NON-DESTRUCTIVE PREDICTION OF QUALITY OF DEHYDRATED PRODUCTS USING NEAR INFRARED HYPERSPECTRAL IMAGING

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ABSTRACT

The quality of any food product processed from fruit and vegetables can vary depending mainly on raw material quality and processing. Near infrared hyperspectral imaging (NIR-HSI) is a reliable and effective online monitoring method of food products and was therefore tested on dehydrated ginger, mango and pineapple. The quality parameters assessed were hardness, total soluble solids (TSS), sulfur dioxide (SO_2) content, water activity (a_w) and moisture content (MC). The models for hardness, TSS, SO_2 content, a_w and MC were established using partial least squares regression (PLSR). Spectral pretreatments were tested in order to get better precision of the models. For dehydrated ginger, smoothing pretreatment was used to create a calibration model of hardness, a_w and MC and original spectra for TSS and SO_2. For dehydrated mango, original spectra was used to create calibration model of hardness and SO_2 content, meanwhile TSS, a_w and MC using smoothing pretreatment. For dehydrated pineapple, original spectra was used to create calibration model of hardness, SO_2 content and a_w, meanwhile TSS and MC using smoothing pretreatment. For the accuracy of the prediction models of dehydrated ginger for hardness, TSS, a_w and MC was achieved correlation coefficient of prediction (R_p) of 0.80, 0.77, 0.78 and 0.71 respectively and root mean square error of prediction (RMSEP) of 3.19 N, 2.72%, 0.007 and 0.77% respectively. The R_p achieved for hardness, TSS, SO_2 content, a_w and MC dehydrated mango were 0.80, 0.86, 0,82, 0.86 and 0.81 respectively and RMSEP were 3.08 N, 2.18%, 58.57 mg/kg, 0.007 and 0.66% respectively. Dehydrated pineapple achieved R_p of 0.77, 0.80, 0.78, 0.74 and 0.77 respectively and RMSEP of 1.05 N, 1,89%, 24.29 mg/kg, 0.0051 and 0.87%

respectively. Results showed that NIR-HSI has the possibility for determining hardness, TSS, a_w and MC of dehydrated ginger, mango and pineapple. Also, SO_2 dehydrated mango and pineapple non-destructively and could be used as part of the production process for online grading in dehydration.

Keywords: hyperspectral imaging, near infrared, quality, spectra, partial least square regression

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CHAPTER 1

INTRODUCTION

Fruit is a good source of vitamins, minerals, and fiber. Agricultural products such as fruits are essential in Thailand for both domestic consumption and export. As the fruit has a moisture level of greater than 80%, it is considered a perishable commodity. World perishable commodities are more than 20%. Drying such fruits would increase shelf-life and promote food security (Yildiz & İzli, 2019). Fruits are generally consumed, but because they are seasonal and perishable, they are processed into commodities with a longer shelf life, such as juice, fruit beverage, wine, jam, marmalade, jelly, frozen and dehydrated fruits, and so on (Megías-Pérez *et al.*, 2014).

Thailand is famous as a producer of tropical fruits. Condition of weather and land support for the cultivation of various kinds of tropical and subtropical fruits. Thailand is also famous as an exporter of tropical fruits in Asia. Tropical fruits exported are guava, mango, lychee, coconut, rambutan, orange, banana, and mangosteen. Thailand also had exported 11 fruit such as pineapple, orange, apple, grape, durian, tamarind, mangosteen, longan, lychee, and rambutan to the international market in 2012-2016 (DOAE, 2017). Pineapple has gained much attention because of its potential uses as a functional food and various pineapple-based products. Based on the physicochemical composition and nutritional values, pineapple can be considered one of the most valuable fruits for value-added manufacturing compounds such as antioxidants, organic acids, bromelain, and phenolic compounds (Mohd Ali *et al.*, 2020). Barretto *et al.* (2013) extracted volatile compounds from the pineapple flesh to be utilized as aroma-enhancing products and the production of natural essences. Pineapple is also processed into pineapple-based products as canned pineapple slices, chunk and dice, pineapple juice, fruit salads, sugar syrup, alcohol, citric acid, pineapple chips, dehydrated pineapple and pineapple puree (Chaudhary *et al.*, 2019). Mango is one of the major tropical fruits processed commercially to improve the quality and utilization of mango as an essential food resource. The commonly processed mango products are puree/pulp, nectar, juice, juice concentrate, and dried/dehydrated mangoes (Siddiq *et al.*, 2012). Thailand produces herbs and spices besides fruits and vegetables. Thailand produces ginger, which is also one of the world's most famous and essential spices. Ginger is mainly marketed raw, but there are also various ginger products for the global market, such as dried ginger, ginger powder, ginger oil, oleoresin, and novel preservation, dehydrated ginger (Choenkwan, 2017).

Fruit should be dried to preserve its shelf life, reduce packing needs, and reduce transport weight. Minimizing packaging and reducing transport weight may increase the possibility of adding value to the agricultural products and maximize the potential for export (Guiné, 2018). Some methods can do drying of fruit. Fruit drying methods consist of sun drying, solar drying, tunnel dryer, cabinet dryer, fluidized bed dryer (FBD), microwave drying, infrared drying (Nunes *et al.*, 2015). The issue in drying fruits is to keep the moisture content low enough to prevent microbial development while preserving high nutritional value. The drying process may influence the flavor, texture, color and nutritional content of the products. As a result, enhancements such as the addition of food additives may be possible.

The quality changes of the product during drying likely affect the consumer's acceptance. Therefore, a quality assessment is needed before distributing the product to the market. The most critical parameters of drying are a_w and MC. The drying process is designed to lowering and reach the ideal a_w and MC that prevent microbial spoilage and extend the shelf life of the products (Ahmed *et al.*, 2016; Ashebir *et al.*, 2009; Belessiotis & Delyannis, 2011). However, during the drying process, water loss occurred related to its hardness, which is one of the critical physical attributes of dehydrated fruit's texture. Higher water evaporation will produce a drier sample that has higher hardness. TSS, which is related to the flavor of the dehydrated fruits, is also important to be measured. TSS content and sweetness have a strong relationship. During the drying, the color of dehydrated fruit is affected, so the usage of SO_2 is considered. However, SO_2 has some health issues, so the usage is needed to be regulated.

Analyzing the critical qualities of dehydrated fruits takes so much time and requires laboratory workers in dehydrated fruits companies. Besides, it is a destructive analysis and produces waste, especially chemical waste. NIR-HSI appeared as an advanced technology that has been considered one of the most promising methods of quality assessment nondestructively that is fast and can reduce chemical waste (Senthilkumar *et al.*, 2016). NIR-HSI combines spectroscopy (NIR) and imaging (HSI) that provide spectral and spatial information. The sample could be scanned entirely using NIR-HSI that may be able to separate different samples or detect various content in the heterogenous sample such as impurities and contaminants (Elmasry *et al.*, 2012). Therefore, the main objective of this study was to create the prediction models for hardness, TSS, SO_2 content, a_w and MC as quality evaluation of dehydrated fruits nondestructively using NIR-HSI. This method is expected to be a practical assessment qualities method in dehydrated fruits companies, reducing time, human labor, and wastes.

1.1. Objectives

The objective of this research is to establish the models for predicting qualities of dehydrated pineapple, mango, and ginger by their characteristics (hardness, TSS, SO_2 content, a_w and MC) using NIR-HSI.

1.2. Scopes of the research

This research will focus on the prediction of dehydrated product quality properties, including hardness, TSS, SO_2 content, a_w and MC. Those qualities will be analyzed using NIR-HSI to determine the prediction equations. The predictions of dehydrated product quality properties will help the company to determine the right processing then uniform products could be produced.

CHAPTER 2

LITERATURE REVIEW

2.1. Ginger

The rhizome of ginger (*Zingiber officinale*) is a strong spice from the *Zingiberaceae* family that is often used as a spice in foods and drinks due to its pungency and peppery flavor (Dash *et al.*, 2019). There are two kinds of fresh ginger: volatiles and non-volatiles. Ginger has a unique scent and flavor due to volatiles such as sesquiterpene and monoterpenoid hydrocarbons. Gingerols, shogaols, paradols, and zingerone are examples of non-volatile pungent chemicals. Gingerols are the primary elements of fresh ginger. They are significantly decreased in dry ginger, but shogaols, which are the primary dehydration products of gingerols, are more prevalent in dry ginger than fresh ginger. The most crucial part of ginger is the rhizome. Fresh, dried, pickled, preserved, crystallized, candied, and powdered or ground ginger are just some ways it is utilized. Ginger in food and beverages is used as sugar candy, carbonated drinks, food seasoning, and ginger wine (Srinivasan, 2017). Besides as spices in foods, ginger is also used for medical purposes, including treating nausea, lose appetite, vomiting, indigestion, and as antioxidant and anti-inflammatory (Mashhadi *et al.*, 2013)

Ginger is one important agricultural product that is consumed worldwide. The selling of ginger is expected to increase until 2020, with a total export value of $629.68M in 2018. The top exporter of ginger globally is China, with a total export value of $262.56M, following Thailand with a total export value of $95.80M in 2018. Thailand is known as the top three exporters of non-crushed and non-grounded ginger. Thailand keeps growing as an exporter of ginger. The export value of Thailand increased 112.8% in 2017 – 2018. That percentage shows exported ginger in Thailand increased significantly and ginger becomes an important agriculture product. The top importer of ginger is the United States following by countries in European Union. Those countries need ginger as a food seasoning and herbal medicine. The demand for ginger peaked in the winter season 2016 – 2017 in European Union. The people there use ginger for health issues during the winter, such as a sore throat remedy (CBI, 2018; Tridge, 2019; Workman, 2019).

Figure 2.1 Fresh ginger in the market.

2.2. Mango

Mango (*Mangifera indica* L.) is included in tropical and seasonal fruits in Southeast Asia. Mango was the most popular tropical fruit variety based on the production volume. In 2017, mango production accounted for more than half of all significant tropical fruit production globally (Altendrof, 2019). Thailand is one major mango producer in Southeast Asia, with 336,000 hectares of harvested land and a total production of 3.1 million tons in 2015 (DOAE, 2017). Thailand is the third biggest exporter of mango after India and China. There are over 100 mango varieties in Thailand, but not all the mango can be sold and liked by consumers. Mango products in Thailand are exported beside consumed inside the country. Export volume and export value for fresh mango in 2012 – 2016 can be seen in Table 2.1.

Table 2.1 Export volume and export value for fresh mango in 2012 – 2016.

Year	Export volume (tons)	Export value (million USD)
2012	44,499,73	28,22
2013	33,035,21	25.77
2014	45,544.16	38.19
2015	33,902.66	36.57
2016	33,346.99	36.93

Source: Win (2017)

Different colors (green, yellow, colored), sizes, appearances, and tastes are available in mango variants on the market. There are about 500 varieties in the ASEAN area, but only a few are grown commercially (Yahia, 2011). Mango is known as the "King of Fruits" because of its great flavor, sweet taste, and excellent nutritional content (Ullah *et al.*, 2010). These factors contribute to the mango crop's importance as a source of food and nutrients. It has a powerful aroma, an intense peel color, a great flavor, and a high nutritional value. Mango is high in vitamin C, antioxidants, carotenