothermic energy of freeze, infrared, microwave, and microwave-infrared dried Orleans flour. The oven dried Orleans cultivar is showing a higher endothermic energy of 2.25 J/g.

The different drying methods have shown to be significantly different ($p<0.05$) on the onset temperature, peak temperature, and conclusion temperature of both Bellevue and Orleans cultivars

Table 5.9. Effects of different drying methods on the thermal properties of orange fleshed sweet potato flour

Samples	Drying method	T_0 (°c)	T_p (°c)	T_c (°C)	ΔH (j/g)
Bellevue	Freeze	72.84 ± 1.35^{g}	80.48 ± 0.69^{f}	85.96 ± 1.97^{g}	4.29 ± 1.38^{c}
	Oven	63.85 ± 1.01^{d}	65.92 ± 1.37^{a}	73.66 ± 1.22^{b}	2.27 ± 0.61^{b}
	Infrared	62.16 ± 0.69^{c}	66.49 ± 0.78^{a}	72.42 ± 0.96^{a}	1.63 ± 0.05^{a}
	Microwave	62.67 ± 0.87^{c}	67.49 ± 0.69^{b}	73.47 ± 0.56^{b}	2.25 ± 0.09^{b}
	Microwave-infrared	61.56 ± 1.02^{b}	67.85 ± 0.99^{b}	72.96 ± 0.94^{a}	2.01 ± 0.07^{b}
Orleans	Freeze	66.96 ± 0.33^{f}	72.63 ± 0.25^{e}	79.60 ± 0.34^{f}	1.08 ± 0.25^{a}
	Oven	62.26 ± 1.22^{c}	68.89 ± 1.09^{c}	76.35 ± 1.29^{d}	2.25 ± 0.77^{b}
	Infrared	60.69 ± 1.98^{a}	66.48 ± 1.57^{a}	75.35 ± 1.26^{c}	1.98 ± 0.64^{a}
	Microwave	61.06 ± 1.91^{b}	66.81 ± 1.68^{a}	73.81 ± 1.56^{b}	1.18 ± 0.08^{a}
	Microwave-infrared	65.61 ± 1.08^{e}	71.22 ± 1.27^{d}	78.83 ± 1.36^{e}	1.62 ± 0.77^{a}

The data is a representative of mean values and standard deviations (n=3). Values with same superscripts in column are not significantly different ($p < 0.05$)

T_o is the onset temperature, T_P is a peak temperature, T_C is a conclusion temperature and ΔH is the heat flow

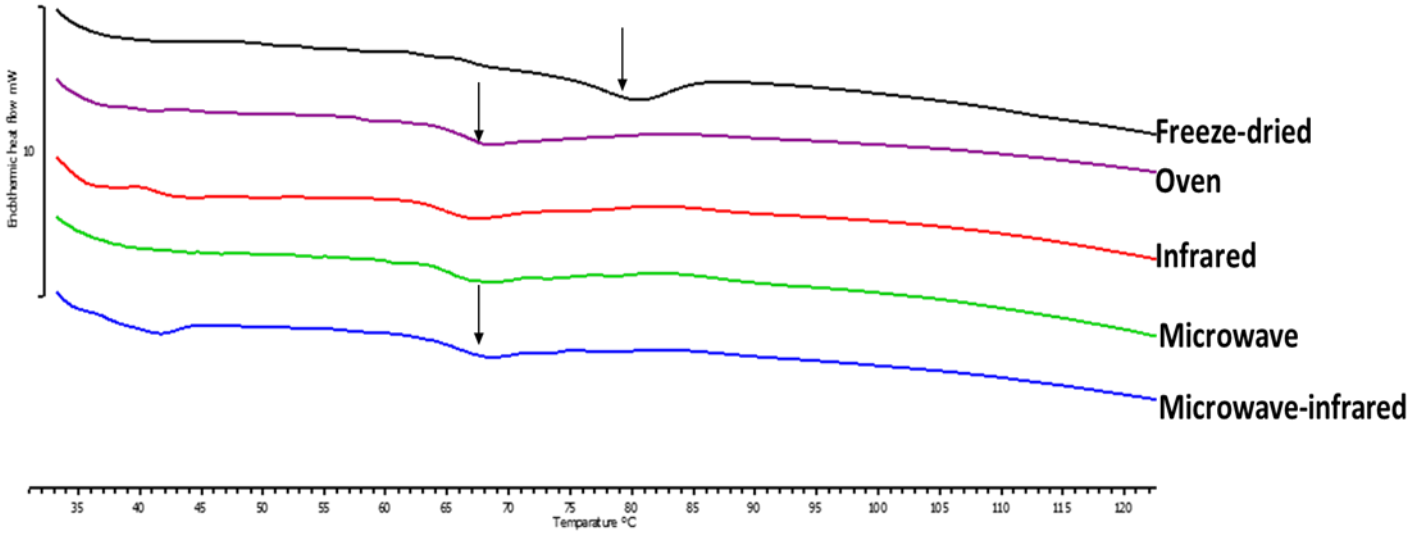


Figure 5.9. Effects of different drying methods on the thermal properties of Bellevue orange-fleshed sweet potato flour. Arrows highlight the enthalpy peak curve

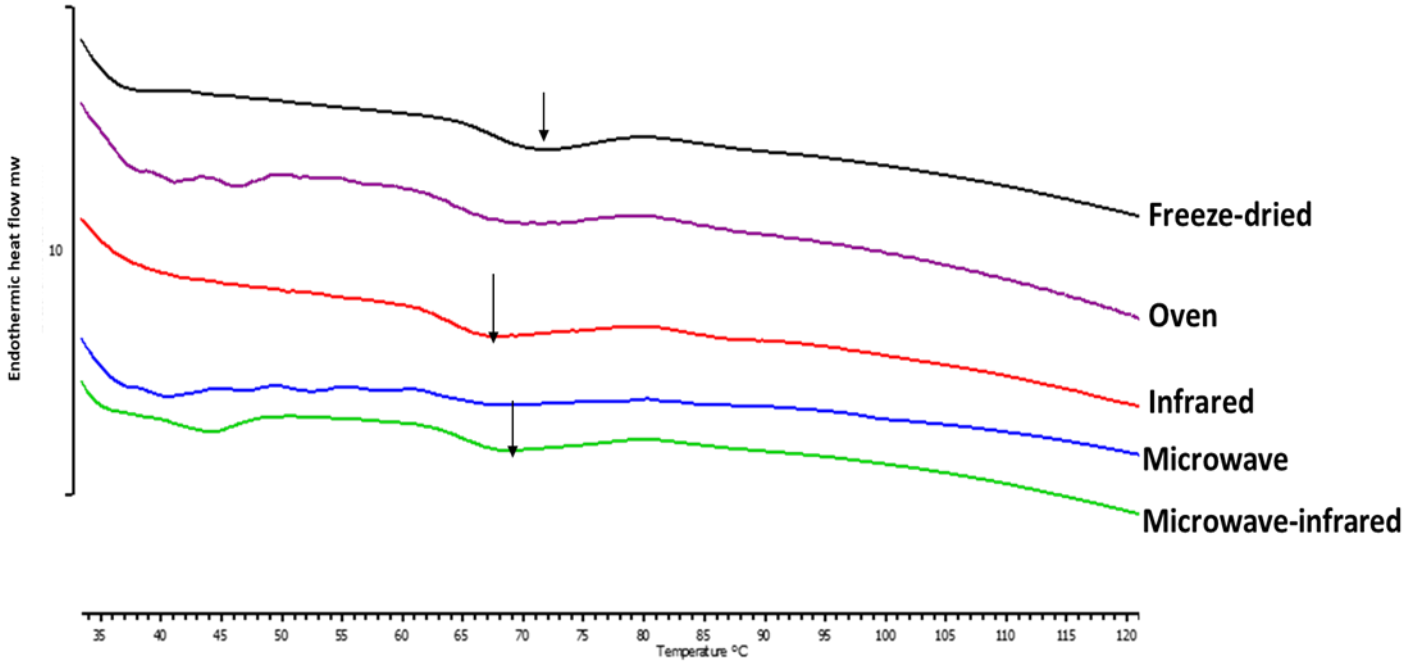


Figure 5.10. Effects of different drying methods on the thermal properties of Orleans orange-fleshed sweet potato flour. Arrows highlight the enthalpy peak curve

5.8. Microstructure of Bellevue and Orleans orange-fleshed sweet potato flour

Figure 5.11 shows the stained starch granules found in the OFSP flour. The microscopic images were visualized under polarized light, after being stained with iodine solution. The images show the dark starch granules pointed by the arrow (Figure 5.11), and some non-starch components, which did not absorb the iodine stain as shown from the infrared dried Bellevue and Orleans flour. The light microscope under polarized light is shown by Figure 5.12. The flour shows that most of the

starch granules were not completely damaged or gelatinized during the drying as shown by the arrows pointing at the birefringence.

The scanning electron microscope (SEM) images of the flours are also presented (Figure 5.13). The graphic images show different granule sizes, which can be due to different flour components such as sugars, protein, starch and non-starch polymers as pointed out by the arrows.

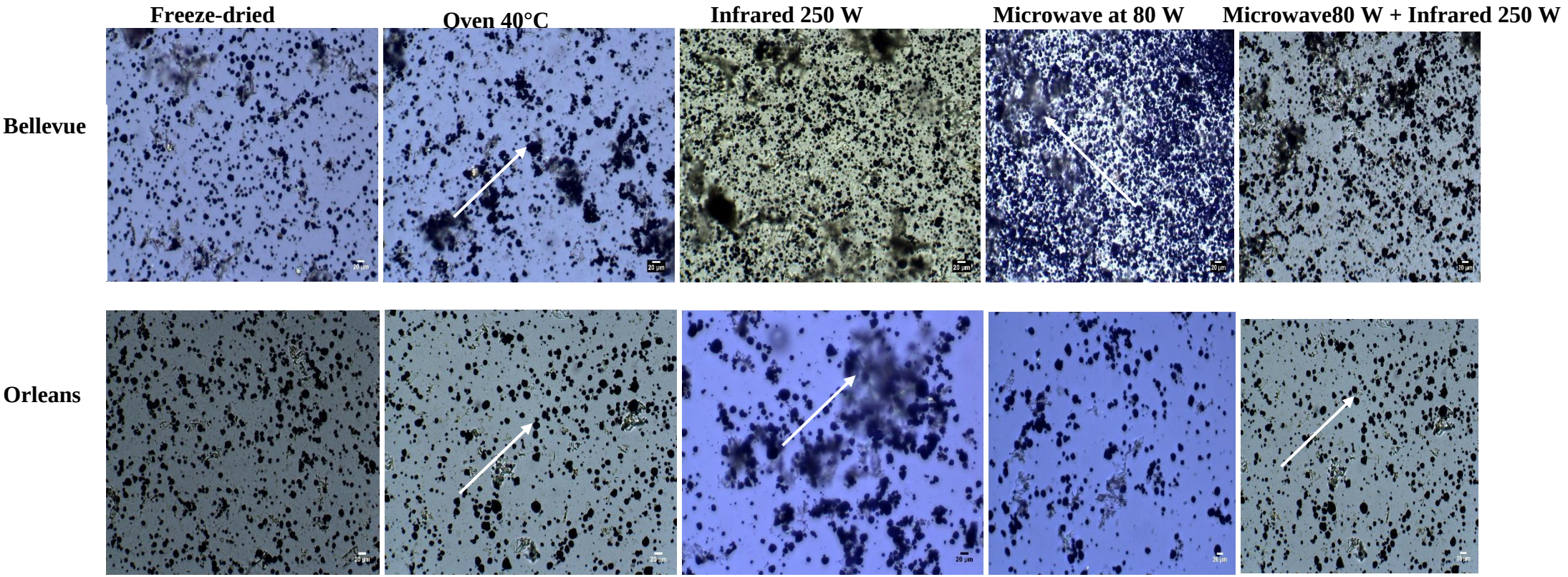
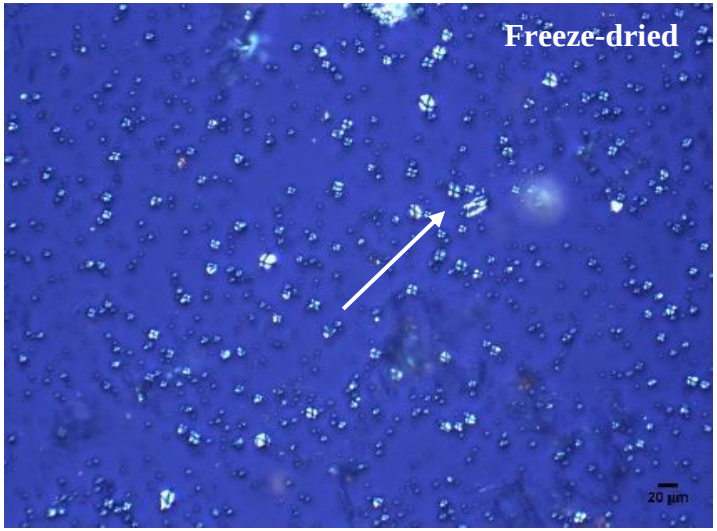
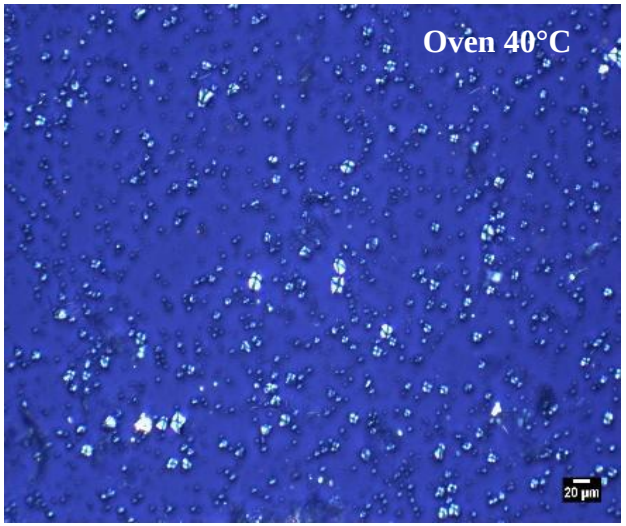
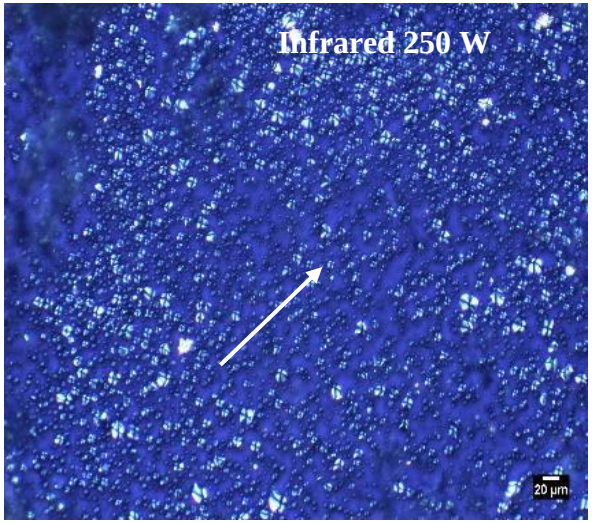


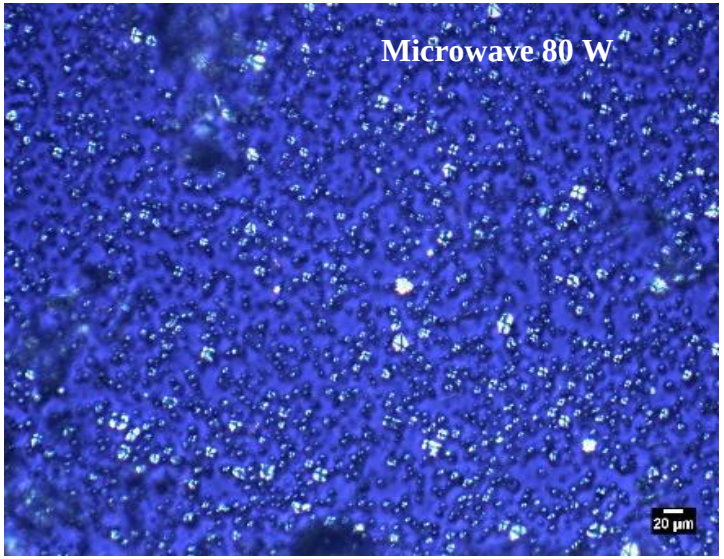
Figure 5.11. Effects of different drying methods on the iodine stained light microscope images of orange-fleshed sweet potato flour, viewed under polarized lens, starch was stained with blue/violet iodine solution.
Scale Bar 20 µm. Arrows highlight starch granule (black stains) and some non-starch polysaccharides.

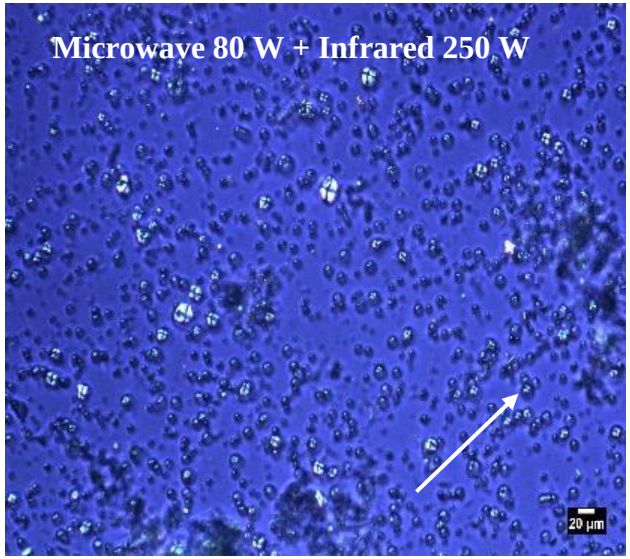
Bellevue











Orleans

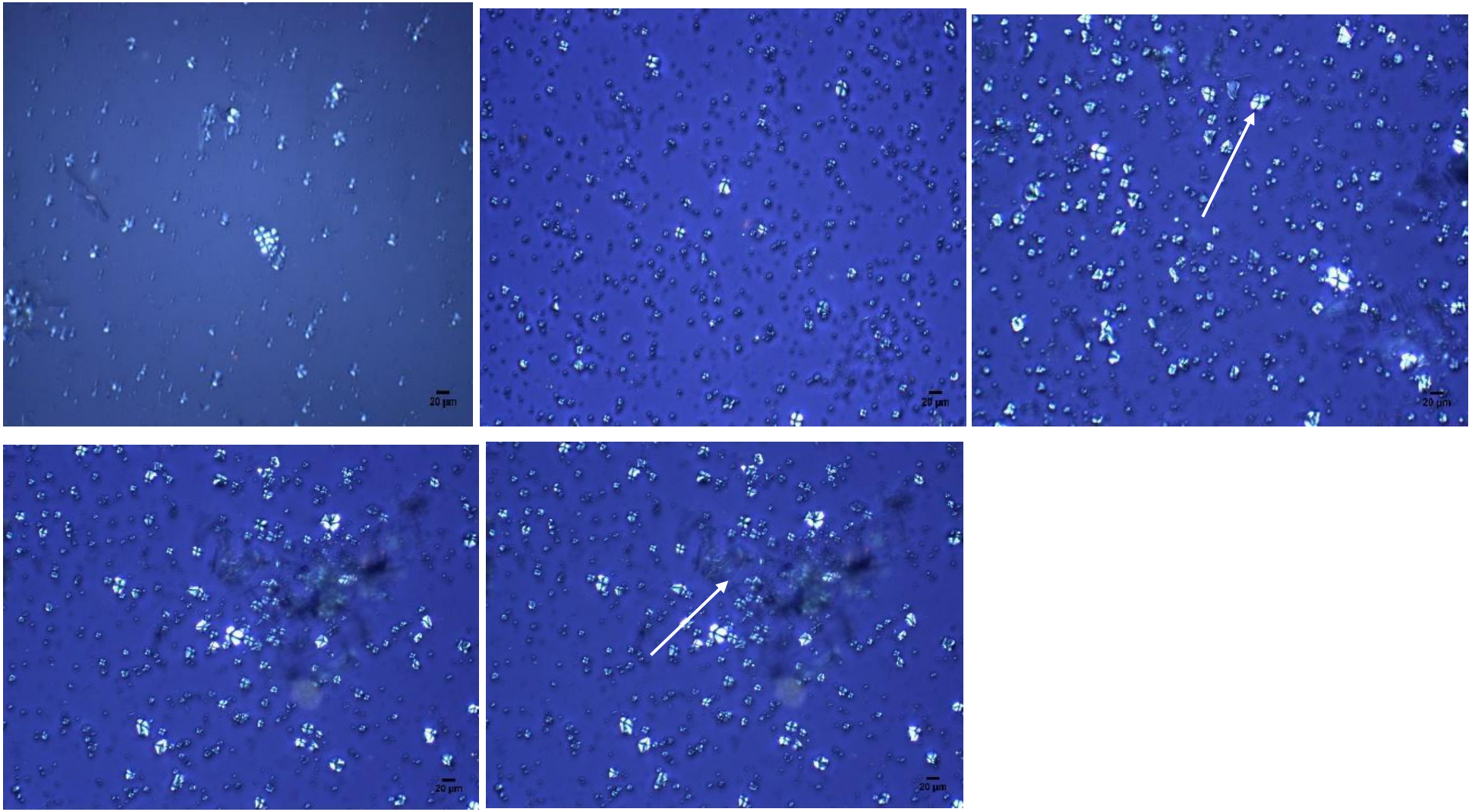
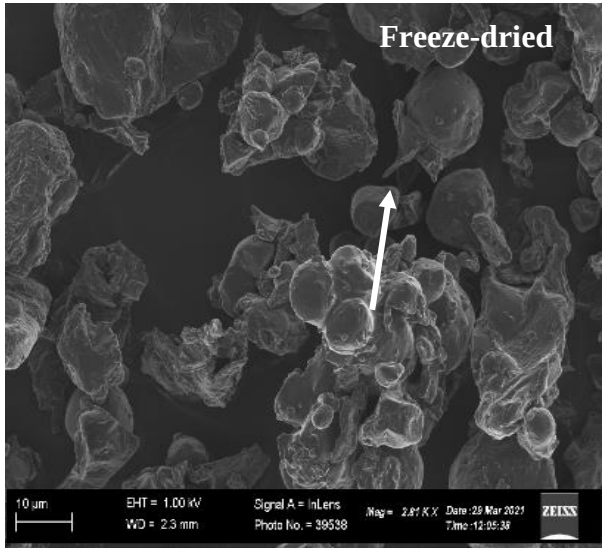
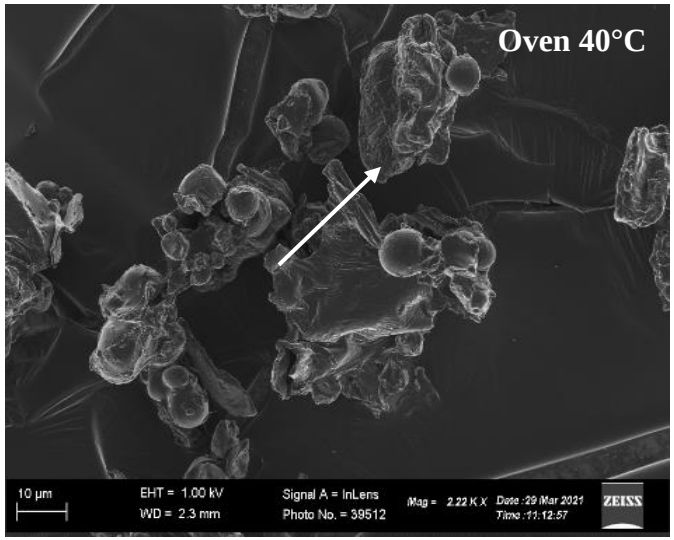
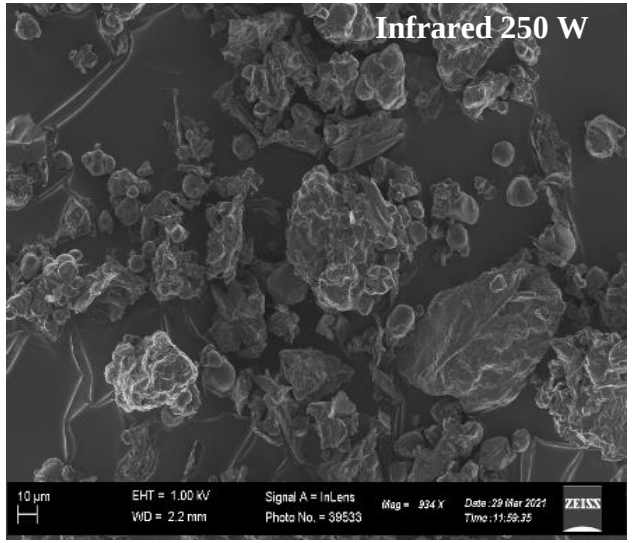


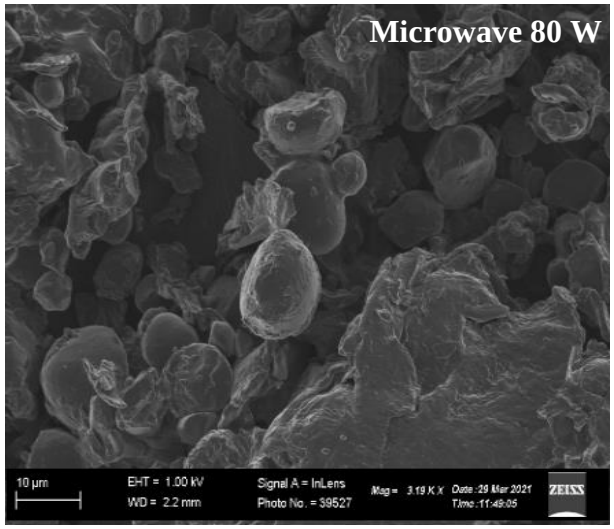
Figure 5.12. Effects of different drying methods on the polarized light microscope of dried orange-fleshed sweet potato flour. Bar 20 µm. Arrows highlight the starch granule, bifranges, and some non-starch polysaccharides.

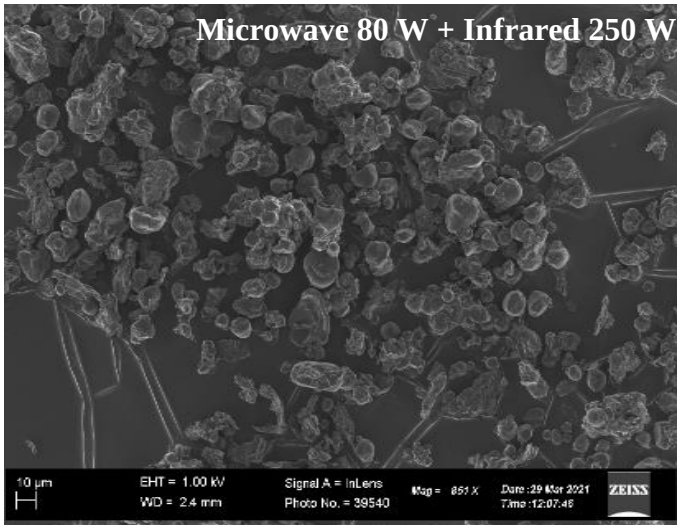
Bellevue











Orleans

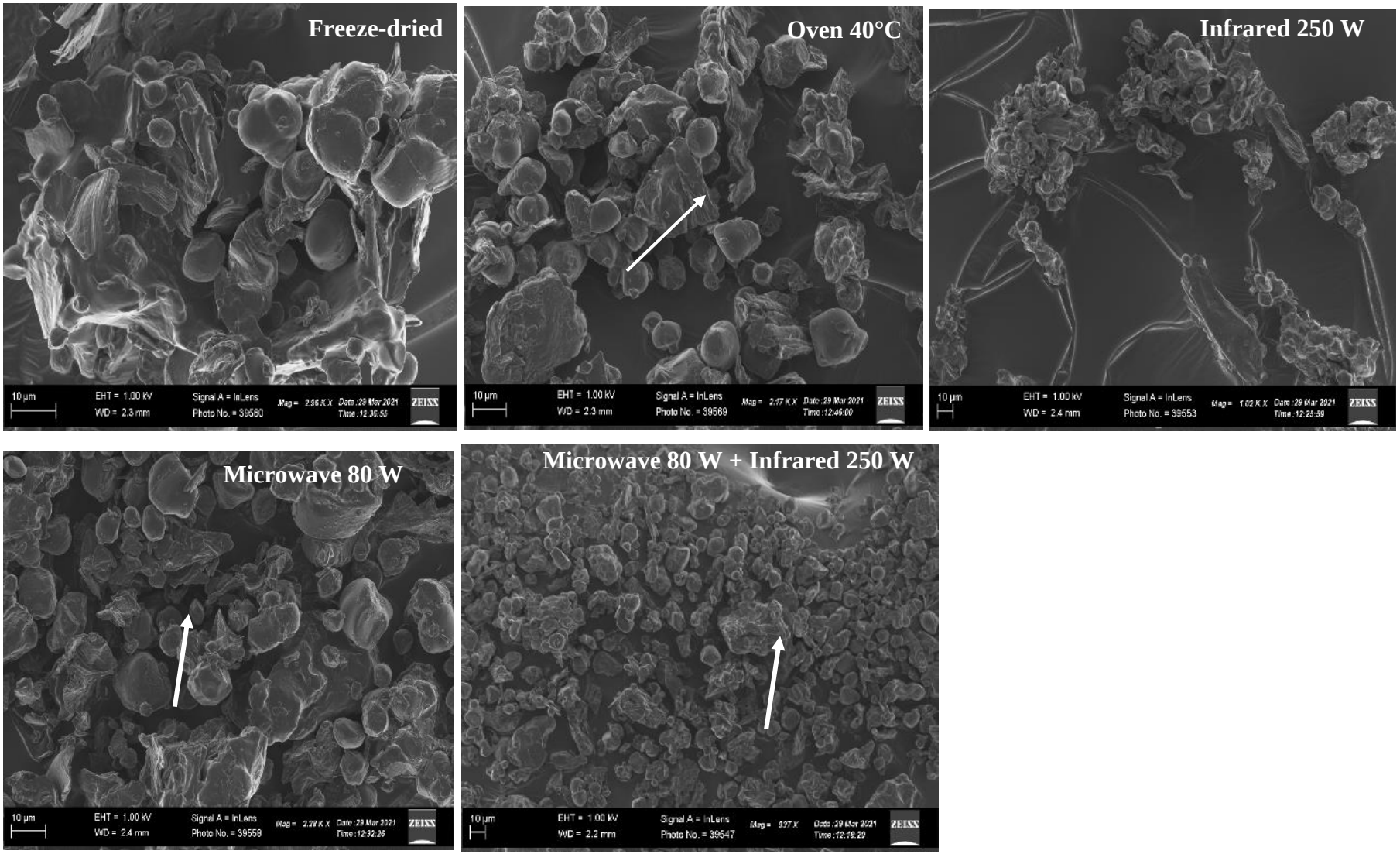


Figure 5.13. Effects of different drying methods on the scanning electron micrograph of dried orange-fleshed sweet potato flour. Scale Bar 10 µm. Arrows showing the flour granules

CHAPTER 6: General discussion and methodology review

6.1. General discussion

The chapter is divided into two sections, where the first part will be focusing on the review of the scientific methods used to conduct the research. Further details are discussed, focusing on the strength and weakness of the methodologies. The second part will be a discussion on the findings of the research, where scientific explanation will be provided, about the effects of each drying method on the drying kinetics, functional properties, physicochemical, and β-carotene content of orange-fleshed sweet potato flour.

6.2. Methodology review

6.2.1. Dehydration methods

Drying is a mass transfer process, which involves the removal of moisture through evaporation or by carrier gas provided by hot air (Onwude et al., 2018). The process requires a source of energy to provide heat energy, and this can be provided by conduction, convection or radiation. The most utilized drying methods for fruits and vegetables are oven, infrared, microwave and freeze-drying methods. With the mentioned thermal drying methods, temperature fluctuates during drying, due to mass transfer, and cooler air entering the drying chamber, with different air humidity (Liu et al., 2018).The rate of moisture transfer is not only affected by drying temperature, but also by the rate of air velocity. Therefore, to ensure that the drying conditions are the same for all drying methods, hot air at a constant temperature and velocity can be applied during drying, to create more continuous moisture transfer system when using oven, microwave and infrared drying methods.

The selected drying methods have also been applied in other food materials such as sweet potato, apple slices, eggplant, and green papers (Yan et al., 2013, Łechtańska et al., 2015, Askari et al., 2016). The drying temperatures used varied for each product, as well as sample parameters such as slice thickness, and pre-treatment methods. In this research, parameters used are comparable to those used by other researchers. The temperature used for oven drying was set at 40°C, microwave power was set at 80 W, infrared power was set at 250 W, and microwave-infrared was set at the same power levels. The air velocity was set at 3.5 m^2/s, the air temperature at 40°C, and circulated in the drying chamber during the experiment. The circulation of the hot air is to mitigate the external temperature fluctuations, and keep the drying chamber temperature constant.

Prior to the drying experiment, trials are conducted to determine optimum drying conditions. This involves testing different drying temperatures for the oven and different drying power levels for other drying methods such as microwave and infrared (Marzuki et al., 2020). For this research purpose, only microwave and infrared drying method trials were performed. The test trials were completed to determine optimum drying conditions, which the focus was to determine power levels that did not result in charring of the sweet potato slices, but resulted in complete drying of the slices at the same drying period.

The power levels tested for microwave were 120 W, 100 W and 80 W. From these power levels it was observed that 80 W for 60 minutes resulted in complete dried samples, without charring the sweet potato slices. Even though the drying rate was slower as compared to the other power levels. However, those higher power levels were resulting in charred samples and uneven dried samples. Therefore, the chosen power level was 80 W for the microwave. The power level tested for infrared drying were 350 W, 300 W and 250 W, from this trial the lower power level (250 W, for 90 minutes) had the same observation as that of microwave drying, therefore, it was chosen for the drying experiment.

6.2.2. Drying kinetics and modelling calculations

Drying kinetics is known as a graphical presentation providing information about the rate and mechanism of moisture transfer shown by the drying curve (Akpinar, 2006). The information used to derive the drying curve is relying on the drying methods, and data obtained from the moisture content during drying (Aamir and Boonsupthip, 2017). The weakness of this methodology is that the data used for this step is dependent on the drying method reliability, good experimental design such as ensuring that the drying conditions were at least the same, having the same slice dimensions (thickness and circumference), and the same air velocity as well as air temperature. Thus, thinner slices enables faster moisture transfer as compared to thick slices, and higher air velocity will also have higher moisture transfer as compared to slower air velocity, with low air temperature (Akpinar, 2006). In order to eliminate this weakness for this experiment, the slices were measured for thickness to test the repeatability of the slice cutter, and the mean, standard deviation were 5.22 ± 0.09 mean value and coefficient of variation was less than 1%. This shows that the slice cutter was precise due to lower coefficient variance.

Selection of appropriate drying models is dependent on the data obtained during drying kinetics calculations. Drying models have been used for a purpose of predicting the drying period of specific drying models (Chanpet et al., 2020). The models used in this research are semi-theoretical models,

and these models can be precise considering that they put into account factors that can influence the drying behaviour, and some can even describe the drying mechanism of other drying methods (Srikiatden and Roberts, 2007). Semi theoretical models work perfectly when drying parameters such as temperature, relative humidity, air velocity, and moisture are in the range for which the model is developed (Onwude et al., 2019).

6.2.3. Functional properties

Most of the functional properties of the orange-fleshed sweet potato flour are influenced by the flour composition, such as starch, non-starch polysaccharides, simple sugars, and proteins. In this research, water absorption capacity, swelling capacity, and solubility index are some of the physicochemical properties that were analysed. The methods used for determining these properties have been used by other researchers in previous studies.

The water absorption capacity studies the ability of the flour to absorb water under room temperature, without heating the flour, this looks at the ratio of water absorbed by 1 g (dry basis) of the flour. The method requires 1 g of flour, added to 10 ml of distilled water, centrifuged and the supernatant separated from the pellet, and weigh the pellet, which contains the absorbed water and the flour. The weight of the flour is subtracted from the pellet weight to give the weight of the water absorbed, and divided by the weight of the flour to give a ratio of flour to water (Ngoma et al., 2019). The method has its weakness, which can involve overestimation or underestimation of the water absorption capacity of the flour. This can be due to some of the flour residues being discarded, with the supernatant or excess supernatant remaining in the flour residue. However, precautions were taken to ensure that no sediment is lost and no excess supernatant remains in the centrifuge tubes.

High temperatures are used to understand the swelling capacity of the flour, this temperature ranges from 60-80°C. Swelling capacity studies the ability of the flour to absorb water under high temperatures, which causes swelling of the starch granule. The increase in temperature allows for the swelling of starch granules, which absorbs more water, and leads to swelling capacity. The method covers for both swelling properties of flour particles, and the solubility properties.

The soluble solids are retrieved from the supernatant after centrifugation, which are dried until constant weight at 105°C. The weakness about the method is that after heat treatment, most of the insoluble solids are unattached. Implying that they can end up in the supernatant, and this can lead to overestimation of the soluble solids if not properly done. More so, some of the free water can still left in the centrifuge tubes, which can result in over estimation of the swelling capacity as it is

expressed in terms of weight. When the experiment is performed with precaution these limitations can be avoided.

6.2.4. Pasting properties

The pasting properties of the orange-fleshed sweet potato flour were performed using the starch cell of a modular compact rheometer, which profiles viscosity of the flour suspension. The method used a programmed heating and cooling cycle and it records pasting temperature, peak viscosity, trough viscosity, breakdown viscosity, setback viscosity and final viscosity (Kaur and Singh, 2015). Other devices such as rapid visco analyzer (RVA) can be used to profile the viscosity properties of polymers. Rheometer and RVA operate on the same principle, and provide comparable results (Balet et al., 2019).

Sample preparation can lead to inaccurate results. It is important to have solid on dry matter basis for preparing the suspension, rather than as basis as differences in water content. Which will affect final solid content and thus can impact on viscosity. Furthermore, due to higher temperatures used for the viscosity profiling, the moisture content can decrease due to water evaporation. This can result in an increase of solid content and can lead to overestimation of sample viscosity. To minimise water evaporation, the cover is used to condense the water and minimise increase in solid content.

6.2.5. Thermal properties

The study of the thermal properties of food material is conducted by using the differential scanning calorimetry (DSC). The DSC has been used to give information about phase and glass transition, gelatinization temperature, melting point, percent of crystallinity and enthalpies of different transitions (Gill et al., 2010). The method uses a thermodynamic process in which the difference in the amount of energy required to increase the temperature of the food material and the reference is measured as a function of temperature. This method has been used in analysing thermal properties of different food components such as starch, non-starch polysaccharides, lipids and proteins (Schindler et al., 2017).

The dynamic nature of the process has been identified as a drawback for the technique, as well as the small sample quantity used for analysis, which is suspended in a ratio of 1:3 in distilled water on a dry basis. This ratio is used for comparison between samples and with literature value, as water affects the thermal transition of starch gelatinization. DSC data also relies on the known sample weight, and sample heat conductivity. Which is ran against the reference blank, and the sample is ran over constant heating and cooling rate at 10°C/ minute. It has been found to have a good endothermic peak, which measures levels of crystallinity accurately as compared to the heating rate

at 5°C/ minute or 15°C/ minute (Cassel, 2001). The blank is used to correct any errors, which can occur during the scanning process (Schick, 2009). In order to minimise moisture loss, the material is run under vacuum, with high pressure. The increased pressure increases the boiling point temperature of water, therefore minimal moisture loss. The increased pressure also increases reaction rate, making it quick for exothermic peaks to appear, and also save the time of analysis (Wang et al., 2016).

6.2.6. β-carotene determination

The methods employed to extract β-carotene are diverse. Utilisation of different organic solvent has been used by different researchers, and most of the organic solvent used include chloroform, hexane, tetrahydrofuran (THF), methanol, dichloromethane acetone, petroleum ether and ethanol (Tiwari et al., 2019). The organic solvent is able to extract the β-carotene because of their solubility nature, and β-carotene is soluble in the organic solvent, making it easy for extraction (Butnariu, 2016). However, another challenge faced by the extraction procedure is the stability of β-carotene compounds, which can be easily oxidized by enzymes, oxygen, metallic ions as well as degraded by exposure to light and higher temperature (Charoensiri et al., 2009). Therefore, the extraction environment needs to be exclusive of these factors, even though oxygen, metallic ions and enzymes cannot be controlled throughout the extraction process, light and temperature can be controlled. Hence, in this experiment the extraction was performed in the absence of light and under room temperature. Furthermore, storage temperatures to reduce degradation of β-carotene have to be low, which can be between -20°C to - 80°C (Stutz et al., 2015). For this study, the orange-fleshed sweet potato flours were stored under -20°C, and sealed in an airtight container, to ensure the minimal loss of β-carotene.

The THF was selected as the extracting solvent, this is because β-carotene is highly soluble in THF organic solvent as compared to other solvent (Stutz et al., 2015). The loss of β-carotene by oxidation in extracting solvent such as toluene, cyclohexane, and dichloromethane as well as in aqueous solution has been stated (Benevides et al., 2011). During extraction of β-carotene, oxygen cannot be excluded from the environment, which can react with the double bonds of the carotenoids structure, resulting on formation of 5,6-epoxy-12´-apo-β-carotenal, 7-apo-β-caroten-7-al (β-cyclocitral), 12´-apo-β-carotenal, amongst others (Benevides et al., 2011). The formation of this molecule results from the degradation of β-carotene. Extra treatments are required, this include addition of anti-oxidant such as butylated hydroxytoluene (TBH), tert-butylhydroqinone (TBHQ), or pyrogallol in the extraction solvent, other treatment can include usage of acid neutralisers such as magnesium carbonate or calcium carbonate (Saini and Keum, 2015). During the extraction

process, these steps were not done. However, other steps such as rapid extraction process, and extracting in the absence of light were followed, which reduced the loss of β-carotene.

There is no universally accepted method for determining the quantity of β-carotene. There are several methods such as usage of gas chromatography, high performance liquid chromatography, ultrafast liquid chromatography (UFLC), and mass spectrometry just to mention a few. For this study, UFLC was selected for quantifying the β-carotene. The UFLC operates by passing an anylate (sample) through a mobile phase in a column filled with solid adsorbent material; the compound in the sample interacts with adsorbent differently according to their molecular size, resulting in a different flow rate. The compounds are identified by detection of UV-Vis detectors, with a reading of between 200 and 600 nm (Wahab et al., 2021). The UFLC has great benefits over other analytical methods, such as giving high peak capacity, small peak widths, and increase in sensitivity, high chromatograph tenacity, and short analysis time (Gupta et al., 2015). However, the drawbacks of this method is that it requires C18 column over C30 column. The problem with octadecylsilane (C18) column is its inability to detect the carotenoids isomers, which can be detected by using the triacontyl (C30) column on reverse phase high performance liquid chromatography (Gupta et al., 2015). Nonetheless, the method has been used successfully to detect non isomer carotenoids, which makes it applicable to the purpose of the study.

6.3. Results discussion

6.3.1. Drying kinetics and modelling

The moisture transfer during oven drying is by diffusion, however, in order to start drying, the drying chamber temperature has to be in equilibrium to the applied temperature, which requires heating of the surrounding environment (Wilson et al., 2002). The initiation of moisture transfer will begin once the sweet potato slice surface temperature is equilibrium to the drying chamber temperature. Once the sample surface has reached equilibrium to the drying temperature, the internal moisture transfer begins. Different parts of the plant, such as intercellular, intracellular and cell wall environments, which have different proportions of water will start to lose water once the temperature increases (Khan et al., 2018). About 2-5% of the tight bound water is found in the cell wall, this type of water is not easily removed during drying (Mahiuddin et al., 2018). The vacuole and cytoplasm are known as water reservoirs, which contribute about 78-95% intracellular water to the cell, the type of water is also known as loosely bound water (Figure 6.1). The free water found within the intracellular environment is the first one to be removed during drying (Khan et al., 2018). During drying at higher temperatures, the plant cell can collapse, releasing bound water, and becomes free water, which is removed by the drying medium (Khan et al., 2018).

Due to the hygroscopic nature of sweet potato slices, the moisture transfer mechanism is by diffusion, which is initiated by free water diffusing to the surface of the food material that is then removed by the evaporating medium (Khan et al., 2018). The removal of intracellular water can follow one of the two phenomena, which is either symplastic transport (via micro capillaries in the cell wall) or apoplastic transport (when intracellular water migrates to intercellular space) (Khan et al., 2018).The bound water removal is also temperature dependent, when samples are dried at higher temperatures (>50°C) this can cause cells to collapse and the bound water will be released as free water to the intracellular environment. However, when lower temperatures are used (<50°C), there is absence of cell rupture, therefore, the intracellular water migrates from cells to the neighbouring cell, and to the intercellular spaces using thin capillaries. This pathway is a very time consuming process, which results in a low drying rate. This can also support the fact that oven drying method resulted in lower drying rate.

The results obtained from this research for oven drying are comparable to the findings reported by Thao and Noonhorm (2011), where they compared drying methods such as infrared, fluidized bed drying, tray drying and oven drying under different drying temperatures ranging from 45°C-65°C. They have reported that oven drying at 45°C was the slowest drying method. Mahiuddin et al (2018) explain that case hardening phenomena can happen when higher temperatures (>50°C) are applied during drying. It has been explained that food material undergoes shrinkage than case hardening under lower temperatures (<50°C) (Figure 6.1). This is because when low temperatures are used, the plant cells experience a low thermal stress, due to low or absence of cell raptures (Mahiuddin et al., 2018). The shrinkage happens because of the main two reasons. These are that the plant tissue is incapable of maintaining the structural integrity when water is removed and also that the surface skin structure collapsing (Mahiuddin et al., 2018). The absence of case hardening also reflects similar functional properties of the flours as affected by the different drying methods.

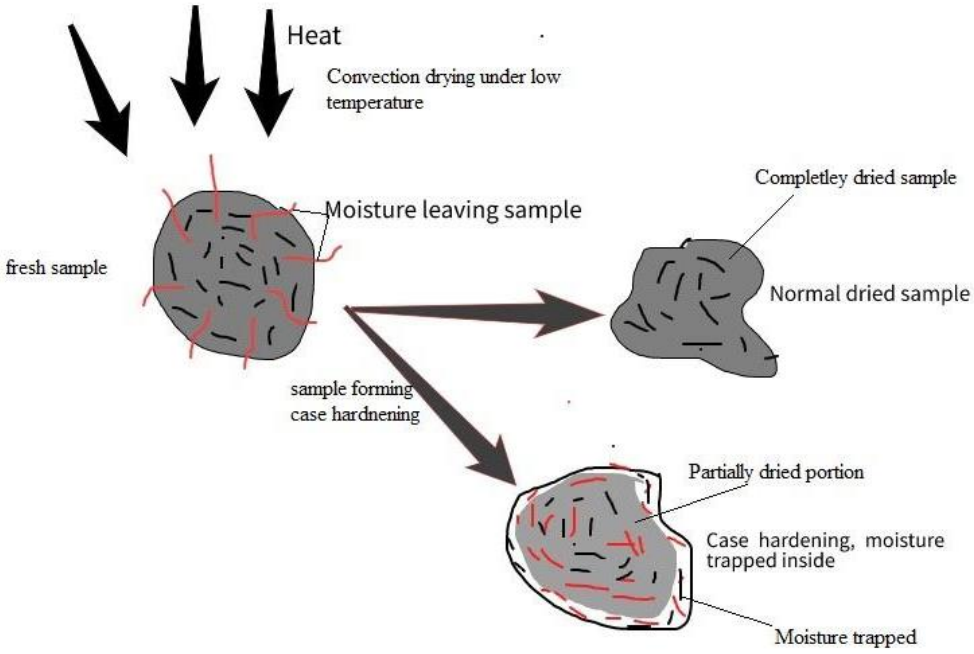


Figure 6.1. The mechanism of case hardening during drying as compared to normal dried food sample. (Own work)

The electromagnetic radiation drying method (microwave and infrared) used in this study had the fastest drying rate as compared to convective oven drying. During the drying experiment, it is worth noting that dry air at 40°C was supplied to the drying chamber at a constant velocity of 3.5 m/s. The dry air applied assisted in removing moisture from the food surface and maintaining constant drying temperature in the drying chamber (Figure 6.2). Most studies have shown that application of hot air can be used as an assistance for drying for effective moisture transfer. Although the hot air is reported to increase the moisture transfer from the sample surface, it can also play a role in structural changes of the plant cells (Mahiuddin et al., 2018). The degree of shrinkage is dependent on the air velocity, as higher air velocity results in a lower shrinkage as compared to lower air velocity (Mahiuddin et al., 2018).

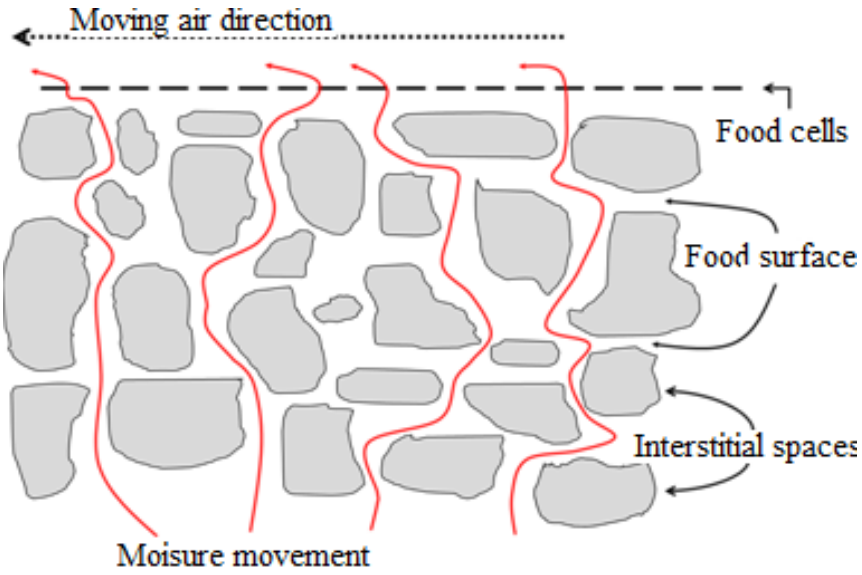


Figure 6.2. Moisture transfer from food sample during drying process (Own work)

Energy generation by electromagnetic radiation (microwave and infrared) is by dipole polarization of water molecules, caused by oscillation or vibration. Energy is produced by the instantaneous rotation of water molecules, as they try to align to the magnetic field of the electromagnetic radiation (Guo et al., 2017). In this study, microwave and infrared energy applied were 80 W and 250 W respectively. These energy levels are different as compared to other experiments from other studies. The study done by Ibrahim Doymaz (2012) of drying sweet potato with infrared at power levels of 104 W, 125W and 167 W, reported that drying at higher power levels can reduce the drying time, which took 120 minutes at power level of 167 W to dry the sweet potato slices. Thao and Moonhorm (2011) also reported that infrared drying was faster as compared to that of the oven drying method, where infrared temperature was at 65°C. This is similar to this current study.

Microwave drying time was shorter than that of infrared in this study. This is attributed to the deep penetration of microwave electromagnetic energy as mentioned above. These results are similar to those produced by Abbaspour-Gilandeh et al (2021), where they used a microwave at power level of 70 W, and hot air at 40°C to dry sweet potato slices. They conveyed that the drying time of the method took about 70 minutes, however, in this study the drying time was 60 minutes. Askari et al (2016) reported the drying time of 110 minutes, when drying apple slices at 200 W using a microwave drying method. Microwave and infrared methods apply electromagnetic energy, which is absorbed by water molecules because of the high dielectric properties of water. The method does not require temperature equilibrium change before they can start moisture transfer from the food material. Simultaneous internal and external moisture transfer takes place upon the application of

the electromagnetic energy, with the assistance of hot air. This increases moisture transfer rate and coefficient of diffusion. Thereby reducing any structural changes, and minimizing shrinkage.

Combination of the two electromagnetic radiation drying technology (Microwave and Infrared), gives the advantage of having both volumetric heating mechanism by microwave and surface heating by infrared, which increase the moisture transfer rate. This is what has been observed in this experiment, which resulted in the drying rate being reduced to 45 minutes. Thus, making this drying technique the fastest one. Similar results have been conveyed by other researchers, where the utilization of hybrid combined drying technologies such as microwave and infrared has significantly reduced the drying time. These same results were reported by Łechtanska et al (2015) that combined hot air, microwave and infrared reduced the drying time of the green pepper.

The oven drying curve shows all the three drying periods, which occurred during the drying process. This period includes a constant drying period, first falling rate period and second falling rate period. These periods occur because of the drying mechanism adopted by oven drying technology, as well as the change in morphological structure of the sweet potato slices, which were mentioned above. Figure 5.2 indicates that infrared only shows the first and second falling rate, while microwave, and combination of microwave and infrared shows only the second falling rate. The absorption of electromagnetic radiation by the water molecules can result in a rapid increase of temperature (>50°C) when converted to thermal energy (Figure 6.3). The rapid temperature increase has been reported to cause cellular structural collapse, which instantly releases bound water from the intracellular to the intercellular area where it becomes free water (Kumar et al., 2016).

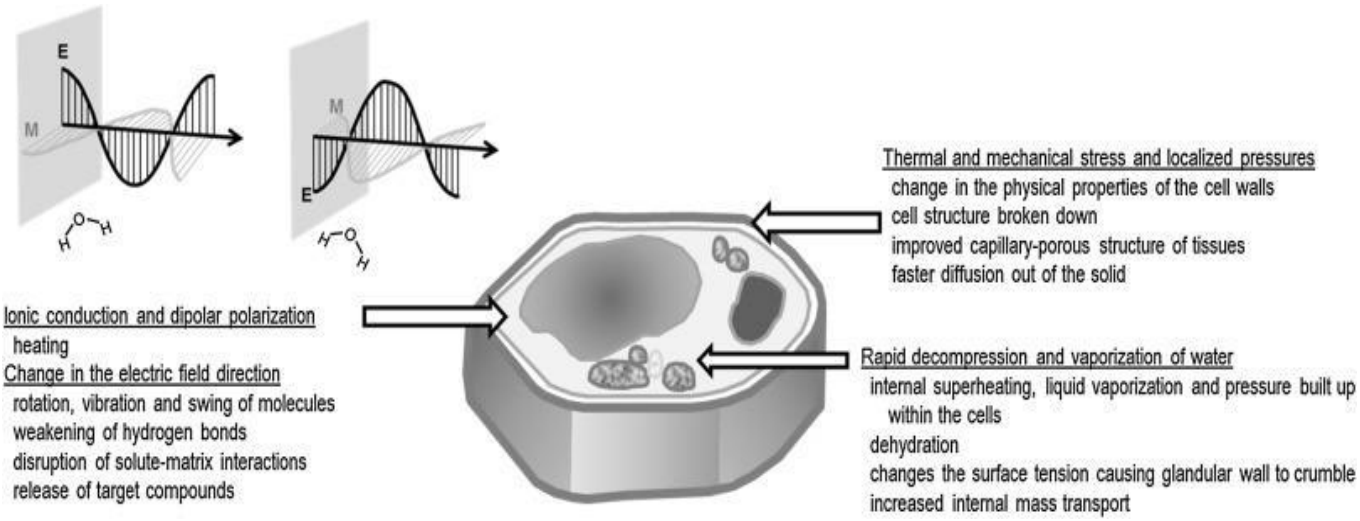


Figure 6.3. Effects of microwave heat mechanism on the microstructure of plant cell and water evaporation during drying (Rodríguez Seoane et al., 2017).

The bound water is instantly evaporated by the volumetric pressure and carried out by the hot air (Khan et al., 2018b). This transition results in the absence of constant drying period, and only shows the second falling rate period in microwave and microwave-infrared drying methods (Figure 5.2). The two falling rate periods observed from drying with infrared can be due to the fact that the drying mechanism caused shrinkage on the samples, owing to rapid heating and high temperatures (Mahiuddin et al., 2018). It is worth noting that infrared has high heating temperatures (>65°C). According to Mahiuddin et al., (2018), these high temperatures can cause thermal cellular stress, which will result in a solid surface due to rapid dehydration on the food surface. The presence of the second falling rate from the infrared graph can be evidence of further cellular collapse.

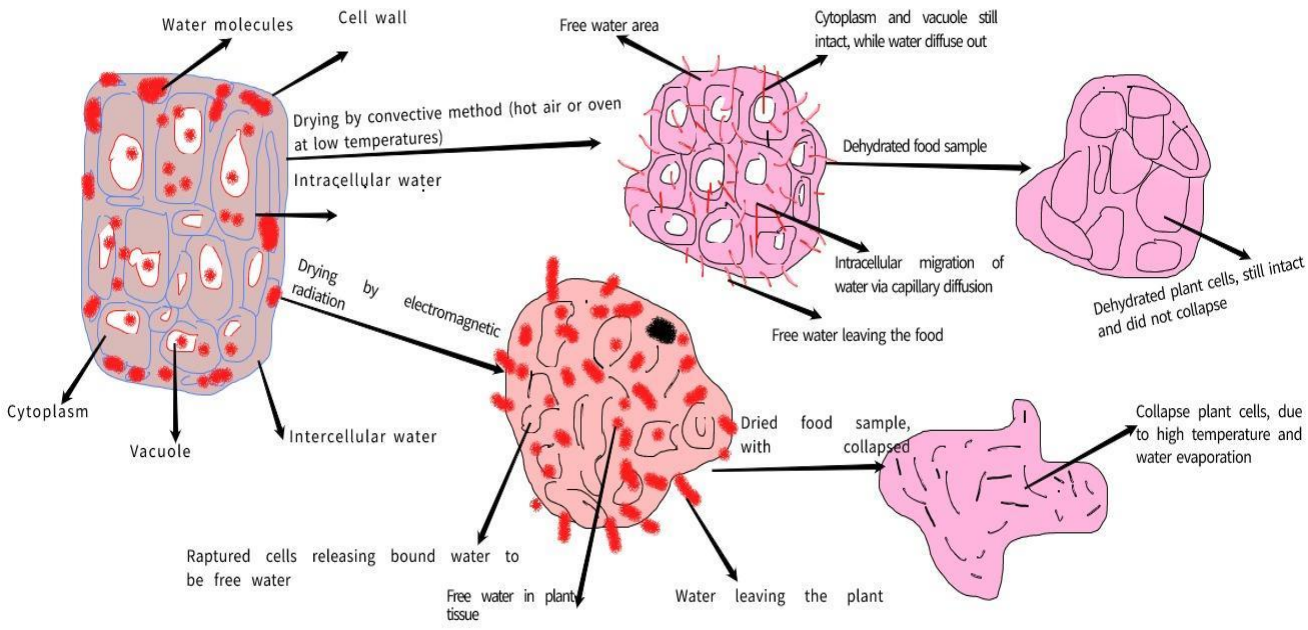


Figure 6.4.Water diffusion mechanism of electromagnetic radiation (microwave and infrared) and convective (oven) drying methods from the plant tissue during drying. (Own work)

Semi theoretical models are used to correctly predict the suitable drying method for the sweet potato slices, under the selected drying parameters. More theoretical methods are described in Table 2.2. Based on the results (Table 5.1), it can be seen that most of the models fitted the data from different drying methods. The high coefficient of diffusion seems to work well with all the models, however, when the coefficient of diffusion is lower, the models seem to be inappropriately fitting (Table 5.1). The change in microstructure such as bursting and collapse of cell membrane caused by microwave and infrared (Figure 6.4), increases the moisture transfer and results in higher coefficient of diffusion. Oven drying does not cause any cell burst and the moisture transfer is by capillary

diffusion, which is a slow process, and therefore results in a lower coefficient of diffusion. Henderson and Pabis models are the same reported by Si et al (2016), where they did a model for drying Raspberry drying by infrared. However, another study by Onwude et al (2019) has shown that even with the other models such as two term exponential, Page and Newton models can best fit for infrared drying methods, where infrared was used to dry orange-fleshed sweet potato. The models can fit for any drying conditions, as long the parameters are suitable (Onwude et al., 2019).

Marzuki et al (2020) 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 this study, the Lewis model reported a lower coefficient of determination for oven drying. However, this can be due to lower temperature used (40°C), which resulted in lower moisture diffusion or drying rate. Microwave drying for sweet potato slices using a microwave at 180 W was also studied by Junqueira et al (2016). From their study, they have reported Two terms as a fitting model for the drying parameter, other models such as 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 a fit for drying power at 80 W. However, other models such as Midilli and Kucuk, Wang and Singh, Parabolic and Weibull distribution have shown to be suitable for microwave drying at 350 and 180 W (Junqueira et al., 2016).

For the combined microwave-infrared method, the three models (Page, Lewis, Henderson and Pabis) have shown a higher coefficient of determination (Table 5.1). The combined drying methods also show a higher coefficient of diffusion, which is due to faster moisture transfer during drying. The high coefficient of diffusion is due to the effect of the rapid heating of microwave and microwave radiations, which might have caused rapid cell rapture and instant release of and evaporation of water (Doymaz, 2012, Feng et al., 2012, Junqueira et al., 2016, Guo et al., 2017).

6.3.2. β-carotene content of the dried flour

Table 5.7 shows the summary about the effects of the drying methods on the β-carotene content of the dried orange-fleshed sweet potato flour. The values obtained are different from other studies due to differences in cultivars, growing conditions and nutrient compositions (Olatunde et al., 2016, Laurie et al., 2012).The results obtained from this study can be compared to those obtained by Yan et al (2013). It was reported that microwave had the highest β-carotene retention (about 80%) as compared to that of hot air drying, which had only 40% β-carotene retention. They argued that hot

air uses high drying temperatures, which has a significant effect on the β-carotene content. As compared to Yan et al (2013) study, the freeze-dried method had the highest retention of β-carotene, while in this study the same drying method had the lower retention. This can be attributed to the pre-treatment, storage and milling conditions, which can also increase the rate of β-carotene degradation, as it can expose it to oxygen, heat and light (Sugri et al., 2017). The study done by Sugri et al (2017) indicate that β-carotene can be degraded over time during storage. This can be attributed to the conversion of β-carotene to other carotene components such as epoxy carotenoids. The degradation of freeze dried β-carotene needs further investigation.

Haruna et al (2018) reported a β-carotene content of 424.50 mg/g for sweet potato dried at 40°C and 202.00 mg/g for sweet potato dried at 60°C, showing that β-carotene is sensitive to high drying temperatures. The reduction in drying time can increase the retention of β-carotene. Drying of carrots by infrared, hot air and combined infrared and hot air drying method indicated that the infrared drying method had higher retention of β-carotene, followed by the combined drying method. It is explained that the short drying time can minimize the oxidation loss of β-carotene and that the combined drying method has introduced more air during hot airflow, which increased the oxidation of β-carotene (Viswanathan et al (2010).

Table 6.1. The retention of β-carotene using different drying methods by different authors

Food product	Drying method	β-carotene retention (%)	References
Carrots	Hot air drying	84.85	(Zhao et al., 2018)
carrots	Microwave + hot air	88.72	(Zhao et al., 2018)
Tomatoes	Infrared + hot air	94.62	(Kocabiyik et al., 2014)
Mangoes	Freeze drying	42.2	(Harnkarnsujarit and Charoenrein, 2011)
Yellow-fleshed sweet potato	Oven drying	37.00	(Clifford et al., 2014)
Orange-fleshed sweet potato	Solar	88.2 ± 3.6	(Bechoff et al., 2009)

The instability of β-carotene in the presence of heat has been reported in many studies (Table 6.1). The study done by Qiu et al (2009) about the effect of heating on β-carotene, has reported that its geometry can be altered in the presence of heat. Transforming from All-trans-β-carotene to mainly 9-cis and 13-cis-β-carotene, consequently other isomers such as 15-cis and 13, 15-di-cis-β-carotene can be formed in the presence of heat and light (Figure 6.5). The formation of these isomers can reduce the vitamin A activity as well as colour intensity (Qiu et al., 2009). The degradation of β-

carotene in the presence of heat is temperature dependent. Qiu et al (2009) observed that All-trans-β-carotene were isomerized only during high temperature treatment that ranged from 40°C to 140°C.

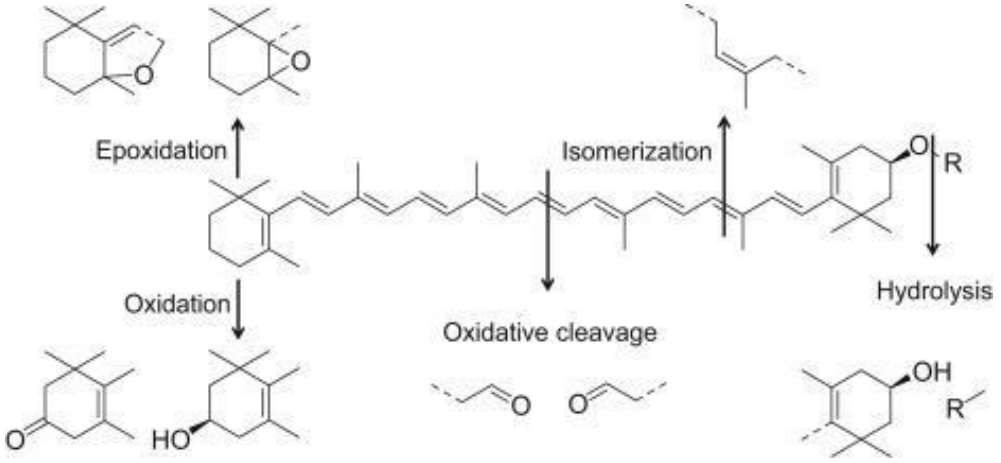


Figure 6.5. By-products produced from oxidation of β-carotene (Schieber and Weber, 2016)

Freeze dried flours have shown to have a lower retention of β-carotene (Table 5.7). These reductions can be due to changes in the microstructure of the sweet potato slices. Harnkarnsujarit and Charoenrein (2011) divulged that the freeze dried mango had a higher β-carotene reduction, as a result of changes in the microstructure. These changes are due to mechanisms of drying, where freeze dried products have high micro-pores, which can increase access of oxygen to the cellular chloroplast and therefore results in oxidation of β-carotene (Harnkarnsujarit and Charoenrein, 2011). Furthermore, the increase in micro-pore and low moisture content increases the reaction of solutes (endogenous enzymes and ionic minerals) and oxygen, which increase auto oxidation of β-carotene (Silva-Espinoza et al., 2019).

The retention of β-carotene for freeze dried products are different from those reported by other researchers, as they have shown that freeze-drying had high retention for β-carotene. However, this study shows that it can depend on the drying period, probably the high retention can be due to shorter drying period, while in this study the drying period was longer (5 days). The degradation of β-carotene was faster during storage (Lagnika et al., 2021). Freeze drying of orange-fleshed sweet potato has resulted in a carotenoids retention of 60.05% after 3 days of drying, from a study done by Lagnika et al (2021). The authors reported that the storage phase of the sweet potato has accelerated the low retention of the carotenoids. Another study of freeze-drying of orange-fleshed sweet potato for 48 hours showed a 86.02% retention of carotenoids (Kręcisz et al., 2021). These

reported findings therefore suggest that longer drying periods (more than 3 days) in freeze-drying can cause a faster degradation of β-carotene, which is what has been found in this study.

There was no significant difference in colour change between microwave, infrared and microwave-infrared dried flour. The most important colours of orange-fleshed sweet potato are represented by redness (a*) and yellowness (b*), there is a significant reduction in these colours for all drying methods (Table 5.8). The change in chroma values (L*, a*, and b*), is associated with loss of colour pigments during drying (Wang et al., 2016). And in this study this can be associated with a loss of β-carotene pigment, which contributes to the red and orange colour of the flour. It has also been stated that a longer drying method can result in higher decrease in colour values and this is what has been observed from the oven and freeze-drying method. While the faster drying methods such as microwave, infrared and microwave-infrared had lower reduction in colour values.

6.3.3. Physicochemical properties of the dried flour

Water absorption capacity shows the ability of the flour to absorb water, after the dehydration process. This process is associated with the integrity of the crystalline structure of starch, and the lower crystallinity is associated with high water absorption capacity (Qiu et al., 2019). The absorption of water by orange-fleshed sweet potato flour is not only facilitated by starch granules, but it is also influenced by association of food components such as non-starch polysaccharides, proteins and soluble sugar. Obomeghei et al (2020) stated that high water absorption capacity shows that there is a great number of water binding sites in the flour, due to the availability of hydrophilic sites in the starch molecules (Figure 6.6) and other hydrophilic biopolymers and compounds. Unfolded proteins during drying can also expose hydrophilic chains to promote a high protein-water interaction. Soluble dietary fibres are known to have high water absorption capacity (Khan et al., 2018). Khan et al (2018) reported that the water absorption capacity is proportional to the amount of soluble dietary fibre. Orange-fleshed sweet potato is a rich source of soluble dietary fibre such as pectin and insoluble fibre such as cellulose, lignin and hemicellulose, which can contribute in the water retention of the dried sweet potato flour (Slavin, 2013).

The dehydrating process can influence the alteration in the structure of starch granules (Xie et al., 2013). The drying methods such as microwave and infrared were reported to cause changes in the crystalline structure of the starch granule. Xie et al (2013) stated that the heat generation from oscillation of water molecules caused by the electromagnetic energy, can cause the loss of Maltese cross even when gelatinization temperatures have not been reached during drying (Figure 5.12). The rearrangement of amylose and amylopectin by electromagnetic energy, which causes the

destruction of the crystalline lamella of the starch chain and destroy the lamellar arrangement of crystalline region, can affect the starch functional properties such as water absorption capacity (Shen et al., 2017). High temperature drying by the oven are known to affect the microstructure of the starch granule, more especially when the drying temperatures are above gelatinization temperatures. However, if the drying temperatures are below gelatinization temperatures, the crystalline structure of the starch granules will not be affected, and this can preserve the functional properties of the starch (Zhang et al., 2014). Freeze-drying is known for its ability to remove bound water, however, the moisture transfer mechanism by this method, has been reported to cause disruption on the structure of the starch granule, creating pores and scratches on the surface of the starch granule and affecting the crystallinity of the granule (Xie et al., 2018).

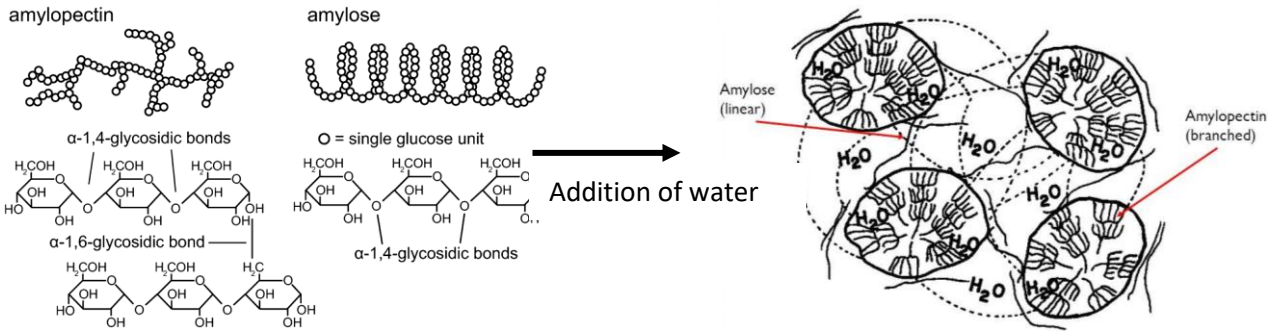


Figure 6.6. The mechanism of the water binding process, showing interaction between starch and water molecules (Own work)

The study done by Gan et al (2019) where they used freeze-drying method, and compared it to hot-air drying, air-impingement jet drying, and far-infrared assisted heat-pump drying, to dry sweet potato, has shown that freeze-drying method resulted in a lower water absorption capacity of the sweet potato flour, while the other method had shown higher water absorption capacity. Similar results were obtained from this study, where freeze-dried flour had lower water absorption capacity. The oven dried flour water absorption capacity are comparable to those reported by Olatunde et al (2016). They compared solar dried and oven dried sweet potato flour water absorption capacity, and reported oven dried flour water absorption capacity values to be around 1.4 to 2.7 g/g, which are similar to those reported in this study.

