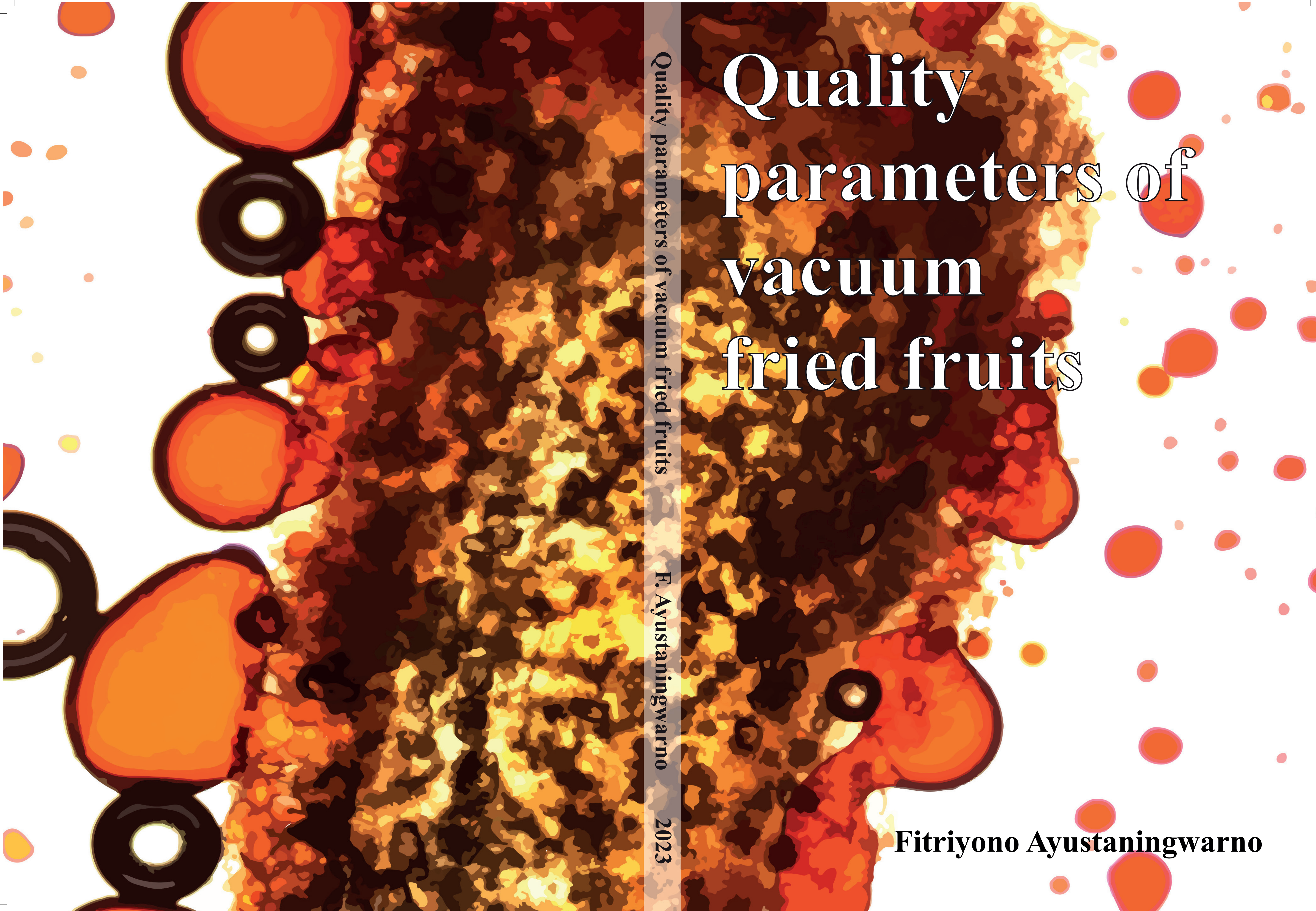

Quality parameters of vacuum fried fruits

Fitriyono Ayustaningwarno

Quality parameters of vacuum fried fruits F. Ayustaningwarno 2023

Propositions

1. Technology has dismantled the paradox of healthy fried food.
   (this thesis)
2. Choosing between an empirical and a mechanistic model is a choice between addressing complexity and usefulness.
   (this thesis)
3. Science is both a responsibility and a bibliometric score.
4. Coffee is essential for the development of science.
5. Bureaucracy is a necessary burden.
6. Bad weather is a mindset.

Propositions belonging to the thesis, entitled

Quality parameters of vacuum fried fruits

Fitriyono Ayustaningwarno

Wageningen, 24 March 2023

Quality parameters of vacuum fried fruits

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Quality parameters of vacuum fried fruits

Fitriyono Ayustaningwarno

Thesis

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Prof. Dr A.P.J. Mol,
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Thesis Committee appointed by the Academic Board
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CHAPTER 1

General Introduction

1

1. Introduction

Tropical fruits are fruits from the warm climate of the tropics, in the region between 23.5º north and 23º south of the equator (1). These fruits are important because they are well known as an important source of bioactive compounds such as polyphenols, anthocyanins, flavonoids, carotenoids, and vitamins (2) as listed in **Figure 1**.

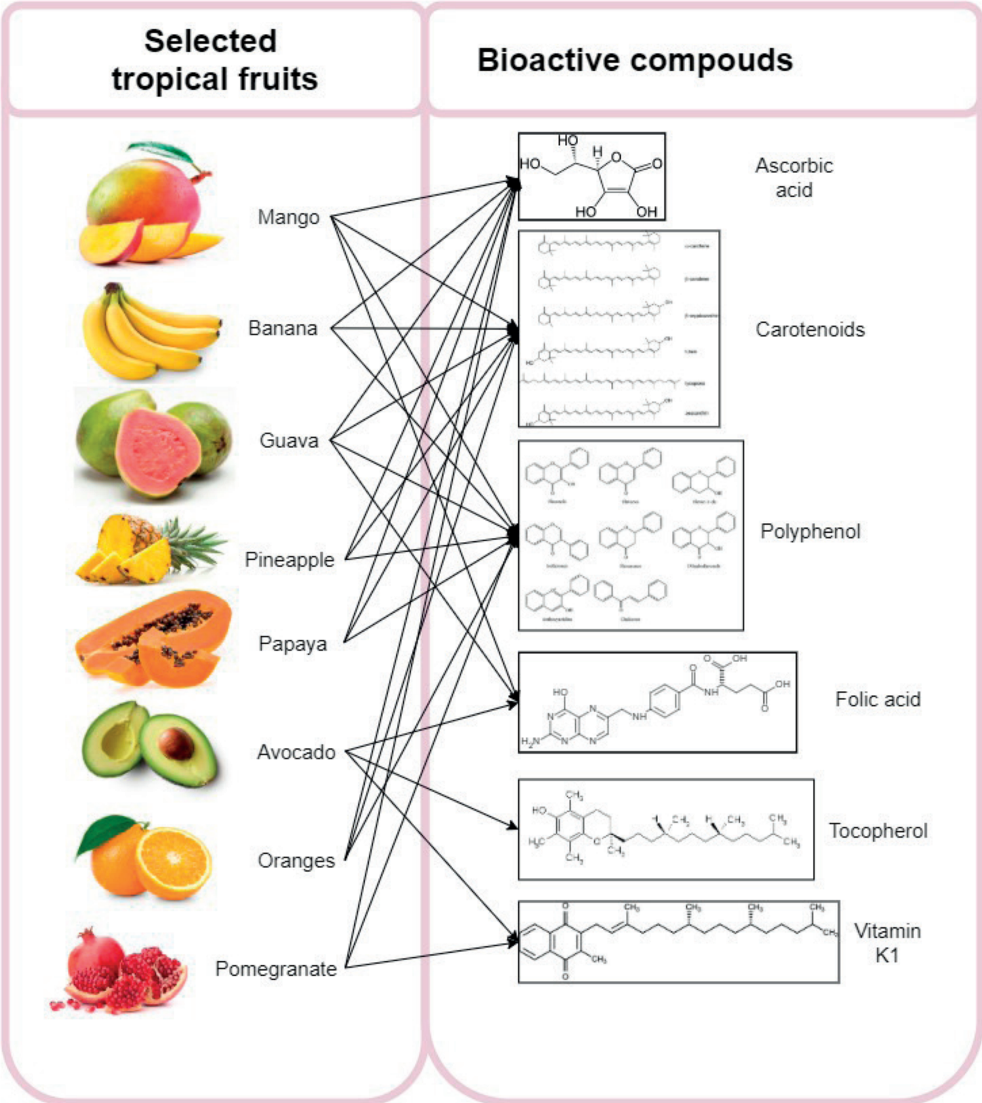

Figure 1. Tropical fruits and its major bioactive compounds (3)

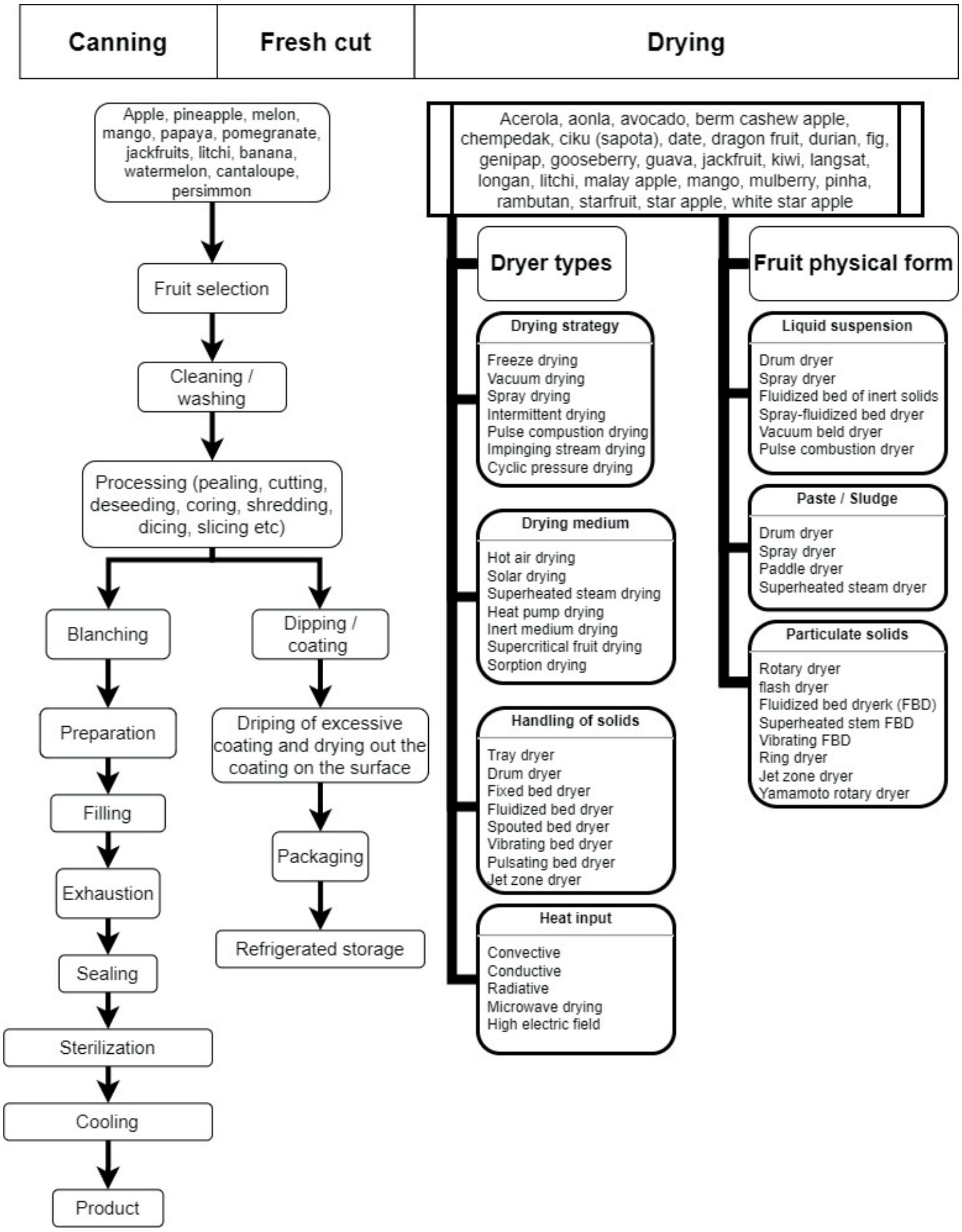

Figure 2. Selected processing methods procedure and the fruits used in the process. Including canning (4), fresh cut (5), drying (6)

Most food commodities including tropical fruits contain sufficient moisture which allows native enzymes and microorganisms to cause spoilage (7). Furthermore, tropical climate are ideal condition for rapid growth of spoilage microbial and for chemical reaction and lead to quality degradation and spoilage (8).

Therefore, to increase the short shelf life of tropical fruit, they need to be processed. There is a list of technological processing methods that can be used to transform fresh fruit into processed tropical fruit. Shelf life extending processes include application of edible coating on fresh cut tropical fruits (5); drying, commercial sterilization by retort (canning) (9); drying which aims to remove moisture from the fruit in order to reduce microbial activity and chemical reaction (7); production of heat and non-heat treated fruit drink (10); and frying (atmospheric and vacuum) which defined as a process of cooking and dehydration of food by hot oil immersion (11). Selected processing methods procedure and the fruits used in the process described in **Figure 2**.

Fruits can both be consumed as a meal and as a snack between regular meals (12) and they are considered a healthy choice from the nutritional point of view. Therefore, having fruits as a snack is recommended to avoid introducing too many calories in between the meal. The upcoming trend called "snackification" involves a shift from regular meals to a frequent snack consumption throughout the day (13). However, regular snacks are classified as unhealthy because their nutrients contents are poor (14). Also, there is a growing demand for more healthy snacks meeting dietary recommendations, such as low amounts of calories, fats, carbohydrates, sodium and a significant dietary contribution of fiber and vitamins, as well as contain health promoting components (15).

Snack with fruit is not also healthy but also more convenient processed fruit based product. Among these products, in south Asia vacuum fried fruit is popular (16).

2. Vacuum Frying

1.1 Description

Atmospheric frying is a well-known food processing technique that involves hot oil or fat at a temperature of 150-200 °C. Frying leads to a product with distinct characteristics in terms of appearance, texture, flavor and taste (17). Despite the advantages, the atmospheric pressure applied in deep fat frying is not applicable for every food. In fact, fruits with high moisture content are not suitable for this process.

Vacuum-frying is a frying process performed below atmospheric pressure conditions. Due to the low pressure in this vacuum frying (1.3 to 98.7 kPa), the boiling point is lower than the atmospheric pressure (16). Consequently, the process can be performed at a much lower temperature compared to atmospheric frying. The main benefits of low temperature frying processes are a low oil uptake and the preservation of color, flavor, micronutrients and bioactive compounds (18).

1.2 Major technological characteristics

Vacuum frying involves major technological characteristics compared to other fruit processing techniques. They include low pressure and temperatures, short time, pre- and post-frying treatment as described in **Figure 3**.

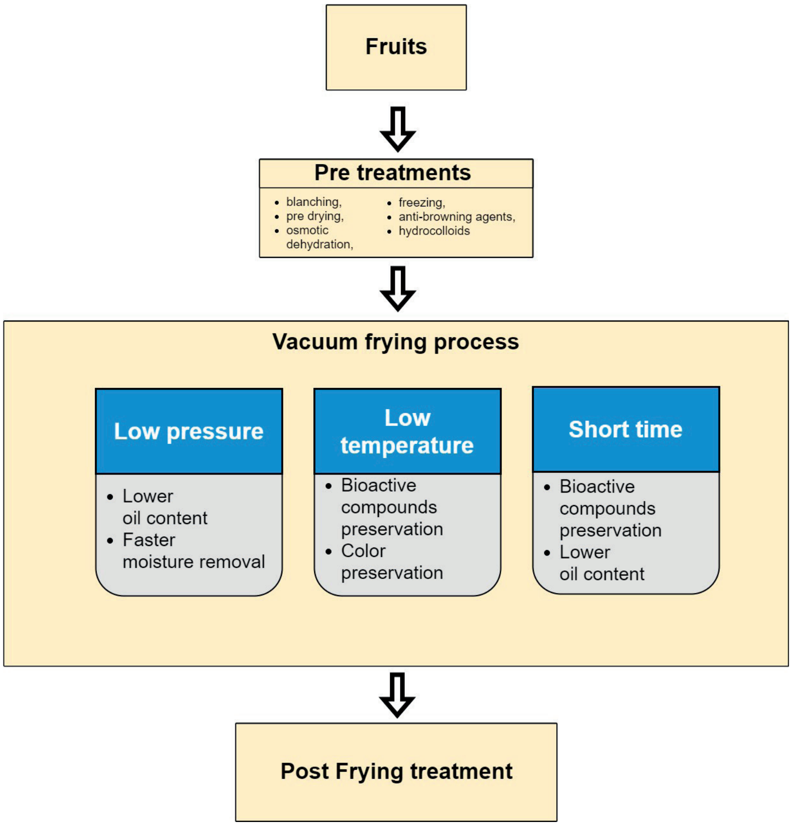

Figure 3 Vacuum frying processing steps and the technological advantages on selected parameters (18-23).

1.2.1 Low pressure

Low pressure processing in vacuum frying enables the moisture content to quickly evaporate at low temperatures as highlighted in **Figure 3**.

This vacuum technology has been applied in many other processing techniques to improve product quality, including in drying Brazilian Cantaloupe melons (*Curcumis melo* var. *cantalupensis* Naud) to preserve its color (24). Furthermore, freezing at vacuum pressure facilitates the moisture sublimed into vapor phase (25). This technique is able to maintain not only a high level of quercetin in Bareburn apple slices, but also the color and shape (26). Vacuum impregnation with a combination of sucrose, calcium lactate and pectin methylesterase maintained the lightness of ripe mango during drying process (27). Also, vacuum microwave drying maintained anthocyanin levels but not the vitamin C content in cranberry, compared to the conventional drying process (28).

1.2.2 Low temperature

Low pressure application enables the frying process to occur at low temperatures. Advantages low temperature processing in vacuum frying are highlighted in **Figure 3**.

Low temperature processing has been generally applied in the combination of vacuum technology with many processes, as mentioned in the previous section. Furthermore, it is possible to perform low temperature processing through other methods such as sous vide and air drying, which results in processing time extension. However, these will not produce a similar quality as vacuum fried fruit does. Baldwin (29) mentioned that non starchy vegetables cooked sous vide at 82-85 °C for about 3 times as long as by boiling will retain all its nutrients and flavor compared to boiling cooking.

1.2.3 Short time

Shorter time processing in the vacuum frying technique involves the application of higher temperatures with advantages as highlighted in **Figure 3**.

A short processing time in the vacuum frying process is possible with the combination of vacuum condition and high temperature. Without this low pressure and temperature combination, a short processing time is only possible with other high energy treatment such as high pressure. A high hydrostatic pressure (HHP) can maintain a higher phenolic compound content in various fruits juice compared to pasteurization and HTST (high temperature short time) sterilization (30). Chen and Yu (31) reported that traditional thermal pasteurization including HTST process at 72 °C for 15 minutes of holding time may degrade the tase, color, flavor and nutritional quality. However, this process is only applicable for liquids, and not solid food as discussed in this thesis.

1.2.4 Pre-treatment

Pre-treatment which are applied before the frying process, is an important way to improve vacuum fried fruit quality. These pretreatments affect the texture, moisture content, color, and bioactive content of the vacuum fried fruit in a positive or negative way.

1.2.5 Post frying treatment

Post frying treatment are another important factor in determining the quality of vacuum fried fruit, especially the fat content. The method applied in this last step is necessary to remove surface fat (32, 33), which can be performed using two centrifugation methods, namely atmospheric and vacuum. Atmospheric centrifugation which is done after frying and vacuum breaking; while vacuum centrifugation which is done after frying but before vacuum breaking. Vacuum-centrifugated potato chips have significantly lower oil content compared to atmospheric-centrifugation (35.01 g oil/100 g and 56.85 g oil/100 g respectively). Apart from the vacuum application, a higher centrifugation force significantly enhances the removal of surface oil (34), however product resistance to centrifugal force should be taken into account.

3. Quality attributes of processed fruits

1.3 Moisture as an attribute of fruit product and its interaction

Moisture is an important property which affects many quality attributes in fruits as it constitutes more than 80% of the fruit mass and plays important roles in their shelf-life. Therefore, fruit moisture removal is important for preservation purposes. Some important fruit processing methods using moisture removal principle including traditional drying, osmotic dehydration, freeze drying and frying.

Drying is a common fruit processing technique, to take out moisture to about 20% to increase self-life by reducing water activity to about 0.7-0.76. This process also increase concentration of other fruit component such as reducing sugar which have a direct correlation to the product sweetness (35).

Osmotic dehydration as one of drying procedure also popular in fruit processing. One of the most widespread products is jam. Jam can be produced by mixing fruit with sugar at 67:33 ratio and then cooked to obtain a 40–60 °Brix product (36). During cooking moisture removed and sugar concentration increased to meet the desired Brix.

Freeze drying is an advanced drying technique which the moisture sublimed under vacuum condition (below 0.612 kPa) at temperature lower than 0.01 °C. Freeze drying application prevent significant damage to the fruit due to low temperature and vacuum pressure application (37).

Frying is another traditional fruit processing which enable moisture migration from the fruit is and replaced by oil in the cooling period which leads to a decrease in moisture and increase in oil content (38). Furthermore, the texture also becomes harder upon moisture loss (39).

Due to moisture significance on product quality, many models are used to describe the moisture change during processing. These models include exponential (40) and the Peleg model (41). A first model exponential kinetic model has been used to model moisture loss in *gethi* strips frying process (40). A four parameters Peleg model has been used to describe water absorption of vacuum fried carrot (41).

1.4 Texture as quality attribute of fruit product

Texture is a complex food quality attribute. (42) reported that texture can be classified into three main categories, namely mechanical, geometrical, and other. Meanwhile, most of attention in the food studies involves mechanical characteristic which includes hardness, cohesiveness, viscosity, springiness, and adhesiveness. However, in this thesis, texture is discussed as hardness which is the force required to attain a given deformation.

Fresh fruit texture is highly related to turgor pressure of the cell and the structure supported it. Along with fresh fruit processing, the moisture content which determined the turgor pressure modified, and the structure altered (43). The mechanism of final texture formation is different for each fruit processing technology. Some distinct fruit processing including high hydrostatic pressure (HHP), drying, freeze drying, and frying.

High hydrostatic pressure (HHP) is a recent fruit processing which could preserve the bioactive content of the fruit. However, the process changes the fruit structure significantly and produce a lower hardness compared to the fresh product, in consequences this process is more suitable for semi solid processed fruit or soft fruit (44, 45).

Drying produce a great damage to the structure, change the shape, and produce product shrinkage (35). An advanced drying technique such as freeze drying could maintain cell structure, and produce a specific high porosity properties (46).

Texture is an important quality characteristic which distinguishes a vacuum fried fruit from other non-fried. Vacuum fried fruits have a higher hardness value which is measured as the resistance to break, compared to other non-fried fruits.

Fresh fruit which has a hard texture consequently first becomes soft during the frying process due to middle lamella between calls solubilized and eventually hardens due to crust formation during frying. Therefore, to describe this texture change, mathematical models have been developed including the exponential kinetics model (47) and two irreversible serial reactions (48). The two irreversible serial reactions which the development of the exponential model able to describes two serial textural changes during frying (48).

1.5 Color

1.5.1 Color as a quality attribute of fruit product

Color is a quality attribute of a product appreciated by consumers before consumption (49). Meanwhile, color changes during processing can be controlled via a suitable processing technique and appropriate process parameters (50) to please the consumer. Furthermore, it has high correlation with strongly colored bioactive compounds such as β carotene and anthocyanin present in the product (51).

An important fruit processing technique able to preserve the fresh fruit color is vacuum drying. Combined with low temperature and vacuum process technique to remove moisture content of the fruit enable the process to maintain the color (52). However, the initial investment required is higher compared to other processing like drying or frying. Drying in general is a low-cost fruit processing. However, since the high temperature utilization, the process produces a significant color transformation. Usually, a high degree of browning reaction occur and produce a darker and higher saturation (35, 53).

Osmotic dehydration is another well known fruit processing method which could preserve fruit for an extended period of time while maintained the original color due to the low temperature processing (54).

When compared to the atmospheric frying method, vacuum frying helps to maintain bright and fresh color in fried fruits, as observed by Da Silva and Moreira (18) in mango.

Color in fried fruit is an important quality characteristic, as during frying the product color becomes darker (55) and browner (56). Therefore, a mathematical model to describe color changes during processing is important, as mentioned by Ansari and Maftoon-Azad (57), which also describe color change in dehydrated fruit as a combined kinetics of zero in the first phase and first order in the second.

Food is not homogenous, instead it has heterogenous matrix at micro and macroscopic scales (58). This matrix variety could have responded differently to the processing and produced a variety of color.

1.5.2 Color measurement

Color can be measured in many ways. Usually food color is homogeneous, or is measured after product homogenization and can be measured using instruments such as the Hunterlab (59). Also, a manual method involving visual observation using color charts can be used, for example to observe potato fries grades (60, 61) and potato chips (62). Meanwhile advanced color measurement using computer aided software such as Adobe® Photoshop® is commonly applied in visual observation of food (63). When the sample color value has been determined after processing, the color difference with the fresh product can be calculated using delta E, which is the distance of two different color in L*a*b* color space (19).

However, fruits including vacuum fried fruits are non-homogenous products (58) which may possess heterogenic colors across the surface. This characteristic is unique and has to be correctly addressed. Also, the color distribution analysis can be used in multiple applications including sorting melon maturity (64). Attention to color distribution analysis grows, Goñi and Salvadori (65) utilized this system and developed a computer vision system (CVS) for detailed comparisons with a portable colorimeter. Therefore, to highlight the emerging importance of color distribution analysis, a commercial color distribution analyzer instrument named IRIS-Alphasoft has been recently released and tested for multiple food color distribution analysis (66).

1.6 Bioactive compounds as quality attribute of fruit product

Fruits in general and tropical fruits in particular possess a variety of bioactive compounds which are beneficial to human health including vitamin C (67) and β-carotene (68).

Vitamin C or L-ascorbic acid is important in human diet because of its beneficial characteristics, including as antioxidant due to its electron donating capability. Furthermore, vitamin C is important to decrease risk of several chronic conditions, including heart disease, diabetes, cancer or neurodegenerative diseases (69). β-carotene is an important bioactive compound because it is a potent antioxidant which is the basis of preventive action to many chronic diseases including Alzheimer (70).

During fruit processing, these beneficial compounds are damaged in certain degrees, depending on the processing techniques and parameters. High hydrostatic pressure (HHP) which commonly carried at 100 – 1000MPa able to preserve more total phenolic compounds compared to thermal pasteurization. This result was mostly contributed by the lower temperature applied in the HHP process compared to the sibling in the product likes longan juices; strawberry and blackberry purees (30).

Hot air drying could remove moisture with high temperature application with a significant cost of vitamin C destruction 46-100 % corresponding to the drying temperature of 80-110 °C (71). Furthermore application of freeze drying, which use a significant lower temperature than air drying at vacuum pressure could preserve a higher vitamin C retention (72). Osmotic drying applied a different drying principles which allow the moisture removed and only leached away a small quantity of bioactive compounds (72).

Compared to atmospheric frying, vacuum frying is able to retain more β-carotene (18) and Vitamin C (21) in fruits.

1.7 Oil as a quality attribute characteristic of fruit product

Oil is the most important quality attribute in vacuum fried fruits. Fat is an important feature in food, as it is not only a flavor and vitamin carrier, but also provides a specific mouthfeel and texture, giving palatability to food. In appropriate amounts, oils constitute a good source of energy, but in excessive amounts, this energy intake can become a health threat.

A significant amount of oil can only be introduced by frying processes, no other processing methods able. Oil content in vacuum fried fruit arises due to its migration from frying oil which is adsorbed on the fruit surface and then absorbs inside the product after the vacuum pressure is broken (73). Multiple measures used to reduce oil content includes drying as a pre-treatment (20) and centrifugation as post treatment (73).

Oil change has been described for vacuum fried potato chips using a mechanistic model (74), and for atmospheric frying of potato chips using an empirical model (75).

4. Objective and outline

The schematic overview of the thesis is shown in **Figure 4**. The overall objective of the thesis is to investigate the effect of ripening stage and structural properties (matrix) of selected tropical fruits on the quality of vacuum fried fruits products. This overall role is further described in **Chapter 2, 3, 4, and 5.**

In **Chapter 2,** the vacuum frying technique and its effect on product quality with a focus on the role of the fruit matrix are reviewed.

In **Chapter 3,** the effect of ripening stages, frying temperature, and time on the nutritional and physicochemical quality of vacuum fried mango are described. Furthermore, the physicochemical quality was characterized by measuring the key parameters including moisture and fat content, color, and texture. In addition, the nutritional value was assessed by analyzing vitamin C and β-carotene content as key parameters for water- and fat-soluble nutrients in mango.

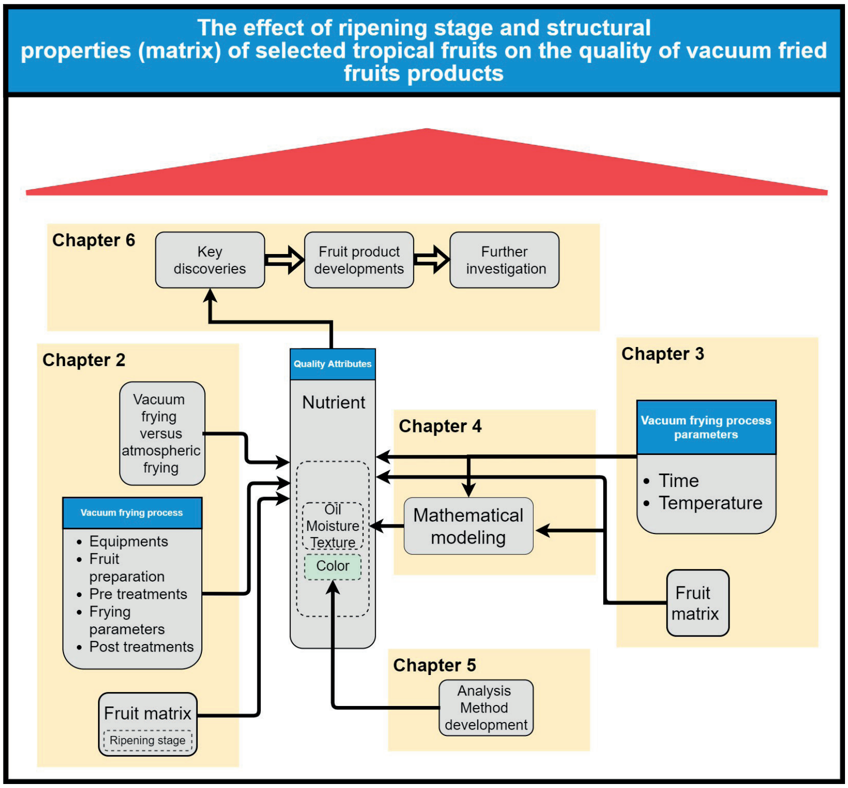

Figure 4. Schematic overview of the thesis

The development of moisture dependent dynamic models that describe the change in quality attributes during food processing is described in **Chapter 4.** This was demonstrated by the models application on vacuum frying on mango at different ripening stages.

In **Chapter 5,** color analytical techniques on the ability to differentiate samples, quantify heterogeneity, costs, and flexibility are compared. These techniques are sensory testing, the Hunterlab colorimeter, the commercial CVS (IRIS-Alphasoft), and the self-developed (Canon-CVS) in analyzing nine different vacuum fried fruits.

Finally, in **Chapter 6**, the key discoveries are summarized and discussed. Furthermore, the findings potential for fruit product development are elaborated. Lastly, recommendations for further investigation are given.

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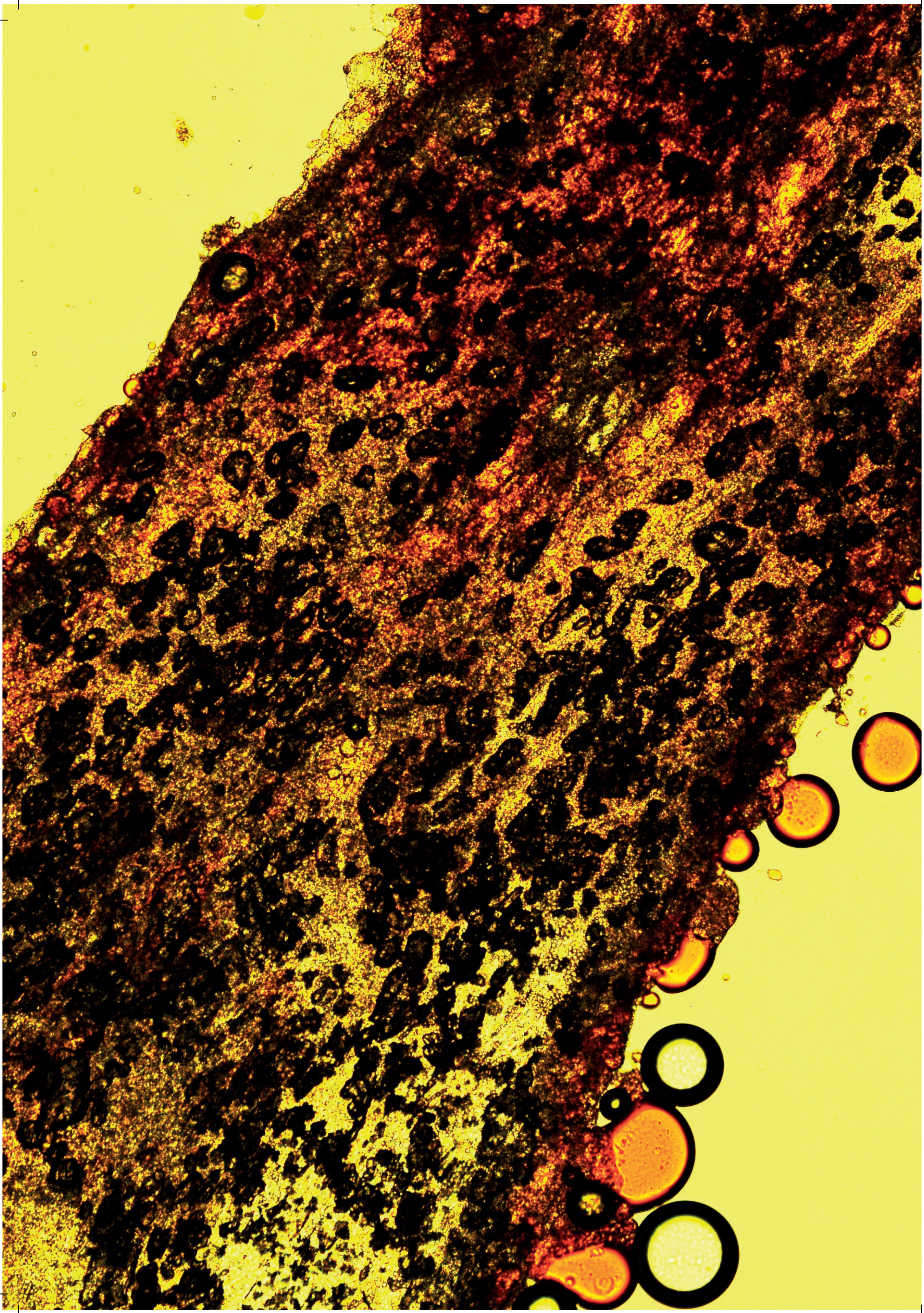

CHAPTER 2

Effect of Vacuum Frying on Quality Attributes of Fruits

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Abstract

Vacuum frying of fruits enables frying at lower temperatures compared to atmospheric frying, thereby improving quality attributes of the fried product, such as oil content, texture, retention of nutrients and color. Producing high-quality vacuum fried fruit is a challenge, especially because of the high initial water content of fruits that requires long frying times. Factors influencing vacuum fried fruit quality attributes are the type of equipment, pretreatments, processing conditions, fruit type and fruit matrix. Pre-treatments such as hot air, osmotic drying, blanching, freezing, impregnation, anti-browning agents and hydrocolloids application strongly influence the final quality attributes of the products. The vacuum frying processing parameters, namely frying time, temperature and vacuum pressure, have to be adjusted to the fruit characteristics. Tropical fruits have different matrix properties, including physical and chemical, which changed during ripening and influenced vacuum fried tropical fruit quality. This paper reviews the state of the art of vacuum frying of fruit with a specific focus on the effect of fruit type and matrix on the quality attributes of the fried product.

Keywords:
Vacuum frying, fruit, quality attributes, matrix, phytochemicals

1. Introduction

Fried products are appreciated by all age groups and play an important role in consumer's diet because of their unique flavor and texture. However, it is difficult to combine fried foods with the contemporary consumer trends toward healthier and low-fat products. There is an increased demand for healthy snack products with good taste, texture, and appearance (1). This demand offers the opportunity to design novel fried products that have higher health properties such as fruit-based products. Increasing fruit consumption is promoted in all parts of the world to increase public health. Fruit implicitly has a strong health awareness based on the content of (micro) nutrients, fibers and numerous bioactive phytochemicals (2, 3).

Vacuum frying is a frying process below atmospheric pressure (~100 kPa). At reduced pressure, the boiling point of oil and water is lower compared to atmospheric pressure (4). Due to a lower frying temperature, vacuum frying better preserves the nutritional value, aroma, and color of the fried product compared to atmospheric frying (5).

Some anecdotic findings from existing studies highlighted several advantages vacuum frying might have over atmospheric frying:

- Oil uptake in vacuum fried apple chips is lower compared frying at atmospheric pressure (6);
- Colour of vacuum fried mango was lighter compared to atmospheric frying (7);
- Carotenoid retention was higher in vacuum fried mango compared to atmospheric frying (8);
- Vacuum fried mango was more uniform and crispier compared to soggy, burnt and oily for atmospheric fried mango (8).

The multiple factors influencing the quality attributes of vacuum fried fruit can be distinguished in: vacuum frying equipment (type and specifications); properties of the raw fruit (fruit matrix); pre- and post-treatments and processing conditions. Time, temperature and vacuum pressure influenced color, texture, nutrients, and oil content of fried fruits (5, 9, 10).

Another relevant aspect is the fruit matrix such as the fruit type and ripening stage that are affecting the vacuum fried product quality attributes (11-13). Pre-treatments such as blanching, drying, freezing, antioxidant and coating applications have been used to preserve color, improve texture and reduce oil absorption (14-16). The use of post-frying steps such as centrifugation has a major effect on the oil content of fried product (17).

Some recent papers dealt with different aspects of vacuum frying technology. The strategies to reduce oil absorption of vacuum fried products have been studied intensively by Moreira (18), including optimizing temperature, pressure, pretreatment, pressurization speed and de-oiling time. The recent review by Diamante, Shi, Hellmann and Busch (19) discussed the product and process optimization; oil uptake; oil quality; as well as packaging and storage of vacuum fried fruits without mentioning matrix factors. Dueik and Bouchon (20) and Ayustaningwarno and Ananingsih (21) compared the quality changes comparing atmospheric and vacuum frying as well as the oil quality and packaging of fried products. Dueik and Bouchon (20) put emphasis on the microstructure, methods to reduce oil uptake, oil quality, bioactive compound degradation and toxic compound generation. Andres-Bello, Garcia-Segovia and Martinez-Monzo (22) reviewed the vacuum frying processing for producing high quality fried products, focusing on equipment types, pretreatments, and vacuum frying conditions.

Based on this existing background information, this review will consider the effects of vacuum frying on changes in quality attributes of tropical fruits with a focus on the role of the fruit matrix, since this is a very relevant but underexposed factor.

2. Vacuum Frying Versus Atmospheric Frying

The main difference between vacuum frying and atmospheric frying is the lower boiling point of water at lower pressures that enables to fry at lower temperatures. For that reason vacuum frying has many advantages over atmospheric frying in relation to product quality attributes. Several comparative studies between vacuum and atmospheric frying were done on apple, plantain, banana and mango.

2.1 Oil and nutrient content

The mechanism of oil uptake in atmospheric frying and vacuum frying is different. Oil uptake occurs mainly after frying: by the lower pressure in the pores, the oil present on the surface of the products is sucked into the pores. During atmospheric frying, this lower pressure in the pores is created by the evaporative cooling after frying (23). On the other hand, at the end of vacuum frying, the vacuum breaking period produces a higher outside pressure then the pore pressure.

The oil content of vacuum fried apples was lower compared to atmospheric fried one. Apple absorbed 1.2 -2.0 times more oil by atmospheric frying compared to vacuum frying (6, 24). This difference was explained by the lower temperatures during vacuum frying due to the lower vapor pressure of water. This low temperature will reduce temperature-induced tissue matrix degradation that increases the oil absorption. Dueik *et al.* (11) found that atmospheric fried apple had a larger portion of small pores and absorbed more oil by capillary suction compared to vacuum fried apple. Larger pores formation was related to the higher specific volume of water vapor at lower pressure. These studies provided a convincing explanation about the mechanisms behind the reduced oil absorption of vacuum fried products.

Shyu and Hwang (25) showed that oil absorption was highly correlated with moisture loss in vacuum fried apple slices. At the beginning of the frying procedure, the outer surface of the product is dried, the moisture inside the product is converted into steam, and a pressure gradient is created. By prolonging the frying, the dried surface becomes more hydrophobic which facilitates the absorption of oil. This can explain the observed oil content that was increased from 33.64 % in first 5 minutes of vacuum frying to 39.38 % after 30 minutes of vacuum frying. This oil absorption mechanism is different compared with atmospheric frying in which most of the oil is absorbed after frying during the cooling period (23).

The situation found in apple is different as found in plantain and mango: as in plantain (5) and mango (7), vacuum frying resulted in a higher oil content compared to atmospheric frying. This difference could attributed by matrix differences of apple with plantain and mango. Wexler, Perez, Cubero-Castillo and Vaillant (26) explained that at the end of vacuum frying of papaya, capillary absorption of surface oil was favored to be absorbed inside the product when the vacuum was broken to restore the system into atmospheric pressure. Additionally, vacuum fried plantain had less gelatinized starch due to the lower temperature, thereby having more pores and absorbed more oil compared to atmospheric frying (5).

In general, a higher nutrient retention is expected with a lower temperature of vacuum frying. Ascorbic acid content of apple was found 1.7-1.9 times higher after vacuum frying compared to atmospheric frying (24). Additionally, carotenoid retention in vacuum fried mango was two times higher compared to atmospheric frying. High retention of carotenoid was attributed by the absence of oxygen, which induce oxidation in atmospheric frying (8). In addition, a lower temperature of vacuum frying compared to atmospheric frying will have an effect on the nutrition degradation. A less pronounced effect was observed by Da Silva and Moreira (7) who found that vacuum fried mango had 20-50% higher carotenoids compared to atmospheric fried mango.

2.2 Color, texture and sensory attributes

Natural fruit color preservation is an important product quality attribute for vacuum fried fruit (18). This color preservation can be attributed to the low pressure and temperature of the vacuum frying process. A low pressure means a low oxygen level, thereby reducing oxidation processes, which could lead to darkening of the color. In addition, low temperature slows down non-oxidative browning reaction. Vacuum frying better preserved the lightness and redness of apple chips compared to atmospheric frying (6, 24). Similar results for lightness and redness was found in plantain (5) and mango (7, 8).

Vacuum frying of plantain produced a crispier product compared with plantain fried in atmospheric pressure, indicated by a lower maximum breaking force value (5). Less effect was observed in mango which had no maximum breaking force value difference between vacuum and atmospheric fried mango (7).

Based on sensory analysis, plantain chips fried in vacuum frying has significantly higher score on all sensory attributes as taste, aroma, overall appearance (color), and texture (crispiness/ crunchiness) (5). Similar result were found by Da Silva and Moreira (7), which vacuum fried mango has significantly higher sensory score in color, odor, texture, flavor, and overall quality than atmospheric fried mango.

3. Vacuum Frying Process

The vacuum frying process consists of several steps as summarized in **Fig. 1**. These steps include fruit preparation, peeling and slicing, pre-treatment, vacuum frying process, and removal of excess oil. Vacuum frying usually uses raw materials as fresh fruits. However, also fruit paste can be used by preparing a dough made up with fruit pulp and starch or flour (10). Utilization of fresh fruit has some advantages as well as disadvantages. The product could be recognized by the consumer as the original fruit, but fresh fruits usually have a variety of shapes and irregularities resulting in uneven heat distribution during frying and a subsequent inhomogeneity in color and texture (27). On the other side, using fruit paste a homogenous product in size and shape can be obtained, but the characteristic of the original fruit is lost (10).

Slicing of the fruit has a large influence on the final product characteristics. Fruit could be sliced into thin pieces from 1.5 to 7.5 mm thickness that need a relative short frying time. Fruit with thicker slices needs longer frying times to lower the water content, to get the desired crispiness and shelf life, leading to an elevated degradation of nutrients and bioactive compounds (7, 28).

Pre-treatments can be used to further improve quality attributes of the fried product, such as oil content, appearance, texture, taste, and retention of nutrients and phytochemicals. In this section common pre-treatments used for vacuum frying processing will be mentioned briefly and discussed further in separated sections. The pre-treatments that are reported in literature are blanching, pre-drying, impregnation and freezing (6, 8, 12, 15, 25, 28-31). Blanching is used to minimize enzymatic browning (6, 25) and also to pre-gelatinize starch. Pre-drying is used to reduce the initial water content before frying, and thus reduce frying time (6). Osmotic dehydration is used to introduce salt or sugar to reduce initial water content (7, 8, 15, 25, 28, 30). Application of antibrowning agents to prevent browning reactions (6). Freezing can be used to create a porous and spongy matrix in vacuum fried fruit (25).

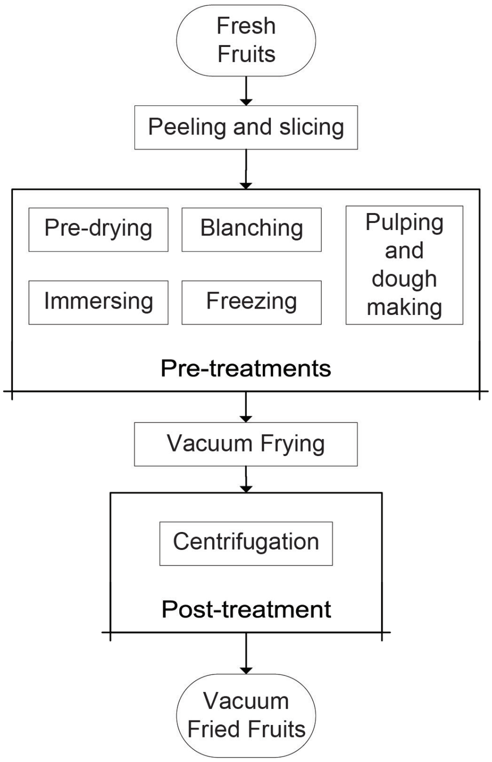

Fig. 1 Flow chart of vacuum frying process

After the pre-treatment, fruits are ready to be fried. In a small-scale fryer the process will start by placing the fruits inside a basket and placed in the vacuum chamber after which the vacuum pump is started. After the oil has reached the desired temperature and the chamber has the desired pressure, the basket is submerged in the oil to start the frying process. At the end of the frying time, the basket is lifted from the oil and shaken or spun to drain the surface oil. The pressure is gradually increased, and the product is centrifuged to eliminate part of the surface oil. Different setup could be found in larger scale and industrial scale vacuum fryer.

3.1 Vacuum Frying Equipment

Vacuum frying is carried out in a closed system below atmospheric pressures. Schematic of a batch vacuum fryer can be observed in **Fig. 2**. Conceptually different devices in batch and semi continuous mode were used in the experimental studies. The batch vacuum frying is suitable for small production sizes (32), as well as for a larger capacity. Vacuum fryers with a low capacity (2-10 L) are also often used for research (8, 9, 11), while Diamante, Presswood, Savage and Vanhanen (33) used a large capacity fryer (460 L) for their research.

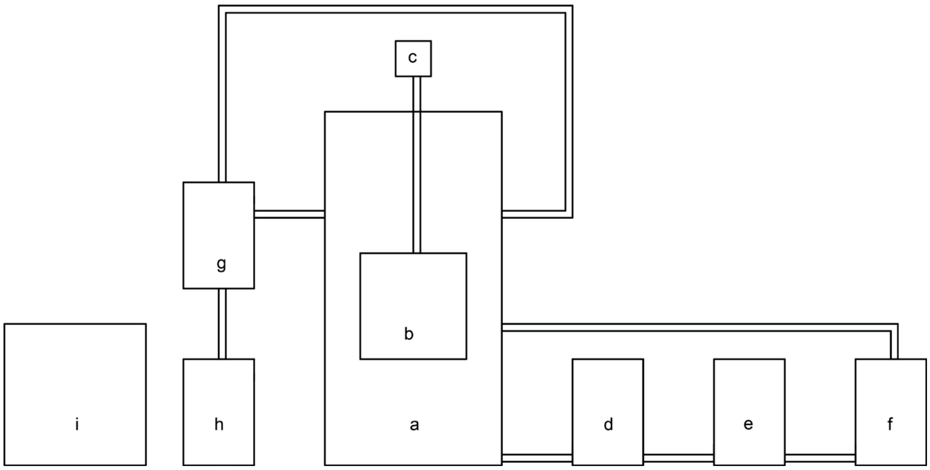

Fig. 2 Schematic representation of a vacuum fryer. **a** Vacuum chamber, **b** Frying basket, **c** Electric motor, **d** Oil filter, **e** Oil heater, **f** Oil cooler, **g** Condenser, **h** Vacuum pump, **i** Centrifuge

On the other hand, vacuum frying is also possible using a semi-continuous method, which is a batch wise process with aspects of continuous processing (32). This process was adopted by Perez-Tinoco, Perez, Salgado-Cervantes, Reynes and Vaillant (34), who used a conveyor belt frying system inside a vacuum chamber. A small vacuum fryer usually not includes a centrifuge inside the vacuum chamber like larger vacuum fryer do. A centrifugation before breaking the vacuum is desired to remove the surface oil that will otherwise get sucked into the pores. A centrifugation after breaking the vacuum could lead to higher oil content then when the centrifugation is done before. A high capacity industrial fryer also usually include several heat exchangers to maintain a constant and equally distributed oil temperature and an oil filter to maintain oil quality.

3.2 Vacuum Frying Pre-treatments

Vacuum frying is an integral process which could contain pre-treatment, frying, and post treatment. Several study used vacuum frying without pre-treatment, but cannot excluded the post treatment. The discussion on effect of vacuum frying parameters includes study which applied pre-treatment in their method. Thus, analysis of effect of pre treatment and vacuum frying parameters was separated into two sections.

Producing a high-quality vacuum fried fruit which has desirable product quality attributes is a challenge in vacuum fried fruit production, especially because of the high initial water content of fruits that requires long frying times. High oil absorptions, burnt product, and low crispness are the possible product quality attributes that are consequences of this high water content. Pre-treatments such as blanching, hot air pre-drying, immersion drying, freezing, anti-browning agent and hydrocolloid application can limit these problems (Table 1).

2

3.2.1 Blanching

Blanching was used to minimize enzymatic browning in vacuum fried apple chips (6, 25). Enzymatic browning in fruits is the result of oxidation reactions of polyphenols with catalytic action of polyphenol oxidase (PPO) enzyme (35). During blanching, PPO in mango can be inactivated by a 5 minutes treatment at 94 °C. However, blanching for more than 5 minutes resulted in color loss (36), even before frying. Blanching of jackfruit produced a negative effect on oil content and texture; a higher porosity matrix was formed during the vacuum frying causing a higher oil absorption compared to non-blanched jackfruit (12), however the mechanism behind the porosity formation is not clear . Nevertheless, Hasimah *et al.* (29) describes that blanched vacuum fried pineapple at 100 °C for 3 minutes has shrunken cell due to air lost by blanching, and consequently produce a hard product.

Table 1 Pre-treatment effect on vacuum fried product quality attributes.

Pre-treatments	Quality attributes				References
	Oil content	Texture	Nutrient	Color	
Blanching	Negative	-	N.A.	N.A.	(12)
	-	Negative	-	-	(29)
	-	Negative	-	-	(25)
Hot air drying	Positive	N.A	N.A.	Positive	(6)
	Positive	Positive	-	Negative	(25)
Osmotic dehydration	Positive	-	-	-	(8)
	Positive	-	Neutral	-	(28)
	-	Positive	-	Negative	(15)
Freezing	N.A.	Positive	N.A.	N.A.	(25)
Anti-browning agent	N.A.	N.A	N.A.	Positive	(6)
Hydrocolloids	Positive	Negative	N.A.	Positive	(30, 31)

N.A.: Data not available

On the other hand blanching were found limits oil uptake since the gelatinization leads to starch swelling and prevent oil to enter the product, as found in atmospheric fried tortilla chip (37), vacuum fried sweet-potato chips (38), and atmospheric fried potato slices (39).

3.2.2 Pre drying

Several strategies have been applied to reduce the initial water content of fruit such as pre-drying with hot air and osmotic dehydration. Hot air-drying as a pre-treatment at 80 °C, which produced final moisture content of 64% w.b., preserved apple slice color, which remains similar to that of raw apple (6). This color preservation correspondents to lower water activity after hot air drying which further inhibit non enzymatic browning. Additionally, at 80 °C, hot air drying could decrease enzymatic activity which might reduce enzymatic browning. Hot air drying reduces moisture loss since the lower moisture content available and crust formation which produce higher resistance during vacuum frying. This crust eventually produced a barrier to further inhibit oil absorption.

3.2.3 Osmotic dehydration

Osmotic dehydration can be applied for reducing the initial water content by applying sugars like fructose, maltodextrin, and salts like NaCl (7, 8, 15, 25, 28). Osmotic dehydration could reduce initial water content by two mechanism the first is water flows from the food to the solution and at the same time solute transfer form solution to the product (40).

Osmotic dehydration reduced the initial water content by 10-70% depending on the process condition and fruit properties (41). After osmotic dehydration with 40-65%

maltodextrin, mango chip will have lower initial moisture content, and thus time needed to reach same final frying time will be shorter (8). On the other hand, in vacuum fried apple, oil content was decreased as the concentration of fructose was increased from 30 to 40% (25). Additionally, Nunes and Moreira (8) explained that the oil content reduction was affected by the water loss during the osmotic dehydration of mango by 40-65% maltodextrin in 5 hours.

Osmotic dehydration by 30-40 % fructose resulted in crispy texture of apple chips measured as low maximum breaking force (25). Additionally, Diamante *et al.* (15) observed immersion with dextrose 55% increases crunchy texture of gold kiwifruit. The osmotic dehydration in fructose solution also produced chips with uniform porosity and reduced surface shrinkage of apple chips resulting in a smoother surface (25).

The negative effect of the osmotic dehydration with fructose on vacuum fried fruits, is the impact on color. Fructose application decreased the lightness of products because of the Maillard reaction during vacuum frying of apple (25). A similar result was also found by Diamante *et al.* (15) whose application of 55% maltodextrin increased the browning index of gold kiwifruit. Surprisingly, at higher maltodextrin concentration, the browning index decreased, the mechanism behind this is still unclear.

3.2.4 Freezing

Freezing is an alternative pre-treatment strategy to achieve a crispy fruit chips matrix in vacuum frying processing (25, 28, 42). Shyu and Hwang (25) found that freezing at -30 °C overnight formed a porous sponge-like matrix in vacuum fried apples. In fact, due to fast heat transfer to frozen tissue, ice crystal inside the frozen cells sublimed under vacuum condition leaving pores in the food matrix, accelerated the moisture loss and sequentially decrease the final moisture content. Albertos, Martin-Diana, Sanz, Barat, Diez, Jaime and Rico (43) found that moisture content in vacuum fried carrot was lower in sample with -20 °C blast freezing followed by overnight freezing pretreatment compared to control. Since it is important that the water is in frozen condition, when using freezing, it is important to fry the fruit directly to prevent thawing.

Freezing rate could affecting vacuum fried fruit. Slow freezing produce big size crystal which damage the cell (44, 45). Then could increase oil penetration, since oil could penetrated into damaged cell during the frying (46). Thus, fast freezing is preferred to minimize oil uptake.

Freezing is also used to preserve the raw material prior the frying process. During slow freezing processes, large ice crystal form that damages the cell membranes and is causing water to leach upon thawing (47). However, fruits have a different susceptibility to freezing injury. This difference is caused by the ability of cell membrane to adapt or resist the phase change during freezing is different for each fruit (48). Apricots, banana, peaches are very susceptible, while apple, grapes and pears are moderately susceptible and dates are least susceptible for freezing damage (49).

3.2.5 Anti-browning agent

The application of an anti-browning agent could prevent further browning reaction in susceptible fruits. Pre-treatment by tartaric acid, cysteine, and calcium chloride have been used to prevent non-enzymatic browning in banana. Synergistic effect was observed by combining tartaric acid-ascorbic acid, calcium chloride - ascorbic acid; and cysteine-citric acid. However, using 1% cysteine-citric acid resulted in the highest overall preference evaluation in vacuum fried banana (14). Citric acid at 5.8% can also be applied to prevent non-enzymatic browning in vacuum fried apple (6) and it was also able to reduce the rate of quinone formation and color development (50).

3.2.6 Hydrocolloids

Dipping the fruits in a solution of hydrocolloids such as guar gum and xanthan gum, pectin, carboxymethyl cellulose (CMC), gum arabic and sodium alginate is a common fruit pre-treatment before vacuum frying to improve product quality attributes. Sothornvit (30) described that 1.5 % of guar gum is able to reduce oil absorption by 25%, and 1.5 % of xanthan gum by 17% in banana chips. The application of hydrocolloids was not significantly improving the color of vacuum fried banana chips. In the same paper it was reported that hydrocolloids application increases the maximum breaking force. However the differences were not observed during sensory study. This is explained because the hydrocolloids created a rigid, resistant film, protecting the inner matrix. Similar observation was made by Maity *et al.* (31) in jackfruit, showing that arabic gum was effective to reduce oil absorption up to 35.3%, on the other hand, increased chips toughness, thus decreased crispness was observed.

Different hydrocolloids produce different effects when applied to the vacuum fried fruits. CMC and other cellulose coating produce a protective layer which induced gelatinization at 60 °C and subsequently prevent moisture loss and oil absorption. Guar gum reduce pores and cracks formation in the fried food, which is access of oil to entering the food. Thus, subsequently reduce oil penetration (51).

3.3 Vacuum Frying Parameters

Vacuum frying process is mainly characterized by time-temperature and vacuum pressure as the main parameters, which should be adjusted to the fruits characteristics to produce high-quality vacuum fried fruit. Vacuum frying temperature for fruits ranged in a wide interval from 72 to 136°C, as well as frying time (from 0.5 to 90 minutes), and the vacuum pressure (from 1.3 to 98.7 kPa).

Clearly, increasing temperature from 70 to 90 °C and time from 35 to 65 minutes results in an increased oil content for gold kiwi fruit (28) . On the other hand , increasing temperature from 112 to 136 °C and time from 3 to 9 minutes results insignificant increase of oil content in plantain (5). Mariscal and Bouchon (6) found that increasing temperature from 95 to 115 °C induces structural changes such as tissue degradation that enhanced the oil absorption in apple chips. Additionally, Shyu and Hwang (25) explained that the increase of oil content when temperature increase from 90 to 110 °C was caused by a higher speed of water escaping from the matrix of apple. When the water is removed from the matrix, the process will damage the cells and make the surface hydrophobic, and thus oil can absorb into the damaged sites.

The maximum breaking force of the vacuum fried apricot (42) increased as the temperature and time was increased from 70 to 90 °C and 35 to 65 minutes, similar effect was observed in plantain (5). Accordingly, Shyu and Hwang (25) found that increasing of frying time (from 5 to 30 minutes) leads to a higher crispness of apple chips. However, Yamsaengsung *et al.* (13) found that increasing temperature from 100 to 120 °C did not affect the crispness of banana chips. At the beginning of the frying, fruit tissue becomes soft due to cell rupture and solubilization of the middle lamellae and leds to rubbery and soggy products. Continuing the frying, the rapid loss of moisture from the surface leads to crust formation and an increase of the maximum breaking force. In the final stages of the process, the crust thickened until the end of the process (5, 13, 42).

Vitamin C content of the vacuum fried gold kiwifruit (28) and apple (24) was decreased as the temperature increased from 70 to 90 °C (gold kiwifruit) and 160 to 180 °C (apple) because of heat sensitivity of vitamin C. However, an increasing frying time from 35 to 55 minutes of vacuum fried gold kiwifruit was found to have only a slight effect on vitamin C (28). Diamante *et al.* (16) found that in apricot, the β-carotene content increased upon frying temperature increase from 70 to 90 °C, they attributed this to the higher accessibility of the β-carotene by the oil which penetrates the fruit.

The color of the fruit chips was affected as the temperature-time of the frying process is increased. Lightness and yellowness values decreased, and redness increased as found in plantain, gold kiwifruit (from 70 to 90 °C and from 35 to 65 minutes), apple, and mango (from 100 to 120 °C, and from 30 to 90 second) (5, 10, 15, 25). No significant color change was found by Dueik and Bouchon (24), Mariscal and Bouchon (6), and Diamante *et al.* (42), who found that there was no difference in color when the frying temperature was increased for apple (from 160 to 180 °C), mango and apricot. Moreover, Mariscal and Bouchon (6) and (42) found that frying time does not influence the color of the vacuum fried apple (between 2 and 15 minutes) and apricot. The a* and L* value as an indicator of the browning reaction was similar to the value of raw product. As the frying time increased for plantain and apple (from 5 to 30 minutes), the Maillard reaction was more pronounced, and as the moisture removed, the lightness was decreased while redness and yellowness were increased (5, 25).

Another vital processing parameter is the pressure: decreasing the frying pressure which decreases the oil content. A lower pressure (from 13.14 kPa to 26.54 kPa) produces a fast moisture removal, reducing the rate of oil diffusion into the pores of vacuum fried plantain (5). On the other hand, a lower pressure leads to decrease of the texture quality, and darker color in vacuum fried plantain and mango (from 40 Pa to 60 Pa) (5, 10).

3.4 Vacuum Frying Post Treatment

Centrifugation for removing the surface oil is an important part of the post-frying process and can be part of the frying equipment. Centrifugation done while the pressure is still low will significantly decrease the amount of surface oil that can penetrate the porous products when breaking the vacuum. Tarmizi and Niranjan (52) found that centrifugation in high vacuum following moderate vacuum frying has potency to reduce oil uptake in potato slices. Furthermore, Tarmizi and Niranjan (53) also found that in potato chip, centrifugation under vacuum significantly lower oil content then atmospheric centrifugation (56.85 g oil/100 g and 35.01 g oil/100 g defatted dry matter respectively).

On the other hand atmospheric centrifugation also promising. Sothornvit (30) compared two atmospheric centrifugation speed 140 rpm and 280 rpm to remove oil after vacuum frying of banana. They found centrifugation at 280 rpm reduced oil content 17.3 % higher than at 140 rpm. Similar findings were reported by Dueik *et al.* (11) who found centrifugation of vacuum fried apple at 400 rpm for 3 minutes reduced the oil content by 24 % compared to without centrifugation. In general, data show that increasing centrifugation speed, decreased the oil uptake. However, the centrifugation speed has to be limited according to the product hardness to prevent product breakage.

4. Effect of Matrix to Vacuum Fried Fruit Quality

The matrix of food products is defined as: "the whole of the chemical components of food and their molecular relationships, the chemical composition of food, and the way those components are structurally organized at micro-, meso-, and macroscopic scales" (54). Tropical fruits have diverse matrix characteristics that could have different effect on vacuum fried fruit quality. Those characteristics includes cell size, cell wall, flesh thickness, firmness, intracellular spaces, sugar content, fiber content, fiber type. Some matrix characteristics of the fruits that are usually quantified and processed by vacuum frying are described in Table 2. The effect of different matrix characteristic will be discussed in this chapter.

Fruits can have two possible types of ripening. The first are called climacteric fruits, whose respiration and ethylene biosynthesis rates increase during ripening. The second are non-climacteric fruits, whose respiration and ethylene biosynthesis rates do not increase during ripening (55). This characteristic is important to select which fruit is suitable for frying. A characteristics of climacteric fruits will change substantially over time during storage. The characteristics of non-climacteric fruits will stay more constant after harvest.

Table 2 Fresh Tropical Fruit Matrix Characteristic

Fruits	Fruit ripening[a]	Firmness	Water content[b]	Porosity	References
Apple	Non Climacteric	4.0 N	85.5	0.15	(56); (57); (58)
Avocado	Climacteric	5.5 N/mm	73.2	0.16	(59); (60); (61)
Banana	Climacteric	12.0 N/mm	71.8	0.06	(62); (63); (14); (64)
Dragon fruits	Non Climacteric	7.0 N/mm	83.6	N.A.	(65); (66); (67)
Jackfruit	Climacteric	14.0 N	73.5	N.A.	(68); (69)
Longan	Non Climacteric	18.2 N/g	81.9	N.A.	(70); (71)
Mango	Climacteric	22.2-35.6 N	83.0	0.05	(72); (73); (64)
Pineapple	Non Climacteric	11.2 N	85.7	0.11	(74); (75); (64)
Rambutan	Climacteric	1.5 N	80.0	N.A.	(76); (77); (78)
Snake fruit	Non Climacteric	32.7 N	81.0	N.A.	(79); (79); (79)
Watermelon	Non Climacteric	24.1 N	91.5	N.A.	(80); (81)

[a]Wongs-Aree, Noichinda, Shewfelt, Brueckner and Prussia (82); [b]US Department of Agriculture. Agricultural Research Service. Nutrient Data Laboratory (83); N.A.: Data not available

Ripening stage has an important role on the vacuum fried fruit quality attributes: as a general rule, the riper the fruit, the higher the oil content in the vacuum fried chips (12). Yashoda, Prabha and Tharanathan (84) explained that during the early ripening stage of mango the cell wall is compact and rigid, and as the ripening continues the cell become more loose and expanded. This expansion is due to the movement of water into the voids that form after pectin solubilization. Pectin is important because of its role in gluing the adjacent cell which results in tissue rigidity and firmness. Moreover, pectin is essential to maintain the matrix cohesiveness during frying (85).

The effect of differences in ripening stages on the texture of vacuum fried banana has been described by Yamsaengsung *et al.* (13). They found that at the first stage of ripening, sugar to starch ratio was 2.95 and the vacuum fried banana chips have the highest maximum breaking value as an indicator of compactness and hardness of the chips. This high maximum breaking value was caused by the high content of starch which helps forming a crust (86). At the second stage of ripening, the maximum breaking value is lower than early ripening stage as an indicator of crispy and porous matrix. At this stage, sugar to starch ratio was 8.75, which is the most optimum value to produce crispy vacuum fried banana. However, at the third stage of ripening, the maximum breaking value is increased again, and the product is becoming hard and compact. At this ripening stage, the sugar to starch ratio was decreasing again to 4.05. The sugar to starch ratio should be increasing during the ripening process, this reverse effect could be because of the high biological variance in the banana. The high sugar content slows down the gelatinization process, thus produces a shrunk banana chip (13).

Similar results were found in mango. Starch and pectin concentrations in mango are decreasing during ripening. On the other hand, sugar is increasing during ripening. Unripe mango has 18% starch, 1.9% pectin, and 1% total soluble sugar. However, after ripening, mango has 0.1% starch, 0.5% pectin and 15% of total soluble sugar (84). This composition changes during ripening could have effect on texture of vacuum fried mango.

Starch content could be a major role to determinate vacuum fried fruit quality. Banana and plantain are example of high content starchy fruit which vacuum fried. Starch in the fruit will be gelatinized, swollen, and prevent moisture and oil transport. Giraldo Toro, Gibert, Briffaz, Ricci, Dufour, Tran and Bohuon (87) found that 35-25 mm vacuum-packed plantain slices were gelatinized at 80% in 85 °C and when the temperature increased, the degree of gelatinization also increased.

Fiber content could playing a significant role to determinate vacuum fried fruit quality. Fruits have high fiber content, and fiber could influenced fat and water transfer to and from the product. Fiber could gelatinized, swollen and inhibit fat entering the product (51).

After vacuum frying, fruit at an early ripening stage produced a low color intensity product, at later ripening stage the color of the product will be more intense, which also contributed by Maillard reaction. The color of the vacuum fried fruit may be affected by the sugar content that increased during ripening. Yashoda *et al.* (84) described that the alcohol-soluble sugar in unripe mango is mostly oligosaccharides, on the other hand, in ripe mango, it is mainly glucose and fructose. The increasing content of glucose and fructose will increase the Maillard reaction that produces brown color. A similar finding was found by Li, Shao, Chen and Jia (88) in banana in which the sugar content was increasing as the starch content was decreasing.

5. Conclusions

Vacuum frying is a processing method that is suitable to produce high quality fried fruit products. Several factors have been reviewed for their influence on product quality attributes like oil content, texture, color and nutrient content. Although some contradictory results have been reported for the different fruits, there are several indications for a higher quality of vacuum frying products compared to atmospheric frying of fruit. Different equipment used in vacuum frying processing has different characteristics which leads to different processing conditions and different product quality attributes. Pretreatments could improve most of the product quality attributes; however, the treatment should be tailored on the characteristics of the raw material and on the desired final properties. We can conclude that information about the role of the fruit matrix is a very important factor in vacuum processing, but is described very limited, fragmentary and anecdotal in the literature. During the ripening process, the fruit matrix and chemical composition will change, which will have an effect on the texture, oil content and color of vacuum fried fruits. Especially tropical fruits have quite different ripening properties, firmness, texture and porosity that will influence the quality attributes of vacuum fried tropical fruits. More systematic research into the effects of the fruit matrix on the vacuum frying process and the quality attributes of the fried fruits is needed. By such research the mechanistic understanding can be used to optimize the frying process to produce high quality vacuum fried fruits.

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CHAPTER 3

Nutritional and Physicochemical Quality of Vacuum-Fried Mango Chips Is Affected by Ripening Stage, Frying Temperature, and Time

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Abstract

For the production of healthier fruit snacks, vacuum frying is a promising alternative for atmospheric frying, to reduce the oil content, while maintaining a high nutritional quality. This paper evaluates the effect of ripening stages, frying temperature and time on the quality of vacuum fried mango. Unripe mango was dehydrated faster than ripe mango and had a higher hardness after frying at 110 and 120 °C. Fat content in fried ripe mango was higher. Total ascorbic acid and β-carotene in both ripening stages was not different, but after frying total ascorbic acid in unripe mango remains higher. A novel image analysis was applied to quantify the color distribution of fried mango. Color changes of unripe mango was more susceptible to temperature and time. Considering all quality parameters, vacuum frying of unripe mango at the optimal condition of 100 °C for 20 minutes is preferred for producing high quality healthier fruit snacks.

***Keywords*:**
Vacuum frying, mango, ripening, vitamin C, β-carotene, fat, color, texture

1. Introduction

Consumers have a strong desire for fried food products because of their unique flavor–texture combination. However, the increased awareness of consumers towards the relationship between food, nutrition, and health stimulates the food industry to use alternative processing methods complying the demand for healthier snacks. In this paper we study an alternative frying process to meet these demands by reducing the oil uptake and maintaining a high nutritional value.

Technically deep-frying is heating and dehydrating foods with associated oil uptake by immersing them in an edible fat at 165 °C to 190 °C (1). Compared to other cooking methods, deep-frying generates products with a unique color, texture and flavor.

Deep-frying dries the product giving it a crust and making it crispy (2). However, excessive oil absorption is an undesired side effect of the process that could be limited by various strategies such as dripping and post frying centrifugation (3). Additionally, a high frying temperature might reduce the content of nutrients present in the raw material (4). In the framework of the increasing demand for healthier snack choices, industries are developing low-fat alternatives. Techniques such as drying, extrusion and baking have not always been able to satisfactorily meet the sensory characteristics of fried foods (5). Consumers do not want to compromise on organoleptic properties in exchange for healthier products (6). Altogether, vacuum frying might be a promising technology for healthier fried products.

Vacuum frying is similar to atmospheric frying, but is carried out under reduced pressure below 10 kPa, causing a decrease in the boiling point of water in the fried products (4). Therefore, the frying temperature can be reduced to as low as 90 °C which allows preservation of the food nutritional characteristics, flavor and aroma. This is of particular relevance for fruits which contains high amounts of thermo-labile vitamins and phytochemicals. In this respect, characteristics of the fruit matrix can play a very important role and is an underexposed factor in the scientific literature up to now (7).

Several studies on vacuum fried food has been done for pineapple (8), and apple (9). The effect of ripening on the physicochemical quality of vacuum fried fruit has already been investigated for banana and jackfruit. Yamsaengsung, Ariyapuchai (10) found that vacuum fried ripe banana has a higher volume expansion than unripe banana, even though there was no difference in between them in overall sensory acceptability. Diamante (11) found that vacuum fried ripe jackfruit has a higher moisture and fat content, while it was more yellow, less crunchy, and has more aroma and is sweeter than half ripe jackfruit.

Studies on vacuum fried mango have been done to compare vacuum frying technique to atmospheric frying on the oil content, color, texture, total carotenoids content, and the like (12); also to study effect of osmotic dehydration on moisture and oil content, expansion, density porosity, color, texture, total carotenoids and sensory (13). However, the effect of ripening stage on the quality of vacuum fried mango has not been studied before.

As a climacteric fruit, mango quality is strongly influenced by ripening. During ripening, physiological, biochemical and molecular changes are initiated in the mango matrix by the autocatalytic production of ethylene and increase in respiration rate. Some of these changes include increased biosynthesis of carotenoids, a decrease of ascorbic acid, conversion of starch into sugars and the softening of the fruit promoted by the pectinase action on the cell wall. Another influenced quality attribute is color. Color changes in mango are resulting from carotenoids accumulation in the pulp (14).

The objective of this study was to investigate the effect of ripening stages, frying temperature and time on the nutritional and physicochemical quality of vacuum fried mango. The physicochemical quality was characterized by measuring the key parameters moisture and fat content, color and texture. While the nutritional value was assessed by analyzing vitamin C and β-carotene content as key parameters for respectively water- and fat soluble nutrients in mango. The research hypothesis was that quality of vacuum fried mango chips is affected by ripening stage, frying temperature and time.

2. MATERIALS AND METHODS

2.1 Raw material

Unripe (stage 2, firmness 68.4 – 87.9 kg/m^2) and ripe (stage 4, firmness 24.4 – 39.1 kg/m^2) mango (*Mangifera indica* L. cv. Kent) from Brazil were supplied by Bakker Barendrecht B.V. (The Netherlands) and stored at 11 °C and used within five days after arrival. Just prior to the frying experiment, the mangoes were selected based on ripeness indicators, including total soluble solids (TSS) to indicate the sugar content and firmness (15) as shown in **Table 1.** In order to study the role of the physiological maturity, stage 2 and 4 was selected to represent the unripe and ripe mango with enough internal matrix differences, while still having suitable properties for handling the fruit.

Table 1. Initial values for firmness and total soluble solids content of unripe and ripe mangoes used for vacuum frying experiments

Ripeness	Firmness (kg/m^2)	TSS (°Brix)
Unripe	78.25 ± 0.44^a	16.03 ± 0.08^a
Ripe	31.91 ± 0.26^b	16.41 ± 0.11^b

Different superscripts at firmness and TSS values shows significant difference (p≤0.01) between ripe and unripe mango. N=423

Firmness was measured using fruit penetrometer FT327, equipped with an 8 mm tip (Nieuwkoop B.V., The Netherlands). The firmness measurements were done on each peeled mango cheek with three repetitions and was expressed in kg/m^2. TSS content was measured three times from juice obtained from mango cheek using a refractometer (HI96801, Hanna Instruments) and was expressed in °Brix. After selection, mangoes were peeled, the seed was removed and halved. The halved fruits were cut into 4 mm thick slices with a mandolin (V5Power, Börner, Germany) to ensure the fast heat penetration to the center of the chips but not collapse during the processing.

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2.2 Vacuum frying procedure

Mango slices were vacuum fried in 2 kg batches using a pilot scale industrial vacuum fryer (Florigo Industry B.V., The Netherlands) containing 250 L fresh high oleic sunflower oil. A high oil to fruit ratio was needed to diminished temperature drop after the fruit was submerged into the oil. The vacuum fryer was equipped by an automatic basket rotator, two heat exchangers to cool and heat the oil and an atmospheric spinner to remove surface oil. Some pilot experiments have been carried out to determine the optimal conditions for thickness of mango slices and vacuum frying pressure. Based on these results, 4 mm mango slices were fried at 10 kPa at times and temperatures as listed in **Table 2**. This working pressure produce water boiling at 44.3 °C.

Table 2. Settings used for vacuum frying mango chips

Oil temperature (°C)	Frying time (minutes)					
90	5	10	15	25	35	50
100	5	10	15	20	27.5	35
110	2.5	5	10	15	20	25
120	2.5	5	7.5	10	12.5	15

Two samples of mango slices (1 kg of each of the two ripening stages) were loaded into the vacuum chamber. After 60 seconds, the desired vacuum pressure was reached, and the basket was submersed into the oil to initiate the frying time. During frying, the basket was rotated back and forth at 17 rpm for 60 seconds to ensure that the heat and oil were evenly distributed. To stabilize the temperature, a heat exchanger to heat and cool the oil was used. Once the frying was finished, the basket was lifted from the oil and shaken for 20 seconds inside the vacuum chamber to remove excess of oil. The vacuum chamber was then pressurized, and the vacuum fried mango was centrifuged to remove surface oil for 60 seconds at 100 g (MSD-500HD, Eillert B.V., The Netherlands). Then, mango chips were packed in sealed plastic bags and stored at -20 °C until further use. All frying experiments were performed in duplicate.

2.3 Moisture and fat content

Moisture content of the samples was determined in triplicate per frying experiment with a forced convection oven at 100 °C until constant weight and described in % fresh weight. Fat content of the fried mango chips was determined in duplicate per frying experiment with the Soxhlet method using 200 ml petroleum ether 40-60 ˚C after dried overnight and then described in % dry basis (db) (16).

2.4 Texture

Texture of the mango chips was measured with a texture analyzer (TA.XT.Plus, Stable Micro Systems, UK) using a three-point bending test according to Da Silva and Moreira (17) with some modifications. One mango chip was placed on two parallel edges (16 mm wide) and the probe selected was a 1 mm thick steel blade. Settings used were as follows: 0.50 mm/s test speed, 10.00 mm/s post-test speed, 15 mm distance and 5 kg load cell. Results from ten replications per frying experiment was expressed as hardness in N.

2.5 Total Ascorbic acid

Since ascorbic acid (AA) easily oxidized into L-dehydroascorbic (DHA). Vitamin C was calculated as total ascorbic acid (TAA) which sums of AA and DHA. The AA was reduced into DHA using TCEP (tris-2-carboxyethyl phosphine) and then calculated together into TAA. The extraction and HPLC analysis was conducted according to the methods of Hernández, Lobo (18) and Wechtersbach and Cigić (19) with modification. Two grams of sample was used and homogenized with 25 ml metaphosphoric acid-tert-butylhydroquinone (MPA-TBHQ) solution using Ultra Turrax at high speed for 45 second and was centrifuged for 20 minutes at 4000 rpm at 4 °C. The supernatant was then centrifuged again in 5 ml preweighed reaction tube at 10500 rpm for 20 minutes at 4 °C. An amount of 1.485 ml sample was added by 15 µl TCEP, filtered using a 0.2 µm CA filter to an amber vial and ready to be injected into the HPLC. Three measurements per frying experiment were conducted and the values are expressed in mg TAA /100 g of dry basis (db). A calibration curve was prepared using 10 mg/ml ascorbic acid in MPA TBHQ, filtered through a 0.2 µm CA filter and diluted in 8 steps to get a range from 200 µg/ml – 1.56 µg/ml with R^2=0.997. HPLC analysis was done using thermo separation products Spectra Series HPLC with a binary gradient pump and UV detector at 245 nm and Polaris 5 C18 A 150 x 4.6 mm 5µm column. Twenty µl sample was injected using orthophosphoric acid 0.2% in milli Q water as mobile phase, with 5.5 minutes run time at 1.0 ml/min flow.

2.6 β-carotene

The extraction and HPLC analysis of β-carotene was conducted according the methods of Salur-Can, Türkyılmaz (20) with modification. During extraction, 1 g sample was used and dissolved into 1.5 ml of milli Q water and 7 ml hexane, then the samples were homogenized using Ultra Turrax, and centrifuged 5 minutes for 3000 rpm to get the supernatant, the pellet were extracted again two times and a third time using 10 ml Tetrahydrofuran (THF) instead of hexane. The orange upper liquid then taken out (from hexane and THF extraction), the solvents were evaporated using vacuum evaporator at 40 °C, 270 mbar vacuum. The extract then dissolved into 2 ml buffer MeOH-THF 1:1 + 0.01% BHT, filtered through 0.2 µm filter and ready to be injected into HPLC. Three measurements per frying experiment were conducted and the values are expressed in µg/g dry basis (db) of β-carotene. A calibration curve was prepared using 0.1 mg/ml β-carotene (Sigma Aldrich, 22040) in THF including 0.1 % BHT, filtered through 0.2 µm and diluted in 6 steps to get a range from 50 µg/ml – 0.78 µg/ml with R^2=0.999. HPLC analysis was done using HPLC with a Dionex Ultimate 3000 RS equipped with Phenomenx Onyx monolithic C18 column (100 x 4.6 mm, pore size of 130 Å). Twenty µl sample was injected with 60% acetonitrile (ACN), 30% MeOH, 10% ethyl acetate (ETAC) and 0.1% trimethylamine (TEA) mobile phase, with run time of 10 min at flow rate of 1.0 ml/min. Compounds were detected at a wavelength of 445 nm.

2.7 Color

The color distribution of mango chips was described by a new approach developed specially for this study (21). Therefore, a detailed description will be given. Four pieces of mango chips from each frying experiment were photographed and analyzed via a color quantization for each pixel based on a method described by Wu (22).

Images of mango chips were taken using color digital camera (Canon 1000D with Canon EFS 18-55mm F3.5-5.6 IS lens) mounted on Kaiser RT1 base 25 cm from the product and was placed inside a closed picture chamber. The light used was produced by 4 x 36 watt 5400k 40hz fluorescent light mounted at 22° from the sample axis. Color calibration was done using Xrite Color Checker Passport and Adobe Lightroom.

Uncompressed picture file (CR2) with image size 3888x2592 pixel was produced and later converted to another uncompressed file (Exif-tiff 8 bit) at same resolution by image processing software (Canon Digital Photo Professional, version 3.14.40.0) prior further analysis. Image background was removed using quick selection tool from an image processing software (Adobe Photoshop CC 2015). The tiff images then analyzed using Color Inspector 3D v 2.3(21) within Fiji (22), an Image J 1.52g repository (23), according color quantization for each pixel. The obtained RGB color table was converted into *L** *a** *b** values using method developed by Boronkay (24). Only the *L** and *a** values were used, as they describe the most important changes in color of vacuum-fried products. (6) The *L** value describes the lightness with 0 for darkest black and 100 for brightest white and was divided into 3 levels, 0≤dark≤60, 60<medium-light≤80, 80<light≤100. The a* value describes the transition from green to red, ranging from -128 for the purest green and +128 for the purest red and were divided into 3 levels, green ≤0, 0<medium-red≤10, red >10. The number of pixel in each lightness and redness level then divided by total pixel of the mango chips and multiplied by 100% to produce % of pixels of each lightness and redness level.

2.8 Statistical analysis

Data analysis was performed using R software by independent T Test for TSS and firmness to test the difference between ripe and unripe mango. On the other hand, ANOVA with Tukey posthoc analysis were performed for moisture, fat, texture, TAA, β-carotene, and color. Numbers and graphs were made based on mean and standard error. Standard error of the mean (SEM) was used to describes the uncertainty of how the sample mean represents the population mean, which is possible at a large number of measurements (23).

3. RESULTS AND DISCUSSION

3.1 Firmness and TSS of fresh/raw mango

Firmness and TSS content of raw mangoes were measured to determine the required ripeness stages (**Table 2**). Commonly during mango ripening, the TSS content increases due to hydrolysis of starch into sugars (14), while firmness of the fruits declines due to breakdown of the cell wall polysaccharide such as pectin (24). However, our data just show just a slight though significant increase in TSS from unripe to ripe mango (0.38 °Brix). While Ibarra-Garza, Ramos-Parra (14) found a higher increase during ripening in Keitt mango, from 10.1 to 12.7 °Brix. This difference could be ascribed by variation among varieties.

3.2 Moisture content

Overall, moisture loss during vacuum frying exhibited a classical drying profile (**Figure 1**). As frying time increases, moisture content rapidly decreases. For all temperatures, an initial rapid decrease in water content was observed, followed by a more gradual decline until a constant moisture value. Moreover, moisture loss increased with increasing temperature, consequently a shorter frying time led to the same final moisture content.

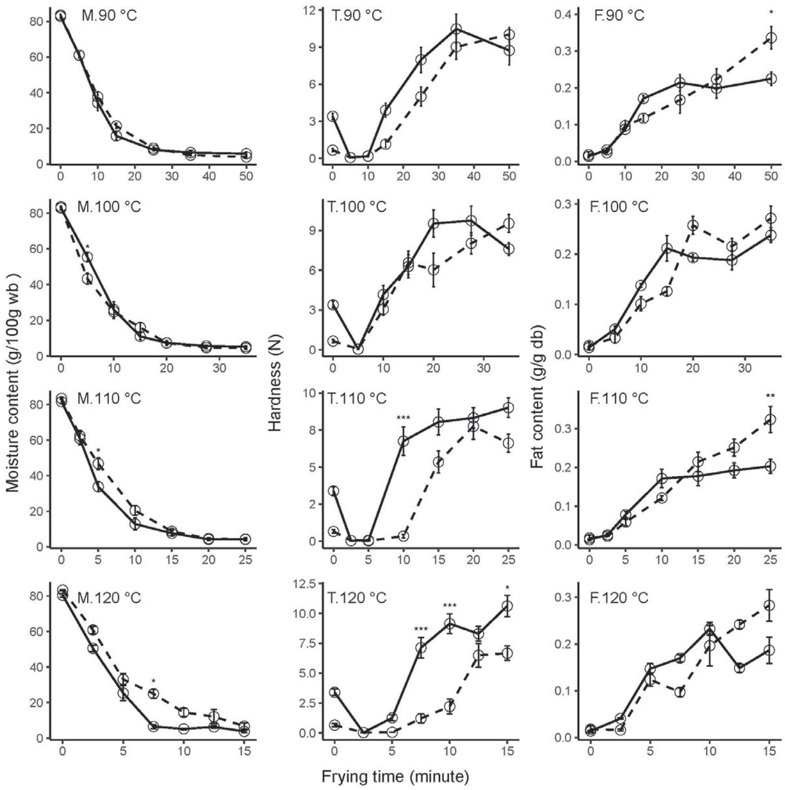

Figure. 1 Effect of frying temperatures, time and ripening stage on moisture content **(M)**, texture **(T)**, and fat content **(F)** of mango chips during vacuum frying at 90, 100, 110, and 120 °C. Solid lines are unripe mango, and dashed lines are ripe mango. Error bars are standard error. Asterisk shows significant difference between ripening stages (*p ≤ 0.05, ** p ≤ 0.01, ** p ≤ 0.001, *** p ≤ 0.0001). N=6 (2 frying experiments x 3 replications) for moisture content; 4 (2 frying experiments x 2 replications) for fat content; 20 (2 frying experiments x 10 replications) for texture

At 10 minutes of frying the moisture content of unripe mango ranged from 34.4 ± 4.4 % at 90 °C to 5.2 ± 0.5 % at 120 °C, while for ripe mango the content was 37.8 ± 2.9 % and 14.5 ± 2.4 % for the respective temperatures. Even though not significant, this result shows the moisture of ripe mango was more difficult to evaporate during frying than for unripe mango. This difference could be explained by the structure, soluble solids, and texture differences. Pectin is an important compound influencing those physical characteristics. Pectin is more abundantly present in unripe mango thereby increasing the water binding properties (25). In unripe mango large pectin molecules firmly hold the water and when heated the polysaccharides shrinks expelling water out and increasing the moisture loss (26). On the other hand, in the ripened fruit the water is already more free because pectin was enzymatically hydrolyzed.

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Moreira (1) described that a moisture content of less than 10% is needed to keep the product stable upon storage. To produce fried chips with less than 10 % moisture content, vacuum frying at 120 °C will need 7.5 minutes for unripe compared to 15 minutes that is required for ripe mango. A similar effect was observed for air-drying of 1 cm thick banana slices, for which the rate constant of ripe banana was lower than in unripe banana, even though the difference was not significant (27).

3.3 Fat content

During vacuum frying there is an increase in the fat content for mango parts of both ripening stages, however the fat content of unripe mango showed a sigmoid trend, while ripe mango showed an almost linear increase of the fat content during frying (**Figure 1**). A similar increase in fat content is also observed in vacuum frying of apple (5).

Fat uptake during vacuum frying is a direct effect of moisture loss. When the mango slices were submerged in hot oil, moisture rapidly evaporated from the surface, and allows oil to adhere to the dry surface (28) and further infiltrate to the chips (29).

At most frying conditions, fat content in unripe and ripe mango shows no significant differences, except at the most intense treatments the fat content in unripe mango is lower as shown at 90 °C for 50 minutes ($p=0.0150$), and 110 °C for 25 minutes ($p=0.0034$), but at 120 °C there was no significant difference for all frying time. The difference could be caused by the higher pectin content in unripe mango, BeMiller (30) describes that pectin consists of hydrophilic and hydrophobic molecules. Pectin could become a barrier to oil absorption (31).

3.4 Texture

After vacuum frying started, the hardness of fried mango chips initially drops for both ripening stages and at all temperature, and subsequently increases in time. Dueik, Robert (32) divided the vacuum frying into fast and slow phases. During the fast phase the plant tissue initially softens and then hardens in the slow phase. The tissue softens because the middle lamella between the cell is solubilized (33). However, during the slow phase there is tissue hardening because the mango dehydrates and forms a crust.

The hardening process accelerates at higher temperatures. Unripe mango chip fried for 15 minutes at 90 °C had a hardness value of 3.9 ± 0.6 N; this value was at the beginning of the slow phase that increased at longer frying time. On the other hand, unripe mango chip fried at 120 °C for 15 minutes had a hardness value of 10.6 ± 0.9 N; this value was at the end of the slow phase. Nunes and Moreira (13) did similar research on Tommy Atkins mango chips and found that when the oil temperature was increased from 120 to 130 °C, the maximum force (N) and the work (N * mm) also increased. However, when the temperature was increased to 138°C, these maximum force and work values decreased because of the brittleness of the chips. A phenomenon also observed in our data for unripe mango fried at 90 and 100 °C, and ripe mango fried at 110 °C.

3

Overall, there was no significant difference between hardness of unripe and ripe mango after vacuum frying at 90 and 100 °C at all time points. At higher temperatures the hardening was faster for unripe compared to ripe mango. A significant difference (p=0.000) is observed after frying at 110 °C for 10 minutes, with a hardness of 6.8±1.0 N for unripe mango, and 0.3±0.1 N for ripe mango. When the temperature increased to 120 °C, the difference (p=0.000) was observed at a shorter frying time (7.5 minutes); 7.1±0.9 N for unripe mango, and 1.2±0.4 N for ripe mango. Again, the difference in matrix could play a role here. The crust formed by unripe fried mango is harder because the pectin polymer is still there and when the water evaporates it is able to form a stronger network and become hard (34).

3.5 Ascorbic acid

Vitamin C (AA + DHA) is an important nutritional parameter for fried food products. The raw material used in this study is characterized by a high total ascorbic acid content; raw unripe mango had a higher TAA content of 156.2 ± 6.4 mg /100 g compared to ripe mango (126.6 ± 3.0 mg/100 g). The TAA decrease could be a result of ascorbate peroxidase (APX) activity which use ascorbates as electron donor to remove hydroxyl radical from the cell that produced during fruit ripening (35).

As expected, thermal degradation of total ascorbic acid (TAA) increased with increasing frying temperature, a similar pattern was observed in both ripening stages (**Figure**

2). AA loss was described to have a linear relationship with temperature in vacuum fried gold kiwi fruit (36) but also by first order kinetic and the Arrhenius equation (37). Reduction of ascorbic acid content (AA) is possible in the absence of oxygen and at relatively low frying temperatures as it can follow an anaerobic pathway of non-enzymatic browning reactions (5). It has been shown in apple and potato that frying at atmospheric pressures substantially reduces the vitamin C content in comparison with vacuum frying conditions (4). Under vacuum pressure, no dehydroascorbic acid is formed in significant amounts; ascorbic acid degrades by the cleavage of ring and the addition of water, decarboxylation also intermolecular rearrangement, followed by dehydrations to produce furfural (38).

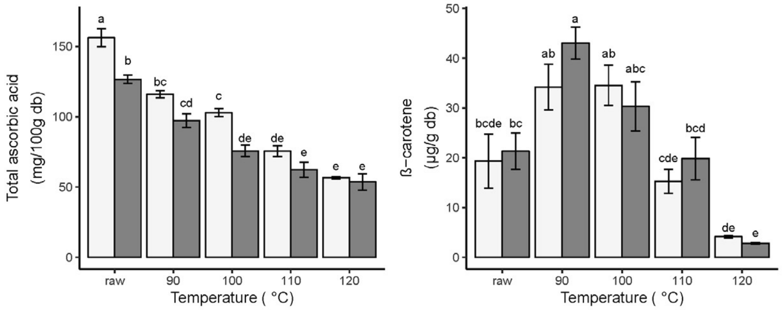

Figure. 2 Effect of vacuum frying and ripening stage of mango on total ascorbic acid (mg/100g db) (left), and β-carotene (μg/g db) (right) during vacuum frying. Light bars represent unripe mango, dark bars represent ripe mango. The different frying temperatures also represent the different final frying times; 90 °C (50 min); 100 °C (35 min); 110 °C (25 min); 120 °C (15 min). Error bars are standard error. Different letters above the error bars shows significant difference between treatments. N = 6

However, the TAA values remain higher in the unripe mango for all temperatures, although only significantly at 100 °C. Frying for 35 min at 100 °C retained 65.8 and 59.8% of TAA in unripe and ripe mango; Even at this severe heating, 100 g unripe and ripe vacuum fried mango is able to provide 114.3 and 84.1% of the recommended daily allowance of vitamin C for adult man (90 mg) respectively. This difference shows the importance of the fruit matrix as the container of the ascorbic acid. Davey et al. (39) mentioned that L-ascorbic acid was present in subcellular level in various cell compartments including in chloroplast, cytoplasm, mitochondria and apoplast. This arrangement could protect ascorbic acid inside the cell, however due to the lower amount of pectin in the cell walls of the ripe mango cell (34) could increase ascorbic acid heat damage in comparison to unripe mango cells.

3.6 β-carotene

Raw ripe mango had a higher β-carotene content compared to unripe mango, even though not significant (27.2 ± 3.6 and 19.3 ± 5.4 μg/g db, respectively). This result was expected since carotenoid content increases during mango ripening (14).

There was no significant difference in β-carotene content for each temperature/time combination between the two ripening stages. While in both ripening stage the initial low β-carotene value increases after frying at 90 and 100 °C, there is a clear decline of β-carotene content for both ripening stages when increasing temperature (**Figure 2**).

The possible explanations for the increased ß-carotene concentrations after frying at 90 and 100 °C; which also found in vacuum fried apricot at 70-90 °C (40) could be connected to the role of the changing fruit matrix on the accessibility of ß-carotene. In mango, β-carotene is located in lipid-dissolved and liquid-crystalline tubular elements of mesocarp chloroplasts. Thermal treatment and the presence of lipids improve the β-carotene accessibility (41).

However, after vacuum frying at 110 and 120 °C, the ß-carotene concentrations decreased which shows the thermal sensitivity of ß-carotene in vacuum frying. Da Silva and Moreira (12) confirm that vacuum frying of mango at 1.33 kPa, 120 °C for 3 minutes resulted in a decrease of 71.3 % of the ß-carotene content. So, it was clear that to maintain ß-carotene content in vacuum fried mango chips, a high temperature processing should be avoided.

3.7 Color

The color of fried mango chips is often inhomogeneous with strong local differences e.g. the occurrence of brown spots in a lighter background. This phenomenon is present in most fried or baked foods. Therefore, measuring the overall color changes e.g. expressed as L*a*b* values is not representative for the visual appearance. In many cases the food matrix and surface are not homogenous and have different structure at micro- and macroscopic scales (42). Image analysis of photographs taken under standard lighting gives the opportunity to assess the local differences in color values in a quantitative way. Instrumental color distribution analysis has been done for food for a variety of applications, including for microwaved pizza (43); however application of this method in vacuum fried food and especially as a time series analysis is a novel approach. The effects of vacuum frying and ripening stage on the color changes have been assessed in terms of the percentage of surface area in levels of lightness (*L**) and green to red (*a**) (**Figure 3** and **Figure 4**).

3

The area in levels of lightness decreased gradually upon increasing frying time and temperature. Though, a faster trend in lightness reduction was observed for the unripe mango chips which was most distinct at 110 °C and 120 °C. The reduction in levels of the light area clearly led to an increase in levels of medium-light and dark areas, also differentiating between the two maturities. Similar result found by Maity, Bawa and Raju (44) that vacuum fried jackfruit bulb at 90 °C for 25 minutes could reduce lightness by 15%, and when extended for another 5 minutes reduced to 32%.

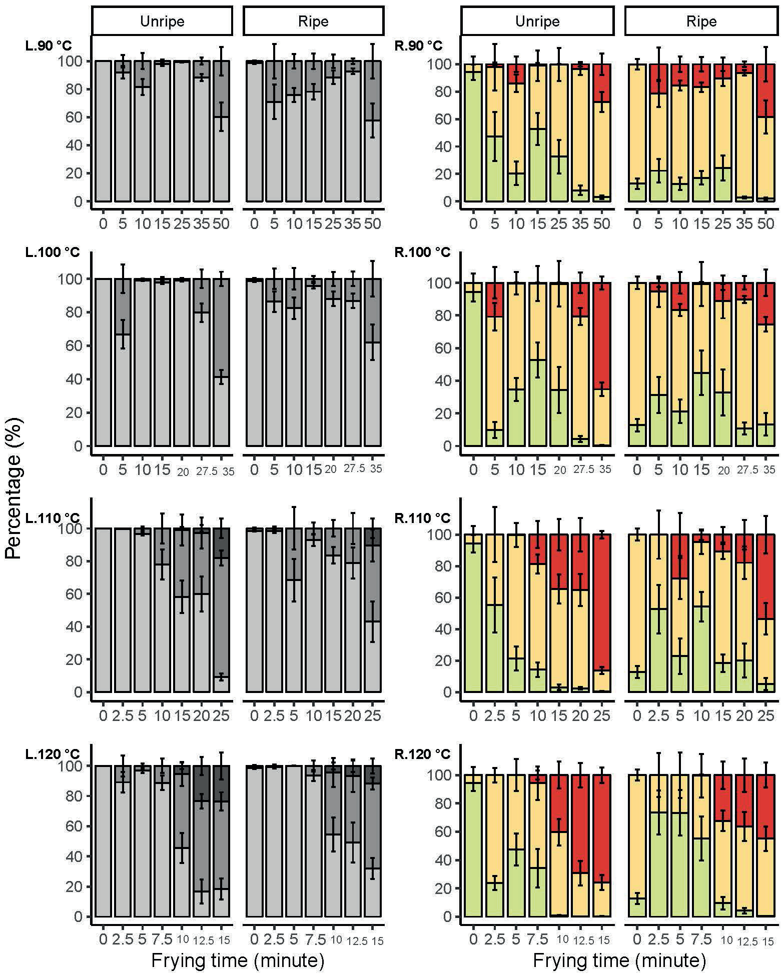

Figure. 3 Color distribution in terms of lightness *L** **(L)** and green to red *a** **(R)** changes during vacuum frying at different ripening stages of mango, fried at 90, 100, 110, and 120 °C. Lightness level of mango were represented in three levels; 0≤dark≤60, 60<medium-light≤80, 80<light≤100. Meanwhile red to green were represented in three levels; green ≤0, 0<medium-red≤10, red >10. Error bars are standard error. N = 8

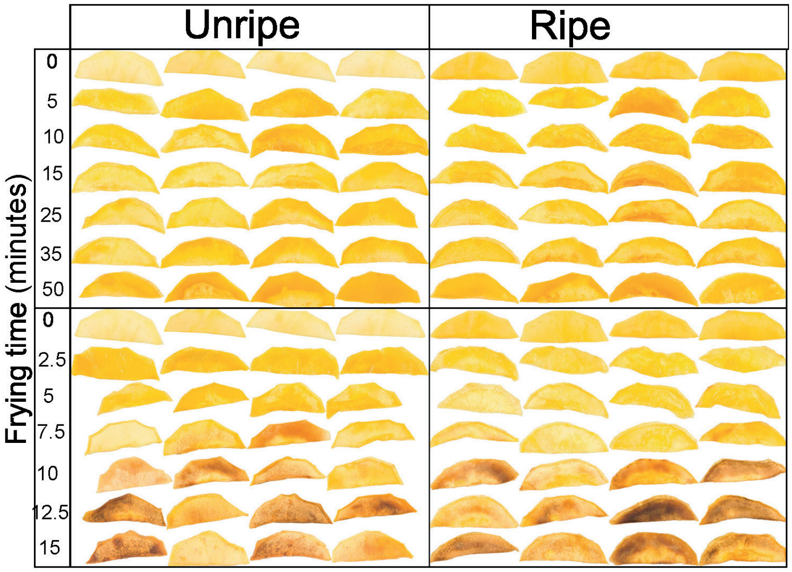

Figure. 4 Unripe (left) and ripe (right) mango slices vacuum fried at 90 (top) and 120 °C (bottom) for different times

Similarly, the areas for medium-red and red increased progressively as the frying time and temperature increased; which was also observed by Maity *et al.* (44) as vacuum fried jackfruit bulb at 90 °C for 10 minutes increased a* value by 168% and by 303% when extended to 20 minutes of frying. Furthermore, when fried at 100 °C, the a* value was increased to 367% after 20 minutes. Whereby a faster and stronger increase in redness areas was observed for unripe compared with ripe mango chips. At all temperatures, the green area decreased in unripe mango, while a fluctuation was seen in ripe mango chips. This trend was most pronounced at the highest temperatures. Additionally, as water evaporated, the boiling point of the moisture in the fruit will be increased and so will the fruit temperature (41) which indirectly contributed to color changes.

It was clear that the combination of ripening stage, frying time and temperature has a substantial influence on the color of the mango chips. Unripe mango fried for a longer time at higher temperature has a darker and redder surface compared to ripe mango. So unripe mango seems more susceptible to the temperature-time treatments towards changes in lightness and redness compared to ripe mango. Similar effects were also found in apple, although they were measured as average color value of the fried apple surface (28). The change in color at 110 and 120 °C at different frying times are probably due to the Maillard reaction and/or caramelization. The darker areas (**Figure 4**), and sometimes spots, would then be caused by locally higher amounts of reducing sugars, which could increase the rate of both the Maillard reaction as well as caramelization (40). Caramelization is likely to occur due to the high amount of sugars (45), also confirmed by Maity, Bawa (46) in vacuum fried jackfruit. However, ripe mango has a significantly higher sugar content (**Table 2**), so the darker color was expected to be dominating, but this is not the case, frying time and temperature and other mechanism could play more role on the color change.

4. CONCLUSION

Moisture loss of unripe mango chips was faster than that of ripe mango chips. There was no significant difference between hardness of unripe and ripe mango after vacuum frying at low temperatures (90-100 °C), but at higher temperatures (110-120 °C), unripe mango had a higher hardness value compared to ripe mango. Vacuum fried ripe mango had a higher fat content compared to unripe mango. No differences between the ripening stages were found on the degradation of ascorbic acid and β-carotene during frying. Unripe mango is more susceptible to temperature and time towards lightness and redness changes compared to ripe mango. Considering all quality parameters, unripe mango is preferred over ripe mango for vacuum frying processing. Furthermore, vacuum frying at 100 °C for 20 minutes was sufficient to decrease moisture content and produce a high hardness chips without adsorbing too many oil, maintain color, without losing too many ascorbic acid and preserve β-carotene content.

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CHAPTER 4

The pivotal role of moisture content in the kinetic modelling of the quality attributes of vacuum fried chips

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Abstract

Moisture content plays a pivotal role in the kinetic modelling of the quality attributes during thermal processing of foods. Vacuum frying of mango chips, was chosen to demonstrate the applicability of this novel modelling approach that links a dynamic moisture model to models for changes in fat content, texture, and color. Results show that moisture loss is best described by an exponential model with an *Ea* of 40.0±4.2 and 27.2±2.3 kJ/mol for unripe and ripe mango respectively. The dynamic moisture content was linked to the fat content by a Gompertz model, and to the hardness by an exponential model. By using thermodynamic principles, the moisture model predicts the dynamic local product temperature that can be linked to the reaction rates of the consecutive color change reaction models. The integration of these models is a powerful tool in product and process optimization to produce high quality vacuum fried fruit products.

***Keywords*:**
Vacuum frying; ripening; mango; quality attribute; moisture dynamic model

Nomenclature

AA	ascorbic acid
A	preexponential factor in Arrhenius equation (min^{-1})
α	parameter in net isosteric heat sorption calculation ($J\ mol^{-1}$)
a_w	water activity (dimensionless)
$a_{w,50}$	water activity at boiling point 50 °C (dimensionless)
AIC_c	corrected Akaike Criterion (dimensionless)
b	displacement value of Gompertz model (dimensionless)
β	parameter in net isosteric heat sorption calculation (dimensionless)
c'	shape descriptor of Gompertz model (dimensionless)
c	shape descriptor of Gompertz model (dimensionless)
C_L	light color proportion in the chip (%)
C_{ML}	medium light color proportion in the chip (%)
C_D	dark color proportion in the chip (%)
C_G	green color proportion in the chip (%)
C_{MR}	medium red color proportion in the chip (%)
C_R	red color proportion in the chip (%)
D	dark color in the chip
δ	parameter in $a_{w,50}$ calculation (dimensionless)
E_a	activation energy ($J\ mol^{-1}$)
F	hardness (N)
F_0	hardness value at the lowest moisture value (N)
G	green color in the chip
γ	parameter in $a_{w,50}$ calculation (dimensionless)
h	parameter in texture model kinetic ($g/g^{-1}db$)
k	moisture loss rate constant (min^{-1})
k_1	rate constant in Peleg model (min^{-1})
k_1	rate constant in color model (min^{-1})
k_2	constant in Peleg model (dimensionless)
k_2	rate constant in color model (min^{-1})
k_{ref}	moisture loss rate constant at a reference temperature (min^{-1})
L	light color in the chip
λ_v	molar heat of vaporization of water ($J\ mol^{-1}$)
M	moisture content (g/g db)
ML	medium light in the chip
MR	medium red color in the chip
M_0	initial moisture content (g/g db)
n	number of data (dimensionless)
O	fat content (g/g db)
O_{eq}	fat equilibrium (g/g db)
p	the number of estimated parameters (dimensionless)
P	vacuum pressure (kPa)

P_0	atmospheric pressure (kPa)
q_{st}	net isosteric heat of sorption (kJ mol^{-1})
R	gas constant (J mol^{-1} K^{-1})
ρ	parameter in T_b calculation (K^{-1})
t	time (minute)
T	oil temperature (K)
T_0	pure water boiling point in atmospheric pressure (K)
T_b	calculated chip temperature in vacuum (K)
$T_{b,w}$	pure water boiling point in vacuum (K)
T_{oil}	oil temperature (K)
T_{ref}	reference temperature (K)
SS_r	sum of square residuals (dimensionless)
φ	parameter in T_b calculation (K)
q_{st}	net isosteric heat sorption (kJ mol^{-1})

1. Introduction

Moisture removal is one of food preservation principles involved in food processing such as frying, baking and drying. The process involves heat and mass transfer which lead to changes in specific product quality attributes (1). Moisture loss is directly related to fat absorption, since oil will enter into part of the space left by moisture during the evaporation process and especially after cooling (2). Also textural properties depend on moisture content, mentioned by Oyedeji, Sobukola, Henshaw, Adegunwa, Ijabadeniyi, Sanni and Tomlins (3) that the increase of breaking force was correlated with the moisture loss of fried cassava chips. Changes in reaction rates during processing can be expected to have an indirect relationship with moisture loss through the increase of the product temperature at reduced moisture content. As water evaporates the boiling point of the moisture in the product increases and so will the product temperature (4). Interaction of moisture and other quality attributes is shown in Figure 1.

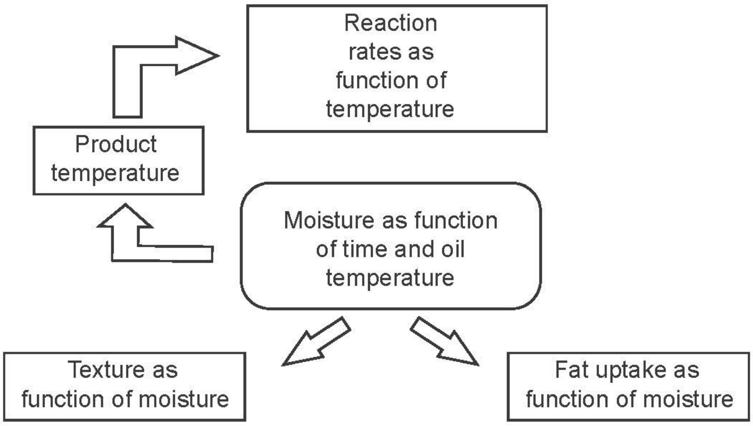

Figure 1. Schematic representation of the pivotal role of moisture with direct and indirect relation on other quality attributes

To demonstrate moisture dynamic interaction to other quality attributes during food processing, mathematical modelling of quality changes during vacuum frying process was chosen as a case study. Vacuum frying is an innovative fruit processing technique to produce fruit chips while maintaining nutritional and sensorial quality by decreasing processing pressure. Operating under vacuum conditions reduces the boiling point of water in the food allowing frying at lower temperatures and shorter times (5). The application of mathematical modelling can describe the effect of the process conditions on the desired quality attributes. The major quality attributes affected during vacuum fried mango chips are the moisture and fat content, texture and color (6).

The effect of the ripeness stage of fruits on the quality of vacuum fried products has been studied previously in banana (7). Additionally, Ayustaningwarno, Vitorino, Ginkel, Dekker, Fogliano and Verkerk (8) found that ripening affects the ascorbic acid content and color of vacuum fried mango. This effect was initiated by the autocatalytic production of ethylene and increase in the rate of respiration during ripening, which induced physiological, biochemical and molecular changes in the mango matrix (9).

Selected quality attributes included in the modeling approach comprised of moisture, fat, texture and color. Moisture is an important quality attribute of vacuum fried mango chips. During vacuum frying, moisture inside the mango chips evaporates due to the heat transfer from the frying oil. The kinetics of moisture loss has been studied for a variety of product on different processes.

Exponential modelling has been used to describe moisture loss in frying of gethi (10). Peleg models have been applied to describe moisture loss during vacuum frying of carrot (11).

Mir-Bel, Oria and Salvador (12) applied a mathematical model for fat absorption during vacuum frying of potato chip. An empirical model (13) was also used to model fat absorption during atmospheric frying of potato chips. Pedreschi, Aguilera and Pyle (14) used exponential kinetics to model textural change, while Moyano, Troncoso and Pedreschi (15) applied two irreversible serial reactions to fit the texture change during potato frying. Even though, two serial reactions model did fit the observed data in the beginning, the residuals between observed and modelled data was increasing in time.

Based on this background, the aim of this study was to develop moisture dependent dynamic models that can describe the quality attributes change during food processing, which was demonstrated by its application on vacuum frying of mango at different ripening stages as the case study.

2. Materials and Methods

The data set used in this paper was acquired from Ayustaningwarno *et al.* (8). In short, mango (*Mangifera indica* L. cv. Kent) from Brazil, supplied by Bakker Barendrecht B.V. (The Netherlands) at ripening stage 2 (unripe) and 4 (ripe). The fresh unripe mango has a moisture content of 5.0 ± 1.0 g/g db and a fat content of 0.01±0.003 g/g db, while ripe mango has a moisture content of 5.1 ± 0.4 g/g db and a fat content of 0.02±0.02 g/g db. After selection, mangoes were peeled, the seed was removed and halved. The halved fruits were cut into 4 mm thick slices with a mandolin (V5Power, Börner, Germany) to ensure the fast heat penetration to the center of the chips but not collapse during the processing. The mango slices have closed arc shape with dimension of 8.8±1.3 x 3.1±0.3 cm. Mango slices were vacuum fried using a pilot scale industrial vacuum fryer (Florigo Industry B.V., The Netherlands) in fresh high oleic sunflower oil. The vacuum frying process was done at 10 kPa at a specified time and temperature as listed in Table 1. The selected frying temperatures are commonly applied during industrial vacuum frying. While the temperature and time intervals provides a measurable and significant effect on the moisture content and the product quality, and keeping an edible fried product. After the frying, the vacuum fried mango was centrifuged to remove surface oil for 60 seconds at 100 g (MSD-500HD, Eillert B.V., The Netherlands). All frying experiments were performed in duplicate.

Table 1 Settings used for vacuum frying mango chips

Oil temperature (°C)	Frying time (minute)					
90	5	10	15	25	35	50
100	5	10	15	20	27.5	35
110	2.5	5	10	15	20	25
120	2.5	5	7.5	10	12.5	15

After frying, various quality attributes of vacuum fried mango were analyzed. Moisture content of the samples was determined with a forced convection oven (16). Fat content in dry basis of the samples was determined with Soxhlet method (16). Texture of the mango chips was measured with a texture analyzer (TA.XT.Plus, Stable Micro Systems, UK) using a three-point bending test (17). Inhomogeneity of color in mango chip was described by surface color analysis using CVS (Computer Vision System). The CVS was composed of a Canon DSLR digital camera and the software Color Inspector 3D v 2.3 (18) to extract color information from the pictures (8). The color values are expressed as percentage of the total chip area belonging to one of three categories that were defined for lightness (light/ medium-light/ dark) and redness (green/ medium-red/ red). The lightness (*L**) value describes the lightness with 0 for darkest black and 100 for brightest white and was divided into 3 levels, 0≤dark≤60, 60<medium-light≤80, 80<light≤100. The redness (a*) value describes the transition from green to red, ranging from -128 for the purest green and +128 for the purest red and were divided into 3 levels, green ≤0, 0<medium-red≤10, red >10. The range and level of lightness and redness was selected based on the color distributions of raw and fried chips in order to have sufficient surface area of the chips in all three levels to describe the color changes and use the data to estimate the parameters of the kinetic model.

3. Fitting method

The estimation of the model parameters was done by fitting the experimental data using Athena Visual Studio 14.0 (Athena Visual Software, Naperville, IL). The aim was to fit parameters in equation of each quality attributes to minimize the sum of squared residual (*SSr*) between the prediction and experimental data set for each equation. The Corrected Akaike Information Criterion (*AICc*), residual plot and parameters correlation coefficient were used to discriminate between different models. *AICc* (eq.1) was calculated according van Boekel (19).

$$AIC_c = n\ ln\left(\frac{SS_r}{n}\right) + 2(p+1)\left(1+\frac{p+2}{n-p}\right) \quad (1)$$

4. Model Development Results and Discussion

4.1 Model descriptions

4.1.1 Moisture loss

Two models for describing the moisture loss were tested: the exponential model and the Peleg model. To start the dynamic moisture content modelling, the kinetics of moisture loss was described using an exponential model (10). The moisture content model used eq.2 and eq.3.

$$\frac{dM}{dt} = -kM \quad (2)$$

$$M = M_0 exp(-kt) \quad (3)$$

An Arrhenius type equation was used to calculate the apparent *Ea* of moisture loss. To improve the degrees of freedom, all data were modelled at once by integrating the Arrhenius equation in the exponential model. Additionally, to avoid strong correlation between parameters causing problems with regression, apparent *Ea* was calculated using the re-parameterized Arrhenius equation (19), using the average frying temperature as reference temperature (eq.5). Then eq. 3 and eq.5 were combined to produce the final equation (eq.6).

$$k = A\ exp\left(-\frac{E_a}{RT}\right) \quad (4)$$

$$k = k_{ref} exp\left(-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right) \quad (5)$$

$$M = M_0 exp\left(-\left(k_{ref} exp\left(-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right)\right)t\right) \quad (6)$$

Alternative to the exponential model, also the Peleg model was used to model water absorption/ desorption during food processing (20), for desorption processes this is given by eq 7.

$$M_0 - \frac{t}{k_1 + k_2 t} \quad (7)$$

The rate constant k_1 was temperature dependent and decreased as the temperature increased. The equilibrium parameter, k_2 is assumed not to be dependent on temperature as described by Planinić, Velić, Tomas, Bilić and Bucić (21) that during carrot drying, k_2 was not significantly affected by temperature. Then, the apparent *Ea* could be estimated using the re-parameterized Arrhenius equation as shown in eq. 8 (21) to produce the final equation (eq.9).

$$k_1 = \frac{1}{k_{ref} exp\left(-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right)} \quad (8)$$

$$M = M_0 - \frac{t}{\frac{1}{k_{ref} exp\left(-\frac{E_a}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right)} + k_2 t} \quad (9)$$

The possibility of using either an exponential or a Peleg model for other products and processing can be considered since the model parameters can be estimated for other processes as well.

After selecting the best performing moisture model, this model is combined with the models for the other quality attributes.

4.1.2 Fat content

Based on the observed data, an empirical Gompertz model (eq.10 - eq.11) was fitted based on the dynamic moisture content (g/g db) to describe the fat content.

$$O = O_{eq} \cdot exp\,(-b \cdot exp\,(c' \cdot \log(M))) \quad (10)$$

$$O = O_{eq} \cdot exp\,(-b \cdot M^c) \quad (11)$$

The possibility of using Gompertz model for other product and processing can be considered since the model parameters can be estimated for other processes as well.

4.1.3 Texture kinetic

Based on the observed data, an empirical exponential model (eq.12) was fitted based on the dynamic moisture content (g/g db) change to the hardness value (N).

$$F = F_0 \, exp \, (-hM) \tag{12}$$

The possibility of using exponential model for other product and processing can be considered since the model parameters can be estimated for other processes as well.

4.1.4 Reaction kinetics (applied on color change)

During vacuum frying the light yellow-greenish color of mango becomes progressively darker and is also gaining red color. The proposed model considers these changes as two irreversible serial reactions. The lightness parameter has two serial chemical reactions as described in eq.13.

$$\text{L (light)} \overset{k_1}{\rightarrow} \text{ML (medium-light)} \overset{k_2}{\rightarrow} \text{D(dark)} \tag{13}$$

It was assumed that proportion of these three stages of lightness will change during vacuum frying according to the reaction kinetics as described in eq.14 to eq.16. Arrhenius equation with re-parameterization was used to calculate the *Ea* of each reaction.

$$\frac{dC_L}{dt} = -k_1 C_L \tag{14}$$

$$\frac{dC_{ML}}{dt} = k_1 C_L - k_2 C_{ML} \tag{15}$$

$$\frac{dC_D}{dt} = k_2 C_{ML} \tag{16}$$

A similar model was applied to redness value. Green to red parameter has two serial chemical reactions as described in eq.17.

$$\text{G (green)} \overset{k_1}{\rightarrow} \text{MR (medium-red)} \overset{k_2}{\rightarrow} \text{R(red)} \tag{17}$$

It was assumed that proportion of these three stages of redness will change during vacuum frying according to the reaction kinetics as described in eq.18 to eq.20.

$$-\frac{dC_G}{dt} = k_1 C_G \tag{18}$$

$$\frac{dC_{LR}}{dt} = k_1 C_G - k_2 C_{MR} \tag{19}$$

$$\frac{dC_R}{dt} = k_2 C_{MR} \tag{20}$$

For both, the lightness and redness change will depend on the local temperature of the mango chips. This temperature will change during frying as the water content of the mango chips will decrease leading to an increased boiling temperature of water inside the chips. The temperature of the chips will only reach the oil temperature once all free water has been evaporated. This temperature change will influence the reaction kinetics of color changes. Therefore, a description of the temperature change of the chips during frying is needed. Previous models of local temperatures have used a sharp boundary between a crust and core region in the chip, but more recent theories indicate that this transition is more zonal and strongly dependent on thickness of the chip and the temperature difference between oil and product (2). In case of vacuum frying the temperature differences between the product and the oil are much smaller than in atmospheric frying. Also in our study the chip thickness is small, we therefore consider the moisture and temperature distribution in the chips as uniform. Thermodynamic theories can be used to calculate the local temperature of the mango chips based on the boiling point of the moisture in the chip that will increase as the water content decreases during frying. To do this the water content can be translated in the water activity (a_w) which is connected to the boiling temperature. Talla, Jannot, Kapseu and Nganhou (22) reported the water activity of various fruits at 50 °C depending on their moisture content (eq.21), whereby γ (6.75) and δ (1.155) are parameters used to calculate the water activity at boiling point 50 °C ($a_{w,50}$). Then, Fontan and Chirife (23) describe the boiling point (T_b) as function of this water activity (eq.22-eq.23) with ρ (0.035 K^{-1}) as one of the calculation parameter, furthermore φ (eq.24) used to as one of the parameter in T_b calculation. To calculate the boiling point of pure water in vacuum pressure ($T_{b,w}$), we use the Clausius–Clapeyron equation (eq.25).

$$a_{w,50} = 1 - exp\,(-\gamma \cdot M^{\delta}) \tag{21}$$

$$T_b = T_{b,w} - \frac{\ln\,(a_w)}{\rho} \tag{22}$$

$$T_b = \frac{\rho \cdot \varphi \cdot R + \sqrt{(\rho \cdot \varphi \cdot R)^2 - 4\rho \cdot R \cdot q_{st}}}{2\rho \cdot R} \tag{23}$$

$$\varphi = T_{b,w} - \frac{1}{\rho}\left\{\ln\,(a_{w,50}) + \frac{q_{st}}{323R}\right\} \tag{24}$$

$$T_{b,w} = \left(\frac{1}{T_0} - \frac{R\,ln\frac{P}{P_0}}{\lambda_v}\right)^{-1} \tag{25}$$

Since the water boiling point in the vacuum fried mango is not equal to 50 °C, a_w should be recalculated using eq.26 (24). The net isosteric heat of sorption (q_{st}) can be calculated by using a relation based on the data for a variety of fruit tissues described by Tsami (25) (eq. 27), α (-7.1·10^5 J/mol) and β (1.155) are parameters used in the equation. Finally, the temperature of the mango chip is limited by the oil temperature eq. 28.

$$a_w = a_{w,50} \cdot exp\left(\frac{q_{st}}{R} \cdot \left(\frac{1}{323} - \frac{1}{T_b}\right)\right) \tag{26}$$

$$q_{st} = \frac{\alpha}{M^{\beta}} \tag{27}$$

$$T_b = min(T_b, T_{oil}) \tag{28}$$

The possibility of using the moisture and temperature dependent model for other reactions and other products and processing can be considered since the model parameters can be estimated for other processes as well.

4.2 Parameter estimations

4.2.1 Moisture loss

Moisture content change during vacuum frying was modeled by an exponential model and compared to the Peleg model. Figure 2 shows that both models could describe moisture loss with low parameters correlation coefficient. Furthermore, both models show randomly distributed and homoscedastic residuals.

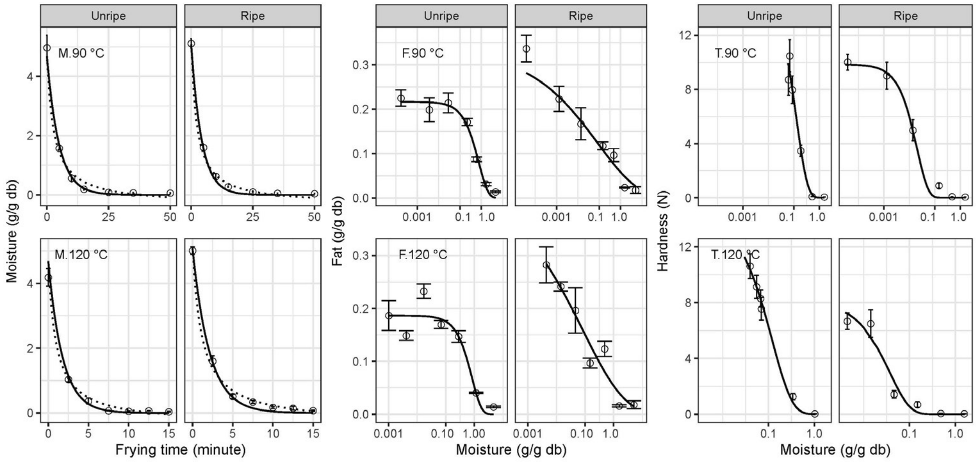

Figure 2. Effect of frying temperatures, time and ripening stage on kinetic of moisture content (M, left column panels) in gram of moisture per gram of dry product, fat content (F, central column panels) in gram of fat per gram of dry product and texture (T, right column panels) in Newton of mango chips during vacuum frying at 90 (top row panels), and 120 °C (bottom row panels). Round symbols (○) are observation data. Solid lines are the model for each quality attributes. Error bars are standard errors. For the moisture content (M), solid lines are the fits of the exponential model, and dotted lines are the Peleg model.

The moisture loss in unripe mango was described better by the exponential model compared to the Peleg model, which is shown by a much lower AIC_c value (-14) (Table 2). On the other hand, the difference between the two models for the moisture loss in ripe mango was much smaller, slightly favoring the Peleg model over the exponential model (AIC_c difference of -3). Thus, overall the exponential model described the moisture change better than the Peleg model. The exponential model was therefore used to model the other quality attributes by integrating the moisture content in those models.

Table 2. Moisture kinetic model parameters during vacuum frying of unripe and ripe mango

Model	Ripening	Temp. (°C)	*k* (min^{-1})	k_1 (min)	k_2	*Ea* (kJ/mol)	SSr	AIC_c
Exponential	Unripe	90	0.204±0.014	-	-	40.0±4.2	25.2	-311
		100	0.291±0.013	-	-			
		110	0.408±0.019	-	-			
		120	0.562±0.037	-	-			
	Ripe	90	0.236±0.009	-	-	27.2±2.3	8.9	-486
		100	0.301±0.007	-	-			
		110	0.378±0.009	-	-			
		120	0.470±0.017	-	-			
Peleg	Unripe	90	-	0.552±0.067	0.199±0.004	41.5±5.6	26.9	-297
		100	-	0.382±0.038				
		110	-	0.269±0.027				
		120	-	0.193±0.023				
	Ripe	90	-	0.421±0.027	0.185±0.002	26.4±2.9	8.6	-489
		100	-	0.333±0.017				
		110	-	0.266±0.014				
		120	-	0.216±0.013				

Moisture loss of vacuum fried ripe mango has a lower apparent *Ea* value (27.2±2.3 kJ/mol) compared to the reported *Ea* value of atmospheric fried gethi (41.5±0.2 kJ/mol) (10), which value was similar to the one found for vacuum fried unripe mango (40.0±4.2 kJ/mol). Which mean gethi is having a similar heat of evaporation as unripe mango.

Moisture loss in unripe mango has higher apparent *Ea* value than in ripe mango. This effect also could be contributed to the matrix differences between ripe and unripe mango. Pectin which has water binding properties is abundantly present in unripe mango (26). In unripe mango large molecule pectin strictly hold the water and when heated the polysaccharides need to shrink to release the bound water before evaporation occurs (27). This mechanism might explain the lower *k* value of unripe mango than ripe mango at 90 and 100 °C and its higher apparent activation energy.

4.2.2 Fat content

The relation between fat uptake and dynamic moisture content during vacuum frying of unripe and ripe mango is shown in Figure 2. A Gompertz model combined with the dynamic moisture content model could describe the relation between moisture content and fat content with the parameter estimates as shown in Table 3, additionally the model has a symmetrically distributed residual and low parameters correlation coefficient. Unripe mango reaches a plateau at low moisture content, however for ripe mango this was not observed. This trend shows that in unripe mango, when the moisture content decreases below a certain value, no more fat is absorbed by the chip. On the other hand, for ripe mango, as the moisture content decreases the fat content keeps increasing. The moisture and fat content has a direct relationship, since oil will enter the space left by moisture during and mainly after the evaporation process (28), which is indeed shown in ripe mango. However, a different trend was observed in unripe mango, possibly due to a less porous structure which could reduce oil absorption.

Table 3. Fat content kinetic to moisture change during vacuum frying of unripe and ripe mango Gompertz model

Ripening	Temp. (°C)	O_{eq} (g/g db)	*b*	*c*	SSr
Unripe	90	0.216 ± 0.010	1.298 ± 0.223	0.991 ± 0.224	0.023
	100	0.213 ± 0.010	1.345 ± 0.266	0.907 ± 0.224	0.024
	110	0.196 ± 0.011	1.302 ± 0.235	0.776 ± 0.213	0.025
	120	0.186 ± 0.010	1.280 ± 0.338	1.321 ± 0.432	0.031
Ripe	90	0.334 ± 0.021	1.746 ± 0.219	0.228 ± 0.040	0.044
	100	0.272 ± 0.023	1.971 ± 0.380	0.454 ± 0.117	0.039
	110	0.411 ± 0.082	2.114 ± 0.256	0.269 ± 0.078	0.031
	120	0.433 ± 0.186	2.087 ± 0.406	0.295 ± 0.142	0.056

At all temperatures, unripe mango has a lower fat equilibrium (O_{eq}) compared to ripe mango (Table 3). This effect could be contributed to the more loose matrix in the ripe mango (9) which allows fat to be absorbed easier than in unripe mango.

When vacuum frying temperature increased, the (O_{eq}) of unripe mango were decreased. This effect could be explained by the moisture loss rate constant, which increases with temperature increase; when the moisture loss rate is increased, vapor formation during the moisture loss increased and prevents fat to enter the pores (29). However, a different result was found for ripe mango, the O_{eq} increased by the temperature increase, although the values for ripe mango had a much higher SD at higher temperatures. The matrix difference could be the reason; ripe mango contains less pectin and less rigid cells, and the result is cells collapse easier and therefore form less pores for oil to penetrate.

4.2.3 Texture kinetic

The relation between hardness and moisture content during vacuum frying of unripe and ripe mango is shown in Figure 2. An exponential model was combined with the dynamic moisture content model to describe the relation between moisture content and hardness well with parameters shown in Table 4, the model has a randomly distributed residual.

Table 4. Effect of moisture change on texture kinetic

Ripening	Temp.(°C)	*h* ($g/g^{-1}db$)	F_0 (N)	SSr
Unripe	90	7.9±1.9	16.0±2.4	1555
	100	3.0±0.7	10.2±0.8	1202
	110	3.9±0.9	10.6±0.8	986
	120	8.3±2.1	14.4±1.7	836
Ripe	90	49.4±9.4	9.9±0.4	773
	100	4.4±1.1	7.9±0.4	1273
	110	26.5±6.9	7.4±0.4	561
	120	26.7±6.3	8.1±0.7	559

The hardness values at low moisture contents for unripe mango were higher than for ripe mango as reflected by the F_0 value. A higher pectin concentration in unripe mango could produce a harder mango chip than ripe mango which has less pectin (30).

The *h* value for ripe mango is higher than for unripe mango, which shows ripe mango has a higher crust formation per moisture loss compared to unripe mango.

4

4.2.4 Reaction kinetics (applied on color change)

Color change during vacuum frying was modeled by two irreversible serial reactions with indirect relation to the moisture content. The observed lightness change at 120 °C is shown in Figure 3B. During the first 7.5 minutes of frying, the lightness distribution did not change much, but then the light area decreased, while the medium-light and dark area increased. To describe this color change, an empirical temperature model as the effect of moisture loss was used and shown in Figure 3A. The integration of the empirical temperature model and two irreversible serial reactions could describe color change with low parameters correlation coefficient as shown in Figure 4.

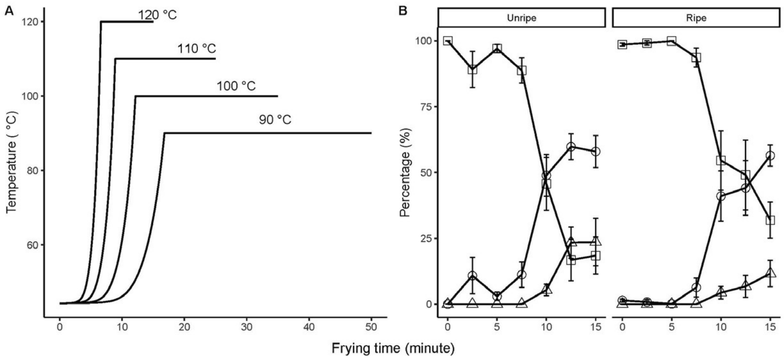

Figure 3. (A)The calculated product temperatures (axis y) based on the moisture change for each oil temperature (solid lines). (B) Observed model of lightness area percentage of the mango surface change during vacuum frying in different ripening stages at 120 °C. Lightness level were represented in three levels; those are 0≤dark≤60 (△), 60<medium-light≤80 (○), 80<light≤100 (⍰). Error bars are standard errors.

The model could describe the lightness area distribution for both ripening stages at all temperatures. The model has relatively large residuals, but the overall trends are reflected well by the model. For the redness area distribution, the model fitted better on unripe mango compared to ripe mango.

The model cannot perform for the redness area (Table 5) on ripe mango because raw ripe mango already has a large portion of medium-red area. In the model, medium-red color was a reaction product of green color (eq.17). Also for the redness area distribution the model for both ripening stages has relatively large residuals but the overall trends are reflected well by the model.

By comparing Ea_1 and Ea_2 values for unripe and ripe mango for lightness, unripe mango needs more energy to change lightness than ripe mango. Additionally, lightness changes from light to medium-light needs less energy the lightness changes from medium-light to dark. Furthermore, lightness changes from light to medium-light needs more energy than the lightness changes from medium-light to dark.

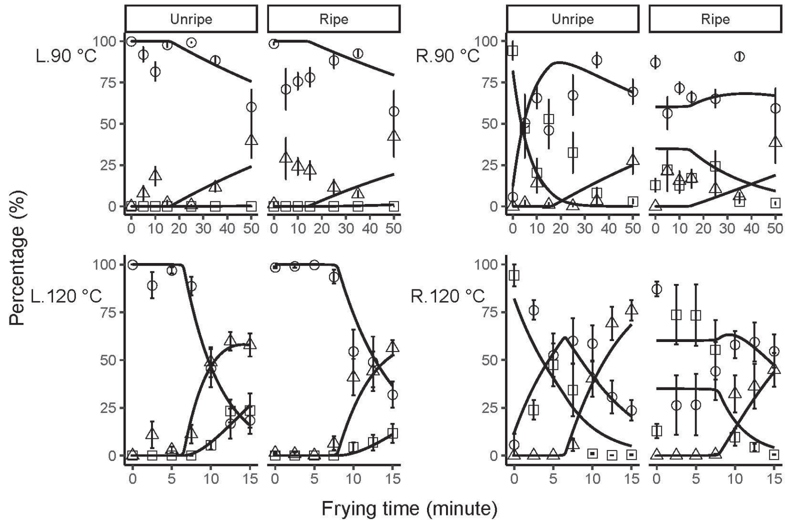

Figure 4. Observed and kinetic model of lightness (L) and redness (R) area percentage of the mango surface lightness change during vacuum frying in different ripening stages at 90 °C (top row panels) and 120 °C (bottom row panels). Lightness level were represented in three levels; those are 0≤dark≤60 (△), 60<medium-light≤80 (○), 80<light≤100 (□). Red to green were represented in four levels; those are green ≤0 (□), 0<medium-red≤10 (○), red >10 (△). Error bars are standard errors.

By comparing Ea_1 and Ea_2 values for unripe and ripe mango for redness, redness change from green to medium-red in ripe mango needs more energy than in unripe mango. On the other hand, redness change from medium-red to red in unripe mango need more energy than in ripe mango.

By comparing k_1 and k_2 values for unripe and ripe mango for lightness and redness, lightness change from light to medium-light in unripe mango were faster than in ripe mango. Additionally, reaction from green to medium-red color were faster than from medium-red color to red color. However, compared to Salehi (31) which used the color difference of raw carrot and the fried carrot, lightness and redness change of vacuum fried mango at both ripening stages at 120 °C was much more higher compared to k value (exponential model) of lightness and redness change of atmospheric fried carrot at 130 °C.

Table 5. Color kinetic during vacuum frying of unripe and ripe mango

Color	Ripening	Temp. (°C)	k_1 (min^{-1})	Ea_1 (kJ/mol)	k_2 (min^{-1})	Ea_2 (kJ/mol)	SSr
Lightness	Unripe	90	$8.3\ 10^{-3} \pm 4.1\ 10^{-4}$	129.0±5.7	$6.7\ 10^{-4} \pm 3.7\ 10^{-4}$	184.0±49.2	122700
		100	$2.6\ 10^{-2} \pm 1.3\ 10^{-3}$		$3.4\ 10^{-3} \pm 1.9\ 10^{-3}$		
		110	$7.7\ 10^{-2} \pm 3.8\ 10^{-3}$		$1.6\ 10^{-2} \pm 9.0\ 10^{-3}$		
		120	$2.2\ 10^{-1} \pm 1.1\ 10^{-2}$		$7.1\ 10^{-2} \pm 3.9\ 10^{-2}$		
	Ripe	90	$6.4\ 10^{-3} \pm 6.4\ 10^{-4}$	122.4±8.3	$2.9\ 10^{-3} \pm 1.9\ 10^{-3}$	111.2±69.6	191410
		100	$1.9\ 10^{-2} \pm 1.4\ 10^{-3}$		$7.7\ 10^{-3} \pm 5.2\ 10^{-3}$		
		110	$5.3\ 10^{-2} \pm 3.8\ 10^{-3}$		$2.0\ 10^{-2} \pm 1.3\ 10^{-2}$		
		120	$1.4\ 10^{-1} \pm 1.0\ 10^{-2}$		$4.8\ 10^{-2} \pm 3.2\ 10^{-2}$		
Redness	Unripe	90	$1.9\ 10^{-1} \pm 4.5\ 10^{-2}$	6±4.7	$9.2\ 10^{-3} \pm 7.5\ 10^{-4}$	122.5±9.8	319520
		100	$2.0\ 10^{-1} \pm 4.8\ 10^{-2}$		$2.7\ 10^{-2} \pm 2.2\ 10^{-3}$		
		110	$2.1\ 10^{-1} \pm 5.0\ 10^{-2}$		$7.7\ 10^{-2} \pm 6.3\ 10^{-3}$		
		120	$2.2\ 10^{-1} \pm 5.3\ 10^{-2}$		$2.1\ 10^{-1} \pm 1.7\ 10^{-2}$		
	Ripe	90	$3.7\ 10^{-2} \pm 7.7\ 10^{-3}$	82.5±20.8	$7.9\ 10^{-3} \pm 8.9\ 10^{-4}$	102.4±13.1	347640
		100	$7.6\ 10^{-2} \pm 1.6\ 10^{-2}$		$2.0\ 10^{-2} \pm 2.2\ 10^{-3}$		
		110	$1.5\ 10^{-1} \pm 3.2\ 10^{-2}$		$4.6\ 10^{-2} \pm 5.2\ 10^{-3}$		
		120	$2.9\ 10^{-1} \pm 6.2\ 10^{-2}$		$1.1\ 10^{-1} \pm 1.4\ 10^{-2}$		

5. Conclusions

During thermal processing of foods the moisture content plays a pivotal role for most relevant quality attributes, either directly for e.g. fat and texture or indirectly for chemical reactions, e.g. color changes. A general framework for mathematical modelling of moisture dependent quality changes is given in this paper. This approach has been applied on vacuum frying of mango chips. The changes in moisture content were best described by an exponential model. The relation between fat uptake and moisture content could be described by a modified Gompertz model, a similar model could also describe the relation between hardness and moisture content. Color change could be described by two irreversible serial reactions with an indirect relation to the moisture content through modelling of the boiling temperature of the moisture within the product. The developed models for the kinetics of quality attributes during vacuum frying can be used to optimize the process conditions to obtain higher quality products in an efficient way. The models can be used to produce a minimal fat content and low moisture content while maintain color; also can be used to produce a specific texture quality while maintain color. The possibility to use the models on other products and process such as baking and drying were explored. Moisture dependent models for quality change have potential to be applied for other products and process.

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CHAPTER 5

Surface color distribution analysis by computer vision technique: vacuum fried fruits as a case study

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Abstract

Color is a main factor in the perception of food product quality. Food surfaces are often not homogenous at micro-, meso-, and macroscopic scales. This matrix can include a variety of colors that are subject to changes during food processing. These different colors can be analyzed to provides more information than the average color. The objective of this study was to compare color analysis techniques on their ability to differentiate samples, quantify heterogeneity, and flexibility. The included techniques are sensory testing, Hunterlab colorimeter, a commercial CVS (IRIS-Alphasoft), and the custom made CVS (Canon-CVS) in analyzing nine different vacuum fried fruits. Sensory testing was a straightforward method and able to describe color heterogeneity. However, the subjectivity of the panelist is a limitation. Hunterlab was easy and accurate to measure homogeneous samples with high differentiation, without the color distribution information. IRIS-Alphasoft was quick and easy for color distribution analysis, however the closed system is the limit. The Canon-CVS protocol was able to assess the color heterogeneity, able to discriminate samples and flexible. As a take home massage, objective color distribution analysis has a potential to unlock the limitation of traditional color analysis by providing more detailed color distribution information which is important with respect to overall product quality.

Keywords

Color distribution, computer vision system, vacuum fried, fruit

Nomenclature

$RGB2Lab$	R function to convert L*a*b*color into RGB color, input and output should be in matrix formula
$[R', G', B']$	data of RGB values (points with R, G and B values in 0-1)
$[R, G, B]$	data of RGB values in 24 bit (points with R, G and B values in 0-255)
$[R_{6}, G_{6}, B_{6}]$	data of RGB values in 6 bit (points with R, G and B values in 0-3)
$[R_{24}, G_{24}, B_{24}]_6$	data of RGB values in 24 bit (points with R, G and B values in 0, 85, 170, 255)
$[R_{12}, G_{12}, B_{12}]$	data of RGB values in 12 bit (points with R, G and B values in 0-15)
$[R_{24}, G_{24}, B_{24}]_{12}$	data of RGB values in 24 bit (points with R, G and B values in 0, 17, 34, …, 255)
$[R_{24}, G_{24}, B_{24}]$	data of RGB values in 24 bit (points with R, G and B values in 0-255)
$Lab2RGB$	R function to convert RGB color into L*a*b* color, input and output should be in matrix formula
$[L, a, b]$	data of L*a*b* values (L should scale in 0-100, and (a,b) in (-110) - 110)
$[L, a, b]_a$	data of L*a*b* values without halo (L should scale in 0-100, and (a,b) in (-110) - 110)
$[L, a, b]_b$	data of L*a*b* values without background (L should scale in 0-100, and (a,b) in (-110) – 110)
$\approx$	rounding operator

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1. Introduction

Food color and color distribution, in raw and processed products, are one of the key sensory quality characteristics for consumers and determine the acceptation of a food product. Therefore, color assessment is highly relevant in the total quality assessment of food products (1). Efforts to measure color of foods have been done using a variety of methods with the final aim of product quality analysis and standardization. Color analysis by sensory testing has been done for quality control of food production. Visual evaluation of color via sensorial experiments is valuable as it can be expanded to the consumer's demands and satisfaction. However, in general sensory testing has some limitations, including subjectivity, response variation and limitation in the number of samples (2).

Instrumental quality control such as colorimetry is applied to overcome these limitations and provide better standardization. The tristimulus colorimeter became the most popular tool to analyze color thanks to the easiness of use and the wide application in color measurement. L*a*b* color space has been used widely by the food industry for measuring color; L* for the lightness (black to white), a* for green to red, and b* for blue to yellow (3).

Conventional instrumental analysis uses a homogeneous or homogenized sample and it gives three coordinate of color in L*a*b* that represent one color as the average color of a product (4). However, in many cases the food matrix and surface are not homogenous but have different structures at micro-, meso-, and macroscopic scales (5). These structures could undergo changes during food processing and produce different local colors.

These different colors on the surface of a food can be analyzed by measuring the color distribution and this could provide more in-depth information than just the average color. Computer vision systems have become more popular as they enable to analyze the whole food product on a pixel-based level. Computer image analysis is very useful to compare samples; pictures are analyzed by various software tools (like imageJ and Adobe® Photoshop®) to get a value of color differences between samples. This approach has been used for raw food products e.g. in plantain (6), apple (7) and potato (8, 9).

Instrumental color distribution analysis has been done for food for a variety of applications such as, sorting date maturity (10), and melon maturity (11), or assessing quality of fresh-cut lettuce (12). Applications of color distribution analysis for more complex food products are microwaved pizza (13), and analysis of changes in surface color of chocolate (14). Goñi and Salvadori (15) developed a computer vision system

(CVS) and compared the color analysis with the conventional portable tristimulus colorimeter (Minolta CR-400) for 40 samples of raw and processed foods. Both systems provided equivalent results for most samples. Though, the color measured by the image analyses technique appeared to be more like the real ones.

A commercial computer vision system, named IRIS-Alphasoft, to perform color distribution analysis has recently been released and tested for different food applications; quality control of cooked ham (16), analysis of fish sauce (17); origin identification of honey (18), to discriminate marine fish surimi (19). This commercial photo box and software (IRIS-Alphasoft) can be operated with minimum knowledge and training, and appeared to be valuable in controlling the manufacturing processes and product quality of foods. Ayustaningwarno, Vitorino, Ginkel, Dekker, Fogliano and Verkerk (20) developed and applied a similar system to analyze the effect of ripening stages and frying temperature on the color of vacuum fried mango, and developed a kinetic model to describe the changes in color distribution (21).

Although many studies on color and color distribution analysis have been done, they were mostly done with a single-color analysis, without proper comparison between methods. Since the proper comparison between color analysis methods was not available, industries and interested parties require a specific color analysis method could have difficulties to choose a suitable color analysis method for them.

Based on those backgrounds the objective of this study was to compare various color analysis techniques on the ability to differentiate vacuum fried fruit samples, with emphasis on quantifying heterogeneity, and flexibility. The investigated techniques are sensory testing, the Hunterlab colorimeter, the CVS (IRIS-Alphasoft), and the self-developed CVS (Canon-CVS) in analyzing nine different types of vacuum fried fruits.

2. Materials and Methods

2.1 Raw material

Vacuum fried apple, banana, jackfruit, pineapple, mango, salak, starfruit, and rambutan were purchased online from CV. Putri Alin Jaya, Batu, Indonesia (https://anekakeripikbatu.wordpress.com/) within their shelf life. These fruit chips were produced from fresh fruits and vacuum fried directly after order using coconut oil, and shipped within one week to Wageningen, The Netherlands to be analyzed. Vacuum fried durian within the shelf life was purchased online from CT Fruit Factory and Farm CO., LTD, Khao Saming, Thailand (https://www.orientalwebshop.nl/durio-durian-chips-sweet-75g). It was vacuum fried with palm oil and sugar coated.

All vacuum fried fruits were packed in multilayer plastic and aluminum primer packaging with nitrogen filled to ensure stability during storage from moisture migration, microbial activity, and color changes. Furthermore, air filling also protects the product from physical damage during handling and storage. Once the packages were opened the fruit pictures were taken within two hours to minimize color changes.

2.2 Color Analysis

As a novel approach, nine vacuum fried tropical fruits were used to compare four color analysis methods on the ability to differentiate vacuum fried fruit samples, with emphasis on quantifying heterogeneity, and flexibility.

2.2.1 Sensory testing

In total thirty seven panelists with an age of 21-54 year participated in the sensory testing based on their ability to rank the intensity of colors with the Farnsworth–Munsell 100 hue test (22). Thirty panelists with an average score (16-100 errors) and 7 panelist with superior score (less than 16 errors) (23) from 11 different nationalities, including Chinese, Dutch and Indonesian. Compensation in the form of a gift card of 15 euro is provided to each panelist after completion of the whole survey.

The tests were done by comparing the nine different vacuum fried fruit types with the Royal Horticultural Society (RHS) color chart containing 920 different colors (24). Each panelist had to judge ten randomized chips. In total twenty chips from each of the nine fruits was used in the tests. The tests were performed in duplicate. In total 180 chips were used, and 370 judgements were taken.

There were two types of color analysis performed by the panelist, namely overall color and color distribution (**Supp. 1**). To assess the individual ability to perceive overall color, the panelist should describe the color of the sample into a color from the RHS color chart. The obtained color information was converted into the L*a*b* color space (25) and further converted into 12 bit color depth **(eq. 1, - 4)** to produce pie charts. Frequency of a color was selected by the panelist used to produce the pie chart. A PCA chart was produced using L*a*b* values.

To assess the individual ability to perceive the color distribution within one sample, the panelist should pick three colors present on the surface and give the percentage of surface area for all three colors with the total composition of 100 %. The obtained color information was converted into the L*a*b* color space (25). In order to keep the color distribution information simple, the color depth was further converted into 6 bit **(eq.1, 2, 5, 6)**. The average percentage of all colors observed per fruit was used to produce a pie chart. The percentage of each color of each fruit was used to produce PCA chart.

$$[R', G', B'] = Lab2RGB[L, a, b] \quad (1)$$

$$[R, G, B] = [R', G', B'] \times 255 \quad (2)$$

$$[R_{12}, G_{12}, B_{12}] \approx [R, G, B] \times \frac{15}{255} \quad (3)$$

$$[R_{24}, G_{24}, B_{24}]_{12} \approx [R_{12}, G_{12}, B_{12}] \times \frac{255}{15} \quad (4)$$

$$[R_6, G_6, B_6] \approx [R, G, B] \times \frac{3}{255} \quad (5)$$

$$[R_{24}, G_{24}, B_{24}]_6 \approx [R_6, G_6, B_6] \times \frac{255}{3} \quad (6)$$

2.2.2 Hunterlab

The Hunterlab Colorflex benchtop spectrophotometer was used to measure color of the vacuum fried fruits (**Supp. 2A**). Commonly homogenized samples are required (26). Samples were milled using a small laboratory Waring blender, then further homogenized with the Fritsch vibratory ball mill (27). The milled material can have a color different from the surface since also the inside of the material is exposed. Then the powdered sample was poured into the sample cuvette for 1 cm high and compacted using a tamper tool. After the machine was standardized with black and white tiles, the cuvette with sample inside was measured three time with turning the cuvette, with three replications and expressed in L*a*b* color space.

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2.2.3 IRIS-Alphasoft

A visual analyzer (VA400IRIS, Alpha MOS, France) was used to take pictures of the fried fruit samples and analyze the data. The instrument is equipped with a CCD camera with resolution of 2592 x 1944 pixels and 24 bit (16). The camera was mounted in a light box equipped by top and bottom lightning (each position using 4x4 White LED) (28) which was stabilized for 15 minutes before used; however since the sample was too thin, and become transparent, only top lightning was used (18). The camera was equipped with a 25 mm f1:2.2 Basler lens by Fujion. The system was calibrated using Xrite Colour Checker Passport. The color sensor data were acquired with Alphasoft, version 16.0 and the background was removed using HSV color space (29). The data were then analyzed with Principle Component Analysis (PCA) and creating histograms using R (**Supp. 2B**).

2.2.4 Custom made CVS

A novel visual analyzer was developed and described in detail. This visual analyzer was used to take pictures of the fried fruit samples and analyze the data. The system consists of two parts; the first part is the image acquisition system (Canon) and the second part is the software (CVS) **(Fig. 1).**

Images of vacuum fruit chips were taken using a color digital camera (Canon 1000D with Canon EFS 18-55mm F3.5-5.6 IS lens, at 55 mm). This camera was mounted 25 cm from the product on Kaiser RT1 base with light sets inside a closed picture chamber (118 cm wide, 108 cm tall, 85 cm depth) made with thick card box laminated with white paper (**Supp. 2**). The light used was produced by 2 x 36 watt 5400k 40hz fluorescent light for each side mounted at 45° after 15 minutes of heating time, 45 cm from the sample. The fluorescent lights used have a color reproduction index (CRI) of 90-100 (30) which is able to reveal the colors of various objects faithfully in comparison with an ideal or natural light source.

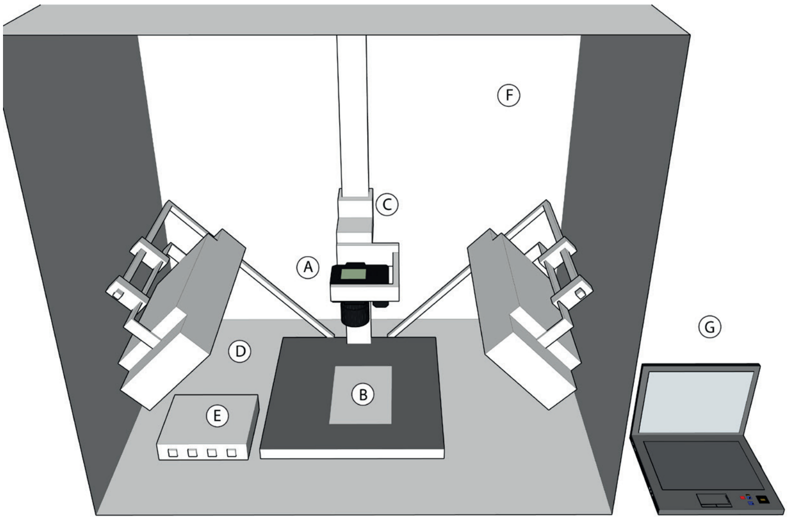

Figure 1 Camera booth design. **a** Camera. **b** Sample. **c** Camera mount. **d** Light source. **e** Light controller. **f** Photo box. **g** Camera controller

Pictures were taken at f16 aperture with 1/15 second exposure time. The small aperture was needed to allow enough light to the camera since the exposure time was fixed. The slow exposure time was needed to eliminate the flicker produced by the fluorescent light, exposure time at 1/15 second able to receive about 2.67 light wave, so the wave signature produced by the fluorescent light flicker was eliminated. However, the exposure time cannot be slower since the aperture cannot be smaller. Pictures were taken remotely through the EOS Utility to avoid camera shaking.

Color calibration was done using Xrite Color Checker Passport and Adobe Lightroom to produce a calibrated tiff file. Then the image background was removed using quick selection tool and color decontamination tool from an image processing software (Adobe Photoshop CC 2015) and the resulting image was saved into a tiff file. The tiff images were then analyzed using Wu (31) color quantization method from Color Inspector 3D v 2.3 plugin (32) within Fiji (33), an Image J 1.52g repository (34).

The obtained data from Color Inspector 3D was a look up table which contain information of 256 colors in a 24 bit RGB color space and how many pixels in the image are having that color within the sample (**Fig. 1**). Color Inspector 3D has been used in multiple fields such as in food chemistry to identify food dyes (35), also to quantify colors in dark field microscopy (36). This RGB coordinate was 24 bit color depth which contains 16 million color combinations (37). To make the color quantification more viable, a color conversion to a lower color depth was applied (**Supp. 3**). The 24 bit colors was reduced into 6 bit **(eq.5,6)** and 12 bit **(eq.3,4)** (38). The obtained RGB color table was converted into L^* a^* b^* values using RGB2Lab function within the patchPlot package in R (39) **(eq.7,8)**. To eliminate halo (a white background artifact around the sample images), **eq. 9** should be used, and to eliminate background, **eq. 10** should be used.

$$[R', G', B'] = [R, G, B] \times \frac{1}{255} \tag{7}$$

$$[L, a, b]_b = RGB2Lab[R', G', B'] \tag{8}$$

$$[L, a, b]_b = [L, a, b] with L' < 99 \tag{9}$$

$$[L, a, b]_b = [L, a, b]_a \, with L' > 0 \tag{10}$$

2.3 Data analysis

Data handling and data analysis was done using R. PCA analysis was used to identify each color analysis procedure discrimination performance and the percentage of variance in the sample explained by the color measurement (40).

3. Results and Discussion

The new and meaningful finding obtained during method comparison used to systematically compare the various color analysis methods and emphasize their pros and cons.

3.1 Sensory testing

Color analysis in the sensory testing by 37 panelists was done to describe overall color and color distribution of nine commercial vacuum fried fruits as shown in **Fig. 2**. Overall color analysis by sensory testing was done by selecting a color within the 920 colors of the RHS color chart which represents the overall color of the sample.

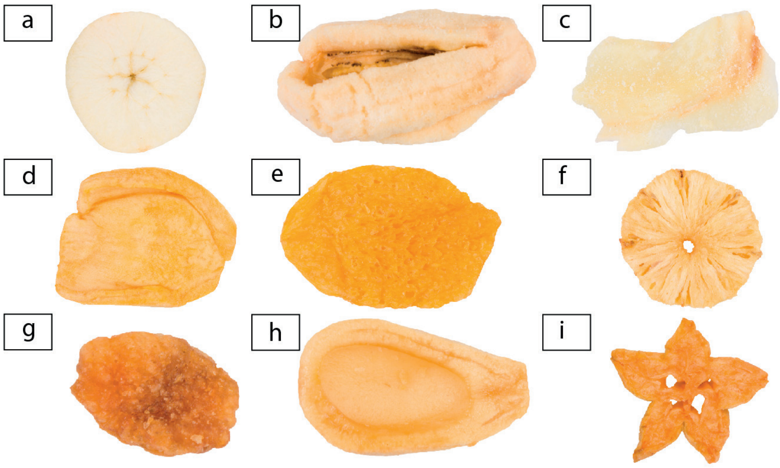

Figure 2 Images of nine vacuum fried fruits: a Apple. b Banana. c Durian. d Jackfruit. e Mango. f Pineapple. g Rambutan. h Salak. i Starfruit.

Despite the panelists were selected to have an appropriate color discrimination ability, when they analyzed the fruit, each panelist had a different perception of the color of the samples, which lead to a variety of colors perceived among the panelists **(Fig. 3 A)**. Furthermore, an actual color variation within the 20 samples per fruit will add to the variation in the observed colors. After a color conversion to 12 bit, we observed that a specific color was chosen by a majority of panelists for each fruit as shown in **Fig. 3 A**. In Fig. 6B apple, banana, and durian were grouped together based on their light yellow; jackfruit, mango, pineapple, salak, and starfruit were grouped based on their orange color, and rambutan was separated because it has a dark brown color. However, the groups overlap considerable. From this result we learn that the overall color analysis by sensory testing can be done easily with help of a color chart, but it is not very discriminative **(Fig. 3 B)**.

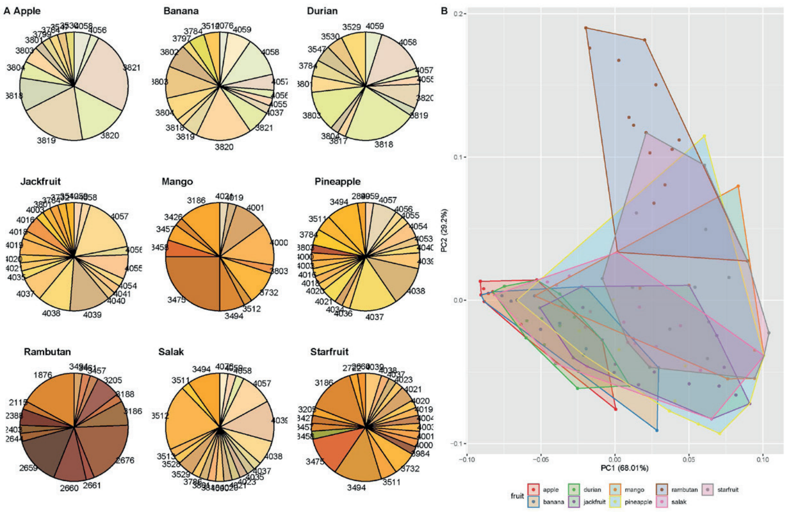

Figure 3 Overall color by sensory test. **A:** The frequency of a color chosen by panelists to describe overall color of fruit chip samples in 12 bit codes. **B:** PCA plot of the L*a*b* value of fruits chips

During color distribution analysis by the sensory test, the panelists were able to perceive that the color of the sample was heterogenous, and they matched the different colors of the sample with the colors of the color chart. In the **Fig. 4A**, we can find that the major area of apple, banana and durian was light yellow (color 47); the major area of jackfruit, mango, pineapple, salak, and starfruit was orange (color 27); and the majority area of rambutan was dark brown color (color 22). This result showed that the color distribution analysis could give more information of the surface color of the fruit. The method showed that each fruit has a variety of colors. Apple does not only consist of light yellow (color 47), but also of darker yellow (color 43) which reflects the core of the apple. In banana, the method also could detect color variance coming from different colors of the core of banana being dark yellow (color 43) and black color (color 21). The method also could reveal the green color (color 10, and 26) which was the outer skin of the starfruit. This method enables quantification of the heterogeneity of vacuum fried fruit samples as shown in **Fig. 4A.**

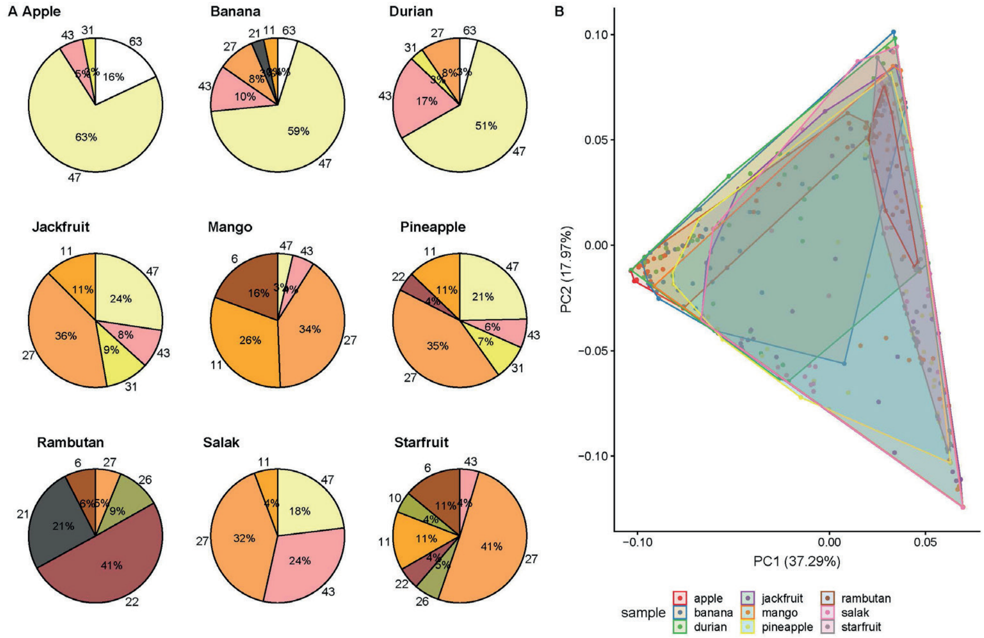

Figure 4 Color distribution analysis by sensory testing for nine different fruit samples in 6 bit codes. **A:** perceived color and area perceived. **B:** PCA analysis on perceived color and area.

The PCA analysis indicates that it is impossible to tell if one fruit is different from another by the sensory color distribution results (**Fig. 4B)**. This result implies that color distribution analysis in a sensory testing is not suitable to use for a quality control procedure related to color inhomogeneity. However, since the method is fast and easy, this method is still widely used in small scale industry, e.g. to evaluate defects in cheese (41).

Sensory testing is a flexible method which can be customized depending on the product characteristics and the features which needs to be extracted from the sample. A wide range of color chart options are available to match the color range of the sample, such as the Pantone color chart (42).

3.2 Hunterlab

A common instrumental method used to measure color is the colorimetric measurement using Hunterlab. Hunterlab readings were translated into 12 bit described in **Supp 2** in order to visually show the color registered by the instrument. The result shows that the main color of apple, banana, durian, jackfruit and salak was brown, and the main color of mango, rambutan, and starfruit was dark brown (**Fig. 5A**). This color reading was darker compared with the overall sensory analysis result. The difference could be attributed to the homogenization process which mixes light and dark color areas and also mixes the surface material with internal tissue and oil which was not visible during the sensory observation (43).

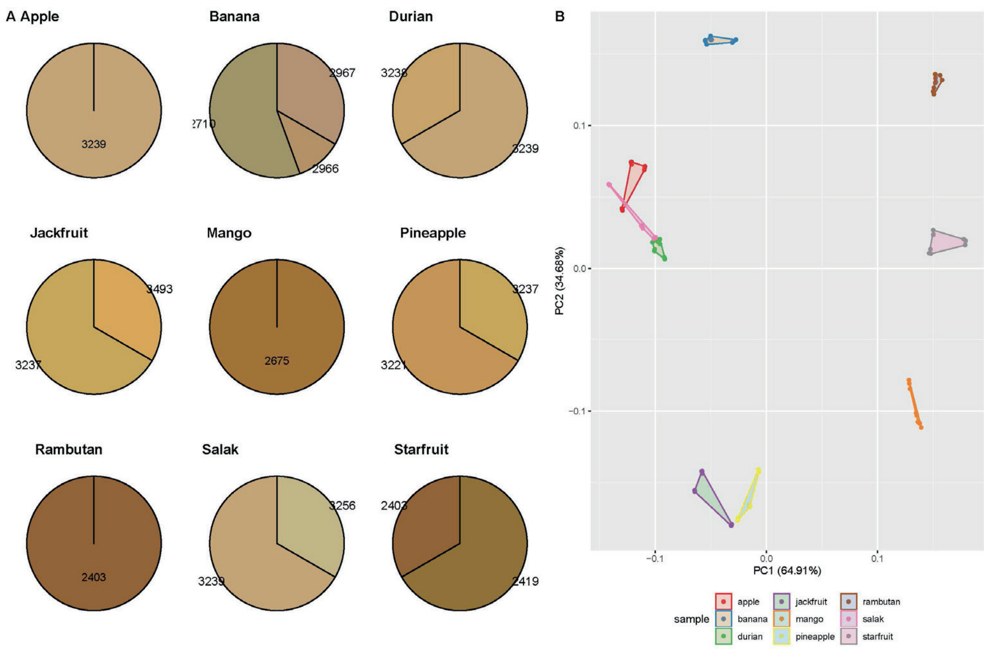

Figure 5 A: The frequency of a color measured by Hunterlab 6 bit for nine different fruit samples. **B:** PCA plot of the L*a*b* value of fruits chips by Hunterlab

The L*a*b* values produced by the analysis was used directly to test the capability of Hunterlab to successfully differentiate fruit colors via the PCA test, having a very high variance contribution of the first two components (**Fig. 5B**). However, during the sample preparation, the sample was homogenized, so only one average color was obtained and it was not possible to describe the color distribution of the sample (27).

The Hunterlab can be an option to evaluate the overall color analysis in a simple way, however it cannot produce a color distribution analysis. Even though the system was able to differentiate samples very well as described in **Fig. 5B.**

3.3 IRIS-Alphasoft

The IRIS-Alphasoft is a computer vison analysis system in a controlled picture box, and measures the colors as a portion of the sample surface using the Alphasoft software. The color information was given in a number as a code for a specific RGB coordinates in 12 bit which can be displayed as a histogram with the color numbers on the X-axis and the percentage of color within the sample on the Y-axis Y, with a 2 % threshold to reduce the complexity of the histogram (16).

The IRIS-Alphasoft analysis was able to describe the color distribution of vacuum fried fruit (**Fig. 6A**). Vacuum fried apple was described as having 30.4% of light pale yellow (color 4075) as the most abundant color which comes from the apple flesh. The system also measured a more dark color (color 4076) for 13.9% which represents the core of the apple. Vacuum fried pineapple was described as 13.1% of bright orange (color 3782) as the pineapple flesh. The system also measured 1.3% darker color (color 3216) as the eyes of the pineapple. Since the proportion of the eyes of the pineapple to the whole surface area is low, the color threshold should be decreased to 1% to make the color available in the graph.

The colors and the percentages were analyzed by PCA (**Fig. 6B**) to discriminate the samples. The system groups yellowish fruits, which consist of salak, pineapple and jackfruit (**Fig. 6B**). Furthermore, the system describes a low percentage of variance of 36.48% (22.86% for PC1, and 13.62% for PC), which may possibly produce a high error during interpretation of the data (44).

This commercial photo box is a fast and easy protocol to perform color distribution analysis, and therefore suitable to analyze high number of samples and requires little training for the operator. However, since the data processing within the IRIS-Alphasoft is a closed system, the researcher is barely able to process the raw data into other forms, for example to decrease the color depth, from 12 bit into 6 bit in the heterogenous sample; or to use full color 24 bit colors, in highly homogenous sample.

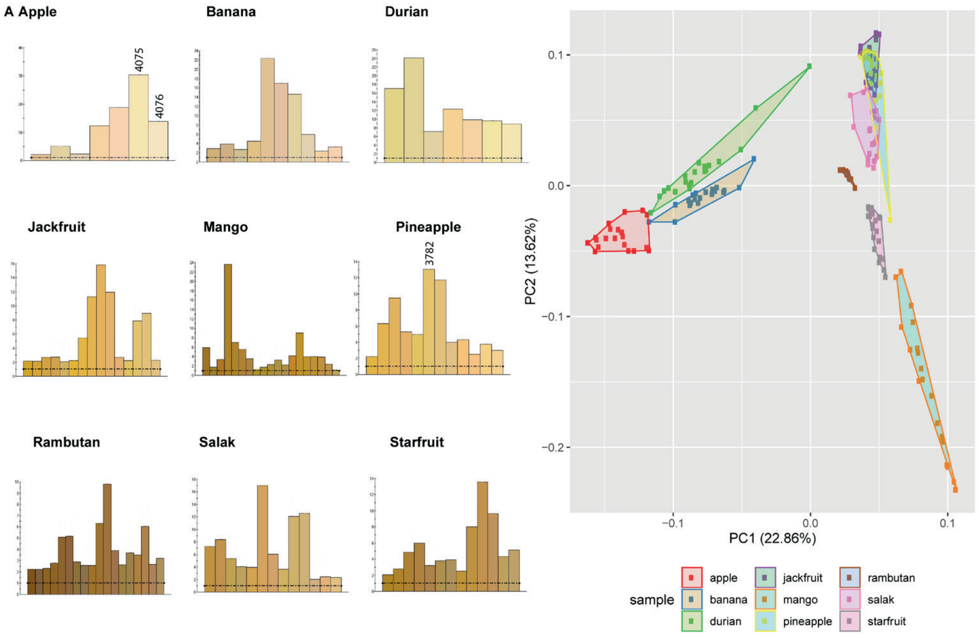

Figure 6 A: Color distribution result from vacuum fried fruit by IRIS-Alphasoft. **B:** The PCA plot from nine different fruits.

3.4 Custom made CVS

The Canon-CVS was used to carry out color distribution analysis in a more flexible manner. The camera and lens used in the Canon-CVS can be substituted by any brand which can produce a raw file format and can be color calibrated by Xrite Color Checker Passport and Adobe Lightroom, while the IRIS-Alphasoft is only able to use a limited option of lenses. The lens focal length can be adjusted according the size of the sample. Initially, the Canon-CVS produce 24 bit and combined with resolution of 10.1 Mega pixel picture produced a highly detailed picture. Analyzing all of the 24 bit color will requires a high computing power. So, the color depth of the color analysis can be adjusted from 12 bit to the 6 bit colors depending on the color homogeneity. Highly inhomogeneous samples require low color depth. Meanwhile, low variety samples require a higher color depth. However, 64 color depth produced a less realistic color (**Fig. 7**) than 12 bit color (**Fig. 8**). Images with 12 bit color looks realistic, however a color reduction to 6 bit leads color which first appeared in 12 bit colors becoming merged into nearby color which fit in 64 color, which mean there was 4032 colors lost. The 64 colors produced sometimes was not the real color of the sample, but the color which lost in the conversion process and merged to the nearby color.

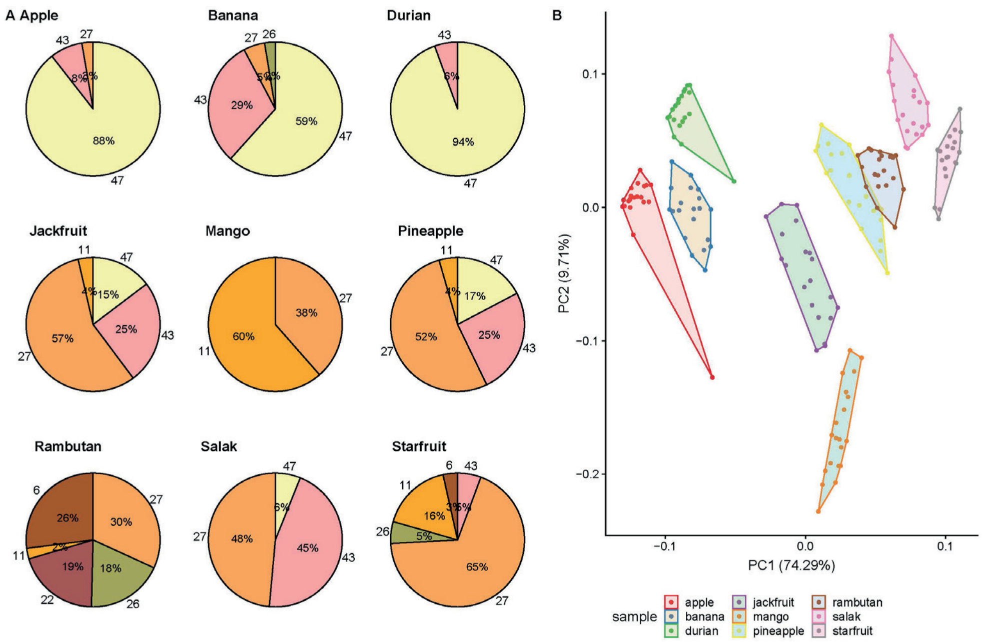

Figure 7 Color distribution of nine different fruits by Canon-CVS in 6 bit. **A:** The color distribution within the sample surface, with 2% threshold. **B:** The PCA plot

Specific attention should be given to the durian fruit chip sample which was sugar coated. In the sensory analysis, respondents reacted in various ways. In the overall color analysis, only a few panelists mentioned the bright color as the overall color, and the majority of the panelists mentioned the darker color of the chips. However, in the color distribution analysis, a 3% area was registered as very bright (color 63) which could come from the sugar-coating color. The Hunterlab could not retrieve this information. While the IRIS - Alphasoft seemed not to produce a color which matched with the color of the sugar, and the same result obtained with the Canon-CSV at 6 bit. But, at 16 bit, the whitish color was detected in a small portion. This comparison show the advantages of the color distribution analysis to describe specific features of a sample. Probably the IRIS – Alphasoft could not detect this color because of the low resolution of the camera, which was improved by the Canon-CVS. But only the Canon-CVS with a 12 bit process was able to detect this feature, and not with the 6 bit process. This result suggests that color depth plays an important role, 12 bit was the lowest color depth to capture this feature.

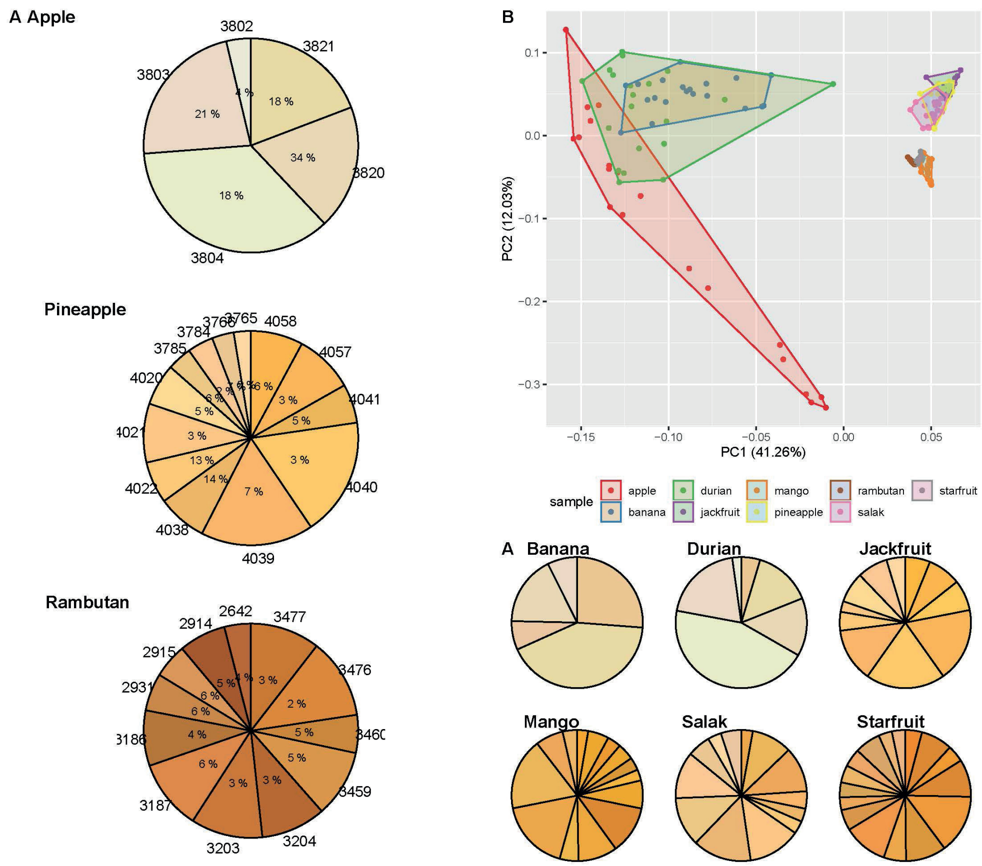

Figure 8 Color distribution of nine different fruits by Canon-CVS in 12 bit. **A:** The color distribution within the sample surface, with 2% threshold. **B:** The PCA plot

The system was able to describe the color distribution of vacuum fried fruits (**Fig. 7A**). Apple, banana, and durian have a big portion of light-yellow color (color 47), and a variety of portions of reddish color (color 43). Mango consists of two shades of orange color (color 11 and 27) which could result from the orange color of the mango and the shadow of the pores.

The combination of a low color number (6 bit color) and the accuracy of the measurement, assures the PCA test of Canon-CVS analysis to provide a good separation between fruits, and also a high total contribution of variance of 84% (PC1=74.29%, PC2=9.71%) (**Fig.7B**).

The color distribution analysis usually requires a severe color reduction and image processing; e.g. (12) applied color reduction to only three colors, while (14) applied the

Gaussian lowpass filter to smoothing the images. The Canon-CVS enables to shows the real color related to the sample with minimum modifications, or image processing which is possible by using a sufficiently high camera resolution and sensitivity to produce grain free images. This approach is necessary to accurately quantify the color distribution.

Canon-CVS was an economical choice for the color distribution analysis system, which additionally is a very flexible system compared to the commercial alternative. A wide price range of the camera body, lenses, camera mount, and lighting made the system affordable yet flexible to use in many cases from small lab to the industrial scale. Furthermore, the flexibility of the software, which described in a clear and precise way in the methodology, can be used and adapted or extended using an opensource program such as R (45).

The disadvantages of Canon-CVS are the requirements of having a skill sets including programing skills to write and adjust the program in R environment; an understanding on photography to select the best camera setting and lightning for a particular sample. Other limitations including the time needed to execute the whole protocol, particularly for the manual background removal. However, the possibility for flexible design and perhaps easier to custom built it in a process line an advantage compared to IRIS the Canon – CVS was appealing to use across the field.

4. Conclusions

The four-color analysis methods have their own advantages and disadvantages. Sensory testing with panelists is a relatively easy method which can be used if always the same product type is considered like it happens in many food factories. Although the sensory color distribution analysis is able to describe color heterogeneity, the subjectivity of the panelist limits the accuracy and the discrimination ability of the measurement. Hunterlab is found to be an easy, handy and accurate method to measure homogeneous samples; the analysis has a high differentiation ability, but the color distribution information was lost. IRIS-Alphasoft is a quick and easy method to perform a color distribution analysis, it is completely automatized and easy to use for untrained operators, however the closed system limits the analysis. The Canon-CVS system and protocol was able to assess sample color heterogeneity as well as to discriminate between the samples; furthermore the method was flexible and economical, which enables the user to customize the protocol based on the sample and the objective of the analysis but it requires trained operators especially for the data analysis. As a take home massage, color distribution analysis has a potential to unlock the limitation of traditional color analysis to give more color information of the sample which is important in product quality analysis.

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CHAPTER 6

General Discussion

1. Introduction

Fruit is an important component of the human diet because it is a source of (micro) nutrients, fiber and bioactive compounds necessary for healthy living. However, fresh fruit has a short shelf life which limits its utilization. Therefore, there is a need to design fruit based products with an extended shelf life while preserving the health benefits of fruit as much as possible. This thesis provides a technological approach to improve the physicochemical quality of vacuum fried fruit. This is based on four integrated studies ranging from literature review, research into process and product optimization, mathematical modelling, and development of advanced analytical methods.

Deep frying is one of the oldest methods of food processing widely used by consumers and the food industry to increase shelf life and it is carried out by submerging the product in hot oil (1). It entails the application of heat, thereby exchanging moisture for frying oil, to achieve cooking and drying leading to the development of flavor, crust and color in the fried foods (1). With low moisture content, the product will have a longer shelf life compared to the fresh product. In addition, it will have different and desired sensory characteristics because of the formation of specific aroma compounds and a crispy texture.

The frying technique has advantages over other processes such as the formation of a specific flavor and a crunchy texture which cannot be replicated by other processes; however, it cannot be applied to all food. Fruit particularly, is rarely fried because it has a high moisture content and therefore requires a long time to remove sufficient moisture. This long frying time at high temperature will reduce the amount of nutrients and heat-labile bioactive compounds in the fruit and give unacceptable browning. In this context a technological upgrade of deep frying is needed to maintain the health properties and preferable sensory characteristics of the fruit. This is actually the big advantage of vacuum frying. However, compared to atmospheric frying, vacuum frying needs more cost to generate vacuum, a vacuum pump, which powered by electricity is required, strong frying vessel also needed to keep the vacuum pressure.

Table 1. Summary of the main findings of this thesis

Objectives	Main findings
Chapter 2 · To review the effects of vacuum frying on changes in the quality of tropical fruits with a focus on the role of the fruit matrix.	· The conceptual difference between vacuum frying and atmospheric frying is the lower boiling point of water at lower pressures that enables to frying at lower temperatures. In general, vacuum frying with a lower temperature produce a higher nutrient retention. · During the ripening process, the fruit matrix and chemical composition will change, which further influence the texture, oil content, and color of vacuum-fried fruits.
Chapter 3 · To describe the effect of ripening stages, frying temperature, and time on the nutritional and physicochemical quality of vacuum fried mango.	· During frying process, vitamin C and β-carotene decreased, hardness first decreased and then increased, color becomes darker and redder, fat content increasing. · Not only the frying time and temperature have an impact on the quality of the vacuum fried mango, but the ripening stages proved to play an important role in determining product quality.
Chapter 4 · To develop moisture-dependent dynamic models that describe the change in quality during food processing.	· The relationship between fat uptake and moisture content was described by a modified Gompertz model, a similar model was applied for the relationship between hardness and moisture content. · The color change was described by two irreversible serial reactions with an indirect relationship to the moisture content by considering the dynamic boiling temperature during the process.
Chapter 5 · To compare color analytical techniques on the ability to differentiate samples, quantify heterogeneity, and flexibility.	· Color distribution analysis unlocks the limitation of traditional color analysis to give more information on the heterogeneity of the sample which is important in product quality analysis.

Vacuum frying is a frying process at a reduced atmospheric pressure compared to atmospheric deep frying. This technique has a main advantage of a lower frying temperature by reducing the boiling point of water in the product during the frying. To improve vacuum fried fruit quality, this thesis explored the current state of the art of this technology, the effect of processing conditions on the retention of bioactive compounds and on the development of color and texture in the final product. In this general discussion I addressed the importance of the findings and how it fulfills the objectives as seen in **Table 1**. The key findings are discussed in four sections. The first is effects of vacuum frying on changes in quality attributes of tropical fruits, and then continued with ripening stages as an important parameter in fruit product development; moisture content as key parameter; and advanced color analysis as the last section. In addition, recommendations for further studies are given.

2 Discussion of the key findings

2.1 Effects of vacuum frying on changes in quality attributes of tropical fruits

Compared to atmospheric frying, the content of bioactive compounds and the color of vacuum fried fruits are mostly improved by reducing pressure and subsequently the boiling temperature during vacuum frying.

Many nutrients and bioactive compounds are known for their sensitivity to elevated temperatures. Vitamin C is an important water-soluble bioactive compound present in most of tropical fruits. Vitamin C can be degraded by nearly 50% during 3 hours fruit air drying at 65 °C (2). On the other hand, vacuum frying of mango for 35 minutes at 100 °C retains 66% of vitamin C. This high degradation rate during air drying was observed when vitamin C was exposed to oxidation at an elevated temperature. However, due to the absence of air and most of oxygen during vacuum frying, chemical detrimental reactions, such as oxidation and enzymatic browning, are inhibited. As a result, the color, nutrients and bioactive compounds of the fried fruits can be preserved to a greater extent.

β-carotene, a fat soluble provitamin A, is also one of the important and abundant bioactive compounds in fruits. Frying has been shown to increase β-carotene accessibility (3). This thesis found that accessible β-carotene in the vacuum fried mango at 90 °C was more than double compared to the raw mango. The presence of oil and the heating process increased the β-carotene extractability from the fruit matrix. Furthermore, frying increased the bioaccessibility of beta carotene in vitro (4). These results support the consumption of vacuum fried fruit products in a healthy diet. The increasing solubility and bioaccessibility of fat-soluble bioactive compounds are not found in non-fat based processes such as drying (5). Kolawole *et al.* (4) mentioned that fat in the fried food act as a sink in which carotenoids liberated from the food matrix are solubilized. Furthermore, fat in the fried food stimulates the secretion of multiple digestion enzymes including lipases, bile salts and phospholipids into the intestinal lumen in order to digest the lipid and creating the mixed micelles which solubilize carotenoids in the aqueous environment of the intestinal lumen. The negative effect of fat will be discussed later in this section.

Color is another quality attribute that needs to be considered in fruit vacuum frying. Fruits are well known to have bright colors which are attributed to the presence of different bioactive compounds. Vacuum frying has been proven to retain fruit color in fried products such as bananas (6), kiwi (7), and mango (8). The results in **Chapter 3** confirmed that the color of vacuum fried mango at 90 °C does not change significantly compared to the raw mango. However, when the temperature increased up to 120 °C for 10 minutes or more the color differences become significant as well as more heterogenous as can be observed in **Figure 1**. This color distribution is quantified and described in **Chapter 5** and then discussed further in section 2.4 of this chapter.

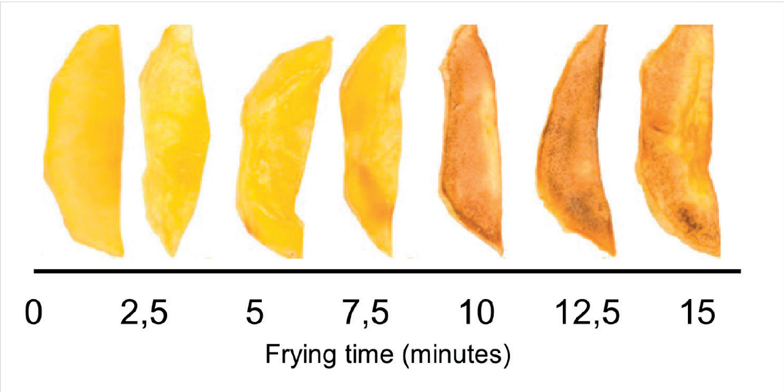

Figure 1. Mango color changes during vacuum frying at 120 °C, adapted from Chapter 3

Other than those mentioned before, many fruits and their color retention are yet to be explored with vacuum frying processing. The color compound solubility in these fruits is an important variable to be considered. Carotene, which is a dominant source of the orange-red color in mango is fat-soluble and its solubility is increased by frying. The involved mechanism that increases the solubility is including that the carotene captured in the frying oil within the product and stays there after the product is drained.

However, some of the carotene leached to the frying oil outside the product and is lost. Another loss is caused by the thermal degradation of carotene. Hot air drying of mango at 70 °C for 9 h (9), destroy 88.0% of β-carotene (10); however at a less temperature of sun drying at 35 ± 5 °C (9) only produce 3.2% β-carotene degradation (10).

Also, chlorophyll in green fleshed kiwifruit (11) has similar degradation properties. Zhu, Zhang and Wang (12) found that vacuum frying of peas at 105 °C at 80 kPa for 20 minutes reduced chlorophyll by 15% by degradation. But there is no current available information on the behavior of chlorophyll at lower temperatures and/or shorter frying time. Nevertheless, drying of amaranth leaf using a cabinet dryer at 65 °C until final moisture content of 7-9% reduces chlorophyll content by 44.1% (13).

Other colorants in fruits that are water-soluble including betalain in dragon fruit (14), anthocyanin in fig (15), java plum (16), and pomegranate (17) should be properly considered as they can degrade during frying. In addition, other colored non fruit foods such as flowers and vegetables are still abundant to be examined in the effects of vacuum frying on color. Some edible flowers that can be fried including courgetti or zucchini flowers (18, 19) which are fried in a dough coating. Those flowers could produce an interesting texture and color when vacuum fried.

Moisture content in fresh fruit is an important attribute during processing. The high content of moisture in fresh fruit produces a wet and soggy product when fried in atmospheric pressure at short time and low temperature. Increasing time and temperature is not an option since it will burn the fruit chips and destroy most of the valuable bioactive compounds in the fruits (20). Vacuum frying allows faster moisture removal at lower temperature by reducing the boiling point of water in the fruit. Further approach to enhance moisture evaporation including pretreatments such as freezing. Freezing damages the fruit structure and allow faster moisture removal during frying process. Furthermore, freezing as pretreatment improved organoleptic quality and antioxidant activity of vacuum fried carrot (21). The importance of moisture will be discussed further in section 2.3.

Fat introduced during frying by the mass exchange between moisture and frying oil enables the creation of calorie dense food. Calorie dense food produced by frying are considerable cheaper per calorie compared to fresh food (22). However, this calorie dense food usually has low bioactive compounds. The production of calorie dense food from fruit which are rich in bioactive compounds could yield a healthy calorie dense food. Furthermore, fat intake at excessive amount could leads to numerous negative effects. Fat contributes 9 cal/g. An average diet in an industrialized countries can up to 3.7-3.8 snack /day, providing 350 kcal/day in US adults. Their snack can have fat content raged from 30.8-37.9 % (23). An excessive amount of fat can increase the energy intake, which without appropriate physical activity could lead to obesity (24). Vacuum fried fruit can be an interesting option of snacking since its low fat content of about 20% for vacuum fried unripe mango, even though for ripe mango the fat content can reached about 30% as shown in Chapter 4. The different fat content of mango at different ripening stages also highlights the importance of ripening stages, which will be discussed further in 2.2.

Considering low fat content and combined with high bioactive compound preserved by vacuum frying processing, vacuum fried fruit overall is a healthy snacking option.

2.2 Ripening stages as an important parameter in fruit product development

Ripening is one of the important characteristics of fruits. Fruits can be classified into climacteric and non-climacteric fruits. The respiration and ethylene biosynthesis rates of climacteric fruits increase during ripening, while there is no increase for non-climacteric fruits. This characteristic is important to select at which ripening stage the fruit is suitable for frying or other processing. The characteristic of climacteric fruits will change substantially over time during storage, while non-climacteric will remain unchanged (25). Important quality attributes such as flesh color, firmness, and phytochemical composition changes during post-harvest ripening of different climacteric fruits can be observed in Table 2.

Table 2. Parameters changing during post-harvest ripening of different climacteric fruits

Fruit	Flesh color	Texture	Phytochemistry
Mango	b* value (blue to yellow) ↑ (26).	Firmness ↓ (27)	Citric acid ↓ (27), total carotenoids ↑ (28), chlorophyl ↓ (29).
	Hue angle ↓ (green↓, yellow intensity ↑) (29)		Glucose ↓, sucrose ↑, fructose ↑, total sugar ↑ (30)
Banana	b* value ↑ (31)	Firmness ↓ (32, 33)	Glucose ↑, sucrose ↑, fructose ↑ (32), total sugar ↑ (33).
			Citric acid ↑ (32), Ascorbic acid ↑ (33)
Papaya	a* value (green to red) ↑ (34)	Firmness ↓ (35)	β Carotene ↑, lycopene ↑ (36), vitamin C ↑ (37).
			Glucose ↓, sucrose ↑, fructose ↑, Total soluble solid ↑ (37),
Avocado	Lightness ↓, chroma ↓ (38)	Firmness ↓ (39)	Ascorbic acid ↓ (39), total carotenoid ↓, total anthocyanin ↑ (38), fat content ↑ (39), Total soluble sugar ↓ (40)

Some physical and chemical characteristics of fruits that are important in processing described in **Chapter 2** include the cell size, cell wall, flesh thickness, and sugar content. These characteristics will determine the structural integrity of food and fruit in particular that are important to maintain the original shape during vacuum frying. Fruit or plant cell in general have a cell wall that limits the expansion of the cytoplasm during processing (41), including frying. Slices thickness is an important characteristic which influenced fried chips hardness. As the slices becoming thicker, the texture also becoming harder (42). Sugar content which directly relates to the ripening stages (43) has a critical effect on color, at higher sugar content, the color becoming less preferable because of the brown color formed by caramelization (44).

Mango at different ripening stages have different optimal product applications. Immature mango can be processed into mango powder. This mango powder, which called *amchoor* in India is used as seasoning which has an acidic flavor (45). This mango powder can only be produced using immature mango, not mature (ripe and unripe) because of its high starch and low fructose content giving it a distinct acidic flavor.

Unripe mango is recommended to produce high-quality vacuum fried mango chips with high-hardness and without adsorbing too much oil, as described in **Chapter 3**. After mango is picked from the tree, although harvested at more unripe stage, mango will continue to ripen. This selection procedure leads to a significant waste of ripe mango. To valorize this excess, a strategy commonly used is re-purposing to other products such as a fresh cut or for juice.

Vacuum frying usually uses a constant pressure which is adjusted for each type of fried fruit. A range of pressures that is reported in literature is summarized in **Chapter 2** which varied from 1.3 to 98.7 kPa. Fan, Zhang, Xiao, Sun and Tao (46) used three pressure settings for vacuum frying carrot. A higher vacuum produced a faster moisture removal and a crispier carrot. However, this high vacuum requires a higher energy to achieve. From this paper could be inferred that a greener process could be achieved using a dynamic pressure system; a combination of initially a relatively high pressure to remove the bulk of the moisture faster and then subsequently reduce the pressure to remove the remaining moisture. However, to quantify the benefits in terms of energy required, many factors should be calculated, such as vacuum pump efficiency and vacuum frying design which not available currently and outside author expertise; and could becoming an interesting research idea.

6

In **Chapter 3** it was assessed that compared to ripe mango, the unripe mango chips have a faster moisture loss, a similar hardness at lower temperature, a lower fat content, and a better retention of vitamin C and β-carotene. Recently Soto *et al.* (3) used three ripening stages of papaya to produce vacuum fried papaya chips. During papaya ripening, skin and pulp hardness decreased. This soft matrix allows moisture to escape quicker than from a hard matrix, and producing a lower moisture content. The difference effect of ripening to the moisture content of mango and papaya could be caused by other component in the mango such as starch.

Soto *et al.* (3) also found that during ripening, glucose, fructose, citric acid and β-carotene content of fresh papaya increased. As the ripening stages increased, the vacuum fried papaya have a decreased L value that correlated to higher β-carotene content. Furthermore, as ripening stage increased, the overall liking of vacuum fried papaya also increased, which might be related to the color and taste; which correlated with increasing glucose, fructose, and citric acid content. However, as ripening stage increased, the hardness of papaya chips decreased and producing sticky papaya chips.

Discovery of the importance of ripening stage in fruit product development might be generalized for other fruits which have similar ripening behavior, although confirmation is needed considering the fruit variety. Also, special attention should be given to non-climacteric fruit, for which the ripening process is stopped or significantly reduced after being harvested. Non-climacteric fruits should be harvested at an optimal ripening stage in order to obtain desired quality attributes of fried fruit chips.

2.3 Moisture content as key parameter

Moisture is considered the variable that plays the most decisive role in the vacuum frying process. In this process, energy in the form of heat is used to evaporate water from the product. This heat can be transferred to the product by hot air or oil. In the case of air as heating medium the air also serves as a way to capture the evaporated water in the form of humidity. In the case of oil, the water will not be captured by the heating medium but will be released as steam. When oil is used, part of the oil will replace the evaporated water, giving the fried product a higher caloric value and also interesting sensory attributes. Since fruit contain about 80-90% water, the moisture removal process has a significant effect on many products characteristics.

Important attributes that drive the preference toward vacuum fried fruit including, texture, color and bioactive compounds can be observed in **Figure 2**. The texture is an important characteristic of fried and dried fruit, and during moisture removal, two phases of texture change can be observed. During the first phase the texture rapidly softens because of the turgor pressure of the fruit cells will be lost due to water evaporation. In the second phase the hardness builds up. Upon further moisture loss, the tissue forms a stiff structure that can be observed by microscopic or by texture analysis. This direct relationship between moisture content and texture is observed in **Chapter 3**, and mathematical models were used to describe this in **Chapter 4**. This relationship between processing time and temperature, moisture loss and texture could be applied to other processing techniques such as atmospheric frying and drying and it is valid for both, fruit and vegetables.

Vacuum fried fruit not only can be produced from intact flesh, but also from pulp (47), with different attributes compared to vacuum fried fruit produced from intact flesh. Mango pulp used for the vacuum frying was produced by pulping washed and peeled mango. The pulp then homogenized in a blender for one minute to produce mango pure, the pure was then mixed with starch and wheat flour to obtain a solid product. The paste produced then molded in 4 cm diameter of round shape and 2 mm of thickness, refrigerated, and then ready to be vacuum fried. The cell or tissue in the pulp can be fully destroyed, does not have turgor pressure, and during frying will only exhibit the second phase of texture development. This processing route can be used for highly perishable fruit (48). The fresh fruit can be pulped and frozen for future use.

Fat is also an important feature in fried products, increasing the caloric value and affecting the sensory properties like mouthfeel and aroma. Uptake of fat can only be found in frying. Even though one can add the oil as an ingredient in the formulation of fruit containing product, the texture of the fruit will not be the same. The relationship between moisture loss and fat uptake in vacuum frying of mango can be described by an empirical Gompertz model. It was concluded that fat uptake in ripe and unripe mango is different. In unripe mango, when the moisture content decreases below 0.1 g/g db, no more fat is absorbed by the chip. On the other hand, for ripe mango, as the moisture content decreases below 0.1 g/g db the fat content keeps increasing. which is assumed to be caused by the structure differences. Unripe mango as described in **Chapter 4** has a higher pectin content compared to ripe mango that hypothetically acts as a barrier for oil penetration.

Color is an interesting attribute in food that needs to be considered because it is the first characteristic recognized by consumers before consumption. To appreciate its importance, multiple approaches were carefully used to describe color changes during vacuum frying. Color has an indirect correlation with moisture content. Firstly, it was postulated that at vacuum pressure of 10 kPa, temperature would be constant at around 50 °C during the first frying phase until moisture gets lower allowing an increasing temperature towards the oil temperature when there is no more evaporating water. This dynamic temperature will affect the rates of reactions involved in color change. These color changes could be modeled by two irreversible serial reactions. The model described color development in vacuum frying as presented in **Chapter 4**. All other frying and drying processes with any food could be described for temperature dependent, multiple reaction, color formation mechanisms (49, 50).

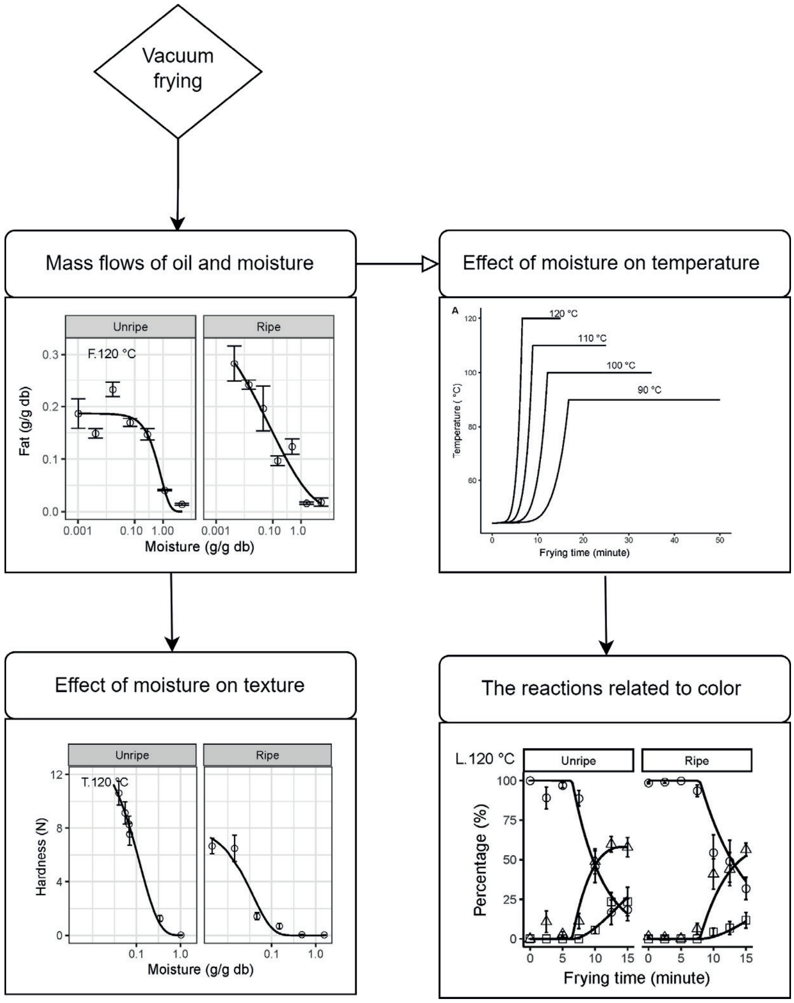

Figure 2. Schematic representation of the pivotal role of moisture with direct and indirect relation on other quality attributes.

To extend this model application, crisps (e.g., *kerupuk* in Indonesian, *kroepoek* in Dutch) is another type of food product that has a very high correlation between moisture, texture and color (51). The crisp in this case refer to a highly expanded product contributed by starch gelatinization which usually contain a small amount of vegetable, fish and shrimp (52). During frying, moisture in the crisp will evaporate, expands the structure and changing the color. The change of these properties is related to the moisture loss and the subsequent temperature increase. Oil migration occurred in exchange for moisture loss. The crisp expansion as indicator of gelatinization only occurred after moisture removed that enable the temperature increasement to the gelatinization temperature;

which then start the browning process. However, the vacuum frying temperature could be below the gelatinization temperature and will not induce gelatinization and at the end does not result in expansion, which is not preferred (53).

Some consideration on how to improve the vacuum frying which can influenced vacuum fried fruit quality attributes including dynamic pressure which already discussed in 2.2. A higher vacuum also could give benefit to the fracturability and sensory value of product as mentioned by Deng, Chen, Tian, Miao and Zheng (54).

2.4 Advanced Color Analysis

Color is an important feature in food quality because it correlated with many other quality attributes. Color changes in food processing determine the quality of finished product. Examples of color changes during food processing and the color analysis method used are given in **Table 4**.

Food product usually have diverse matrix characteristics at micro-, meso-, and macroscopic scales that could have different color changing during processing as described in **Chapter 2**. As observed in **Table 4**, most of the products used, including tomato fruit, *Huyou*, apple, beetroot and French fries, have a high color variation. However, most of the color analysis used was average surface color analysis because of the simplicity of the method but at a cost of losing color distribution information as described in full in **Table 4**. To overcome this problem, Mesias, Delgado-Andrade, Holgado, González-Mulero and Morales (55) did six individual measurements at different point on the surface of French fries to obtain the color distribution information.

The pros and cons of various color analysis methods were discussed in **Chapter 5**. The comparison of average and distribution analysis is valuable to the interested parties using the color distribution analysis. All the compared methods have their advantages and disadvantages. Published examples of color distribution analysis, thesis contribution (comparison of average and distribution analysis), and future potential development of color distribution analysis can be observed in **Figure 3**.

An interesting application is to a highly heterogenous product such as pizza (62). This product has varieties of colors, namely green for basil, red for tomato sauce, brownish-red for sausage, white for cheese, and others. The visible color distribution of the product could be quantified and associated with consumer preferences using the hedonic score.

Table 4. Quality determinant of color during certain processing or storage

Process	Product	Color variation	Color changes	Quality indicator	Method	Ref.
Storage	Strawberry yoghurt	Low	L* value ↑	Anthocyanins degradation	Average surface color using a Konica Minolta colorimeter (CM-3600d)	(56)
Vacuum-microwave drying	Tomato fruit	High	L* value ↑,a* value ↓	Lycopene degradation	Average surface color (L*, a*, and b*) using a Konica-Minolta chroma meter (CR-13)	(57)
Microwave vacuum drying-freeze drying combination	Huyou (*Citrus changshanensis*)	High	ΔE value similar to freeze drying	FRAP and DPPH value higher than freeze drying	Average surface color (L*, a*, and b*) using a Konica-Minolta (CR-400) model colorimeter	(58)
Hot air drying	Apple slices	High	a* and b* value ↑, L* value ↓	Browning reaction	Average surface color (CIE L*, a*, b*) using a Digi Eye system	(59)
Fraud	Turmeric powder	Low	Different color distribution	Chickpea adulteration	Color distribution using Computer Vision System	(60)
Different drying technique	Beetroot	High	Lightness in different B channel (RGB scale)	Attractive-ness similar to raw	Color distribution using Computer Vision System	(61)
Frying	French fries	High	L* and E values ↓ and a* and b* values ↑.	Acrylamide formation	Color distribution (L*, a*, and b*) using a Konica Minolta spectrophotometer (CM-3500D)	(55)

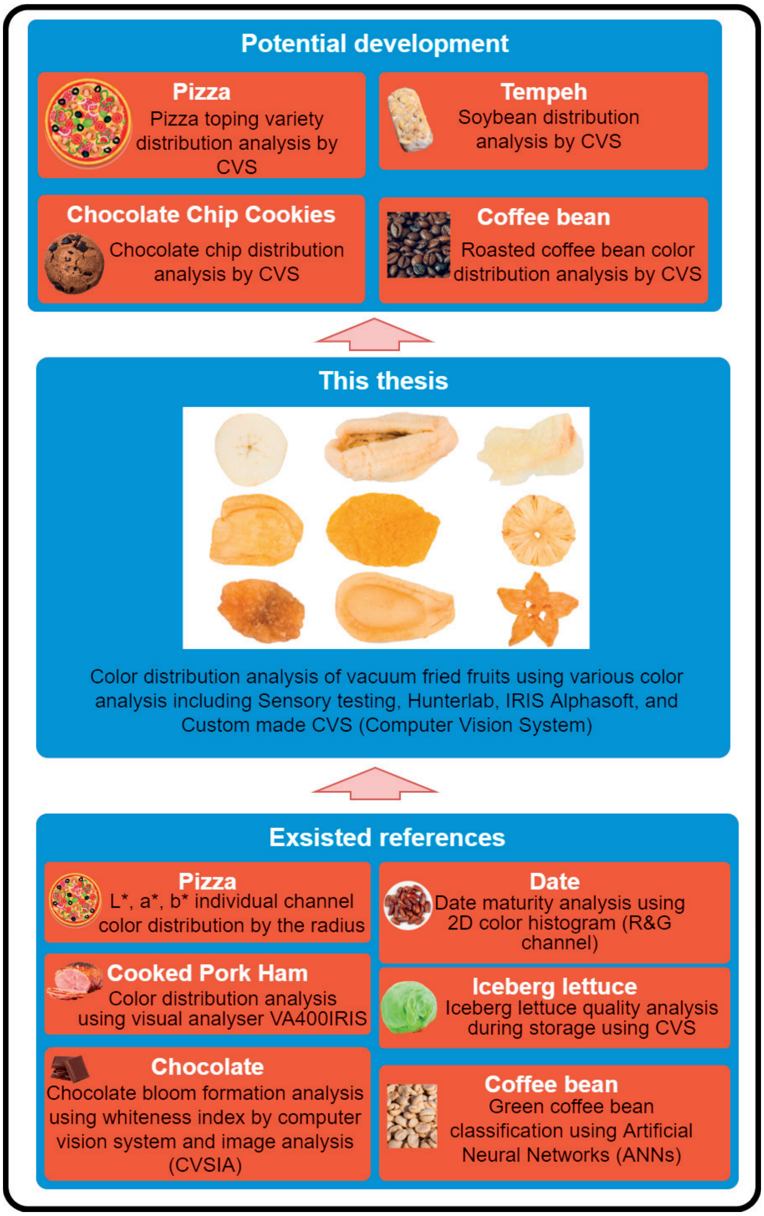

Figure 3. Published examples of color distribution analysis, thesis contribution (comparison of average and distribution analysis), and future potential development of color distribution analysis from existing references and new application. The existed references include pizza (62), cooked pork ham (64), chocolate (63), date (65), iceberg lettuce (66), and coffee bean (67).

6

A wide resolution range of computer vision systems can be adjusted to the product. The Canon-CVS could produce 24 bit color resolution. This high resolution is required to analyzed a less heterogenous sample. Sample with a high color heterogeneity may only requires 12 or even 6 bit color. Also, less distinct colors of products such as chocolate chips chocolate cookies have less chroma variance, which could be difficult to distinguish at low-resolution analysis. A high-resolution analysis can separate the chocolate chips among other cookie parts.

Color distribution analysis also has the potential to be a quality control tool, specifically for automatic machinery as in the case of chocolate chips cookies (63). The number of chocolate chips should be distributed evenly from cookie to cookie, and batch to batch, to prevent product variants beyond an acceptable limit. such as mango and jackfruit. A dark spot can be marked as an indication of a less quality product. Therefore, analysis of the number of spots and the intensity can be performed with this system to control the color quality.

Another example can be applied to a product that should have a homogenous color

3 Main conclusions

The overall objective of the thesis was to investigate the quality of vacuum fried products of selected tropical fruits and how this quality is affected by the process conditions, the fruit type, the ripening stage and the structural properties of the matrix.

The attributes most improved by the vacuum frying process compared to frying at atmospheric pressure are the retention of bioactive compounds and improvements in color formation. These two quality attributes are greatly improved due to the lower temperature at reduced frying pressure. The fat content of vacuum fried fruit was increased at low amount.

Improvement of the vacuum frying technology is an important aspect to consider. Optimization of dynamic pressure during vacuum frying could improve energy efficiency.

The maturity stage of the fruit is an important characteristic to consider when selecting fruit for frying or other processing due to the effect of structural and chemical changes on the final quality attributes.

Moisture plays the most decisive role during vacuum frying, first since it determines the dynamic product temperature during the process which affects the reaction rates of the color formation reactions as well as degradation rates of bioactive compounds. Therefore, it has a large influence on texture, fat content, color and the retention of bioactive compounds.

Color is an important characteristic determining product perception by consumers. It is traditionally described using average color analysis. More advanced color analysis can be applied to describe the color distribution in products. Color distribution analysis is much closer related to the actual human perception of product surfaces.

Considering low fat content and combined with high bioactive compound preserved and crispy texture produce by vacuum frying processing, vacuum fried fruit overall is a healthy snacking option, which cannot be replicated by other fruit processing techniques. However, the implementation of vacuum frying technology also come at a higher cost compared to atmospheric frying.

Overall, knowledge gained by the research described in this thesis can be used to optimize the process to improve processed fruit quality. Some knowledge gaps that were identified in this thesis that need to be addressed in the future including the application of dynamic pressure to improve product quality and at the same time improve energy efficiency. The application of a higher vacuum also needs to be addressed as the benefit of improving texture and consumer acceptance.

Furthermore, the importance of moisture content could be applied to other processing methods which utilizing moisture removal at elevated temperatures such as drying. The advanced color distribution analysis also could play an important role in heterogenous food color analysis produced by various processing techniques such as baking.

Vacuum frying is popular in Indonesia, for example vacuum fried jackfruit, mango, banana, apple, pineapple, starfruit, snake fruit, and rambutan. Most of vacuum fried fruit in Indonesia was sold by street vendors. The finding of this thesis has some important societal relevance including how to choose the best frying setting and fruit ripening stage to improve the quality of the street-vended products. This street vendors will benefit from the higher margin of the higher vacuum fried fruit quality.

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SUMMARY

1. Background

Vacuum-frying is a frying process performed below atmospheric pressure conditions. Due to the low pressure in this vacuum frying, the boiling point is lower than the atmospheric pressure. Consequently, the process can be performed at a much lower temperature compared to atmospheric frying. Multiple factors contributing to quality of finished vacuum fried fruit chips including fruits matrix and technological characteristic. Previous vacuum studies were focused on various quality attributes of different fruits. But lack of coherence to understanding the mechanism contributing to those quality attributes. There were no studies taking into account fruit matrix, moisture dependent dynamic models, and the color distribution analysis.

2. Objective

The overall objective of the thesis is to investigate the effect of ripening stage and structural properties (matrix) of selected tropical fruits on the quality of vacuum fried fruits products. This overall role is further accomplished by following approach i) reviewing the vacuum frying technique and its effect on product quality with a focus on the role of the fruit matrix. ii) Describing the effect of ripening stages, frying temperature, and time on the nutritional and physicochemical quality of vacuum fried mango. iii) Describing the development of moisture dependent dynamic models that describe the change in quality attributes during food processing. iv) Comparing color analytical techniques on the ability to differentiate samples, quantify heterogeneity, costs, and flexibility

3. Results

The role of the fruit matrix is a very important factor in vacuum processing, but is described very limited, fragmentary and anecdotal in the literature. **Chapter 2** describes that during the ripening process, the fruit matrix and chemical composition will change, which will have an effect on the texture, oil content and color of vacuum fried fruits. Especially tropical fruits have quite different ripening properties, firmness, texture and porosity that will influence the quality attributes of vacuum fried tropical fruits. More systematic research into the effects of the fruit matrix on the vacuum frying process and the quality attributes of the fried fruits is needed. By such research the mechanistic understanding can be used to optimize the frying process to produce high quality vacuum fried fruits.

A follow-up study to quantify the effect of matrix to the quality attributes of vacuum fried is presented in **Chapter 3**. Moisture loss of unripe mango chips was faster than that of ripe mango chips. There was no significant difference between hardness of unripe and ripe mango after vacuum frying at low temperatures, but at higher temperatures, unripe mango had a higher hardness value compared to ripe mango. Vacuum fried ripe mango had a higher fat content compared to unripe mango. No differences between the ripening stages were found on the degradation of ascorbic acid and β-carotene during frying. Unripe mango is more susceptible to temperature and time towards lightness and redness changes compared to ripe mango. Considering all quality parameters, unripe mango is preferred over ripe mango for vacuum frying processing.

During thermal processing of foods the moisture content plays a pivotal role for most relevant quality attributes, either directly for e.g. fat and texture or indirectly for chemical reactions, e.g. color changes. A general framework for mathematical modelling of moisture dependent quality changes is given in **Chapter 4**. This approach has been applied on vacuum frying of mango chips. The changes in moisture content were best described by an exponential model. The relation between fat uptake and moisture content could be described by a modified Gompertz model, a similar model could also describe the relation between hardness and moisture content. Color change could be described by two irreversible serial reactions with an indirect relation to the moisture content through modelling of the boiling temperature of the moisture within the product. The developed models for the kinetics of quality attributes during vacuum frying can be used to optimize the process conditions to obtain higher quality products in an efficient way. The models can be used to produce a minimal fat content and low moisture content while maintain color; also can be used to produce a specific texture quality while maintain color.

Sensory analysis, Hunterlab, IRIS-Alphasoft and Canon-CVS color analysis methods have compared in **Chapter 5**. Sensory testing with panelists is a relatively easy method which can be used if always the same product type is considered like it happens in many food factories. Although the sensory color distribution analysis is able to describe color heterogeneity, the subjectivity of the panelist limits the accuracy and the discrimination ability of the measurement. Hunterlab is found to be an easy, handy and accurate method to measure homogeneous samples; the analysis has a high differentiation ability, but the color distribution information was lost. IRIS-Alphasoft is a quick and easy method to perform a color distribution analysis, it is completely automatized and easy to use for untrained operators, however the closed system limits the analysis. The Canon-CVS system and protocol was able to assess sample color heterogeneity as well as to discriminate between the samples; furthermore the method was flexible and economical, which enables the user to customize the protocol based on the sample and the objective of the analysis but it requires trained operators especially for the data analysis. As a take home massage, color distribution analysis has a potential to unlock the limitation of traditional color analysis to give more color information of the sample which is important in product quality analysis.

4. Conclusions

The overall objective of the thesis was to investigate the quality of vacuum fried products of selected tropical fruits and how this quality is affected by the process conditions, the fruit type, the ripening stage and the structural properties of the matrix.

The attributes most improved by the vacuum frying process compared to frying at atmospheric pressure are the retention of bioactive compounds and improvements in color formation. These two quality attributes are greatly improved due to the lower temperature at reduced frying pressure. The fat content of vacuum fried fruit was increased at low amount.

Improvement of the vacuum frying technology is an important aspect to consider. Optimization of dynamic pressure during vacuum frying could improve energy efficiency.

The maturity stage of the fruit is an important characteristic to consider when selecting fruit for frying or other processing due to the effect of structural and chemical changes on the final quality attributes.

Moisture plays the most decisive role during vacuum frying, first since it determines the dynamic product temperature during the process which affects the reaction rates of the color formation reactions as well as degradation rates of bioactive compounds. Therefore, it has a large influence on texture, fat content, color and the retention of bioactive compounds.

Color is an important characteristic determining product perception by consumers. It is traditionally described using average color analysis. More advanced color analysis can be applied to describe the color distribution in products. Color distribution analysis is much closer related to the actual human perception of product surfaces.

Considering low fat content and combined with high bioactive compound preserved and crispy texture produce by vacuum frying processing, vacuum fried fruit overall is a healthy snacking option, which cannot be replicated by other fruit processing techniques. However, the implementation of vacuum frying technology also come at a higher cost compared to atmospheric frying.

Overall, knowledge gained by the research described in this thesis can be used to optimize the process to improve processed fruit quality. Some knowledge gaps that were identified in this thesis that need to be addressed in the future including the application of dynamic pressure to improve product quality and at the same time improve energy efficiency. The application of a higher vacuum also needs to be addressed as the benefit of improving texture and consumer acceptance.

Furthermore, the importance of moisture content could be applied to other processing methods which utilizing moisture removal at elevated temperatures such as drying. The advanced color distribution analysis also could play an important role in heterogenous food color analysis produced by various processing techniques such as baking.

Vacuum frying is popular in Indonesia, for example vacuum fried jackfruit, mango, banana, apple, pineapple, starfruit, snake fruit, and rambutan. Most of vacuum fried fruit in Indonesia was sold by street vendors. The finding of this thesis has some important societal relevance including how to choose the best frying setting and fruit ripening stage to improve the quality of the street-vended products. This street vendors will benefit from the higher margin of the higher vacuum fried fruit quality.

CURRICULUM VITAE

Fitriyono Ayustaningwarno was born on October 1st 1984 in Semarang, Indonesia. After graduation from high school (SMA Kolese Loyola, Semarang) in 2002, he started his bachelor Food Technology at the Soegijapranata Catholic University, Semarang. His bachelor study was completed with a thesis on Effectiveness level of lactoperoxidase system (LPS) in enhancing storage duration of fresh milk. In 2005, he continued with the master Food Science at Bogor Agricultural University. His master study was completed in 2008 with a thesis on Kinetic of oxidation stability parameter of red palm oil. in 2015 he started his PhD research in the Food Quality and Design under supervision of Dr. Ruud Verkerk, Dr. ir. Matthijs Dekker, and Prof. Dr Vincenzo Fogliano. The result of his PhD research are presented in this thesis. Since 2010 he working as lecturer at Nutrition Science Department, Diponegoro University, Indonesia.

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LIST OF PUBLICATIONS

Ayustaningwarno, F., Dekker, M., Fogliano, V., & Verkerk, R. (2018). Effect of Vacuum Frying on Quality Attributes of Fruits. *Food Engineering Reviews*, 10(3), 154–164.

Ayustaningwarno, F., Vitorino, J., Ginkel, E. V., Dekker, M., Fogliano, V. & Verkerk, R. 2020. Nutritional and Physicochemical Quality of Vacuum-Fried Mango Chips Is Affected by Ripening Stage, Frying Temperature, and Time. *Frontiers in Nutrition*, 7(95).

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OVERVIEW OF COMPLETED TRAINING ACTIVITIES

Discipline specific activities

Courses	
Visit to CAT-AgroFood	2016
Sensory perception and food preference	2016
Reaction Kinetics in Food Science	2016
Exposure Assessment in Nutrition Research (1st ed)	2016
Microscopy and Spectroscopy in Food and Plant Sciences	2017
Healthy Food Design	2018
Conferences	
GOH Symposium "Sustainable Food Systems for Healthy People"	2016
Wageningen Indonesia Scientific Expose Symposium [a]	2016
Wageningen Indonesia Scientific Exposure (WISE) [a]	2017
EFFoST International Conference [a]	2017
VLAG Symposium "PUFA –MICROBIOTA–IMMUNE HEALTH"	2017
Thermodynamics and Phase Transitions in Food Processing	2018
Symposium "Edible Insects: The Value Chain"	2018
General courses	
Data Management	2015
Entrepreneurship in and outside Science	2015
Reviewing a Scientific Paper	2016
Applied Statistics for VLAG PhDs	2016
Multivariate analysis for food data/sciences	2016
Techniques for Writing and Presenting a Scientific Paper	2016
Introduction to R for Statistical Analysis	2017
Project & Time Management	2017
Scientific Writing	2017
Masterclass Git, GitHub and Markdown in a R-environment	2018
Philosophy and Ethics of Food Science and Technology	2018
Chemometric	2018
Last Stretch	2018
WIAS: The Final Touch: Writing the General Introduction & Discussion	2019

Optional courses and activities

Preparation of research proposal [b]	2015
PhD study tour to Italy [b,c]	2016
PhD study tour to Australia [a,b]	2018

a Poster presentation

b Oral presentation

c Organizing committe

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