The high water absorption capacity reported from thermal drying methods can be due to partial-gelatinization of some starch granules (Marzuki et al., 2020). During gelatinization, there are some structural changes of the starch granule such as swelling of the granule, loss of crystallinity and

some amylose leaching, and this can expose more hydrophilic side chains, which can result in higher water absorption capacity (Marzuki et al., 2020). Water absorption capacity is not influenced by electromagnetic radiation energy, but governed by food components of the flour (Marzuki et al 2020). Marzuki et al (2020) reported similar values obtained from this study, where they used microwave to dry sweet potatoes, the values reported were ranging between 2.96 g/g to 4.79 for microwave power levels of 450 W. Microwave-infrared dried flours also reported higher values as compared to those of freeze-dried flours. This can be due to higher temperatures generated during drying, which can partially gelatinized the starch granules during, and further damages and changes of the starch, non-starch polysaccharides during milling (Barak et al., 2014). Furthermore, the polarized microscope images (Figure 5.11) shows that there is a partial starch gelatinization for microwave-infrared drying methods, which is depicted by the white arrows. The iodine stained microscopic images, also shows non-stained non-starch polymers (Proteins, sugars and dietary fibre), which can contribute to water absorption capacity (Figure 5.12).

Solubility index shows the amount of soluble materials in the flour released during the treatment of flour, with water at higher temperature (>60°C). These soluble materials refer to proteins, amylose, sugars, oligosaccharides and other soluble components (Bala et al., 2020). Oven and infrared dried flour showed to have lower solubility index as compared to microwave, freeze-drying and microwave-infrared drying methods. The change in the microstructure of the orange-fleshed sweet potato chips during drying can be attributed to the increase in solubility index of microwave-infrared, microwave and freeze-dried flours. The moisture transfer adopted by microwave during drying increases the vapour pressure within the food material to the surface, resulting in a more porous and crispy chips (Feng et al., 2012). The loose structure of the flour, allows more soluble materials to be accessed by water, thereby increasing the solubility index of the flour. The solubility index values obtained from this study ranged from 39.37% to 46.78%. These values are comparable to those reported by Jayanthi et al (2021), 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.

Bulk density of the flour is influenced by the particle size and moisture content (Chandra et al., 2015). Drying methods can also influence the bulk density, more especially if there was a damage of starch through gelatinization (Patria et al., 2013). Freeze-drying is known to have significant changes on the structure and volume of materials, due to the ice sublimation moisture transfer (Oikonomopoulou et al., 2011). The drying technique by freeze-drying can create a more porous product, which can also decrease the bulking density. The high bulk density from thermally (Oven,

microwave and infrared) dried flours on this study can be due changes in microstructure as well as macrostructure (shrinkage) (Koç et al., 2008).

6.3.4. Pasting and thermal properties of the dried flour

Generally Bellevue cultivar flours have shown to have higher pasting viscosity as compared to Orleans. The high viscosity properties can also be influenced by the high soluble dietary fibre on Bellevue cultivar as compared to those of Orleans (Table 5.3), as soluble dietary fibre possess viscous properties, or higher starch content [as evidenced by higher enthalpy by DSC]. Compared to other researchers who have studied the pasting properties of orange-fleshed sweet potato flour, the values reported in this study are not the same as their studies. This can be attributed to the different varieties of sweet potato used for the study, which have different food composition and they can play a role in pasting properties. Liao et al (2019) reported a peak viscosity of 5227 cp, final viscosity of 322 cp and setback viscosity of 756 cp for native sweet potato starch. While Sajeev et al (2012) reported a peak viscosity of 617 cp, final viscosity of 955 cp, setback viscosity of 217 cp, and breakdown viscosity of 738 cp for orange-fleshed sweet potato flour. Sajeev et al (2012) postulate that the variation in viscosity is attributed to the composition of starch, dietary fibre and sugar content, which is different between cultivars.

There was not much significant difference observed between the drying methods on their effects on thermal properties of the orange-fleshed sweet potato flour. The freeze-dried Bellevue flour has been found to have a higher enthalpy value of 4.29 (J/g), while other flours dried by oven, infrared, microwave and microwave-infrared methods reported lower enthalpy values ranging from 1.18 (J/g) to 2.27 (J/g). Generally Bellevue cultivar showed higher enthalpy values as compared to Orleans cultivar. The thermograms shows endothermic peaks, with temperatures ranging from 6.69°C to 72.84°C for onset temperature (T_0), 66.48°C to 80.48°C for peak temperature (T_p), and 72.42°C to 85.96°C for concluding temperature (T_c). The temperatures and enthalpy values reported can explain that there was no significant damage done to the starch granule, as shown by the light microscopic images on Figure 5.11 and 5.12.

The enthalpy values from our study are comparable to the values reported by Romano et al (2018), where they reported enthalpy values ranging from 1.0 (J/g) to 2.20 (J/g) for the sweet potato flours. They explained that the high enthalpy values can be associated with the amount of energy required to gelatinize the starch granule, therefore meaning that the starch is resistant and still strongly associated with its native structure. This is furthermore supported by Ngoma et al (2019) explaining that high enthalpy values are expected from a high degree of crystallinity, which makes the starch

granule and more resistant to gelatinization. Ngoma et al (2019) reported that low enthalpy values can be attributed to the high number of short amylopectin chains in the sweet potato starch.

The drying conditions used in this study did not have effects on the thermal properties of the orange-fleshed sweet potato flour. This can be owing to the fact that the drying temperature for the oven was lower than the gelatinization temperature of starch, which is above 60°C, and that the microwave, infrared and microwave-infrared powers did not reach the gelatinization temperature of the starch. In addition due to the fact that the latter drying method had faster drying rate and therefore did not expose the flour for a longer period to the drying energy and consequently prevented any damages to the starch granule and hence retained the thermal properties of the flour.

6.3.5. Application of OFSP flour

Orange-fleshed sweet potato flour has potential application in the food industry. The flour obtained from the sweet potato flour has beneficial functional properties as well as nutritional properties. There are many researches who reported on the partial or complete replacement of other flours such as wheat, maize and cassava with sweet potato flour (Akintayo et al., 2019, Sebben et al., 2017). The potential application of sweet potato flour has been identified in the baking industry, where it is used for bread baking, and pie fillings. This is due to the low viscosity of the flour, which also does not affect the rheological properties when composited with wheat flours (Nogueira et al., 2018). Other applications include using the sweet potato flour in production of pasta, noodles and cookies.

Table 6.2. Value added product produced from sweet potato composite with other products by different researchers

Product name	Food main component	References
Bread	The bread is prepared from wheat flour substituted with different parts of yellow sweet potato flour.	(Nogueira et al., 2018)
Extruded pasta	Carboxy methyl cellulose, a pinch of salt and an egg are added to the sweet potato flour, mixed thoroughly to produce pasta.	(Olubunmi et al., 2017)
Instant noodles	Wheat flour, sweet potato and other major ingredients are used for the noodles preparation.	(Taneya et al., 2014)
Biscuits	Biscuits were prepared from doughs containing starch, sweet potato flour and fibre at different levels and also from dough containing wheat flour as control.	(Srivastava, 2012)
Ketchup	Made from sweet potato, water, vinegar, sugar and flavourings.	(Oke and Workneh, 2013)
Complementary food for infants (Weanimix)	Sweet potato flour mixed with lemon solution, ground nuts and cooked soya beans	(Obiri-Asamoah and Fraikue, 2018)

Recent studies also reveal that orange-fleshed sweet potato has been used in food fortification, to increase the nutritional content. Some of the food used are infant products, where it is used to increase the β-carotene content of the product (Francis et al., 2012). The study by Francis et al (2012) shows that the inclusion of sweet potato flour in infant feed is suitable for 6-8 months old infants. Orange-fleshed sweet potato flour can also be composited with legume flours to make the feed more nutritious (Makame et al., 2019). The study by Makame et al (2019) concluded that porridges composited with orange-fleshed sweet potato flour had satisfactory oral texture at its highest solid content as compared to the commercial reference used in the study.

CHAPTER 7: Conclusions and recommendation

Combination of microwave and infrared as an energy efficient technology has potential to produce dried OFSP. The combined use of microwave and infrared produced flour had the highest retention of about 80-90% of β-carotene. This is because of the relatively highest drying rate, and less exposure to heat for destruction of β-carotene. The heat transfer mechanism by molecular vibration as well as depth of the radiation energy increases the drying rate and reduces drying time of microwave and microwave-infrared drying methods. Models such as Page, Lewis, Henderson and Pabis as well as Logarithmic, can be used to predict drying kinetics for all thermal drying methods. The flour properties in terms of pasting, water absorption capacity, thermal properties, bulking density, and swelling capacity produced from dehydrated OFSP by oven drying, microwave, freeze drying, and microwave-infrared drying are similar. The low pasting viscosity suggests that orange fleshed sweet potato flour is a good candidate as complementary foods. The instability of β-carotene by freeze-drying suggests that freeze-drying, coupled with oxidative agents such as light, oxygen, and endogenous enzymes can be responsible for its degradation. It can also be concluded that β-carotene oxidation is time dependent as slow drying methods (oven and freeze-drying) have lower β-carotene retention, while faster drying methods (infrared, microwave and microwave-infrared) show higher β-carotene retention.

Further studies can be conducted to explore the application of the dried orange-fleshed sweet potato flour. The produced flour can be included in many food ingredients, as it has shown that the flour had high water absorption capacity, high swelling capacity, high bulking desnsity and high solubility index. These mentioned properties are desired for most food product, however, there is not enough scientific study reporting the effects of the OFSP flour in the food system. Further, more thorough studies about the effects of different drying methods on β-carotene are required, as freeze-drying has shown lower retention of β-carotene. This opens up a gap to understand the mechanism of β-carotene degradation from freeze-dried products. Moreover, the bio-accessibility and vitamin A activity from the dried OFSP flour studies are recommended for further studies. This study did not focus on the energy consumption of each drying method, further studies are required in order to conclude if the novel drying methods are energy efficient.

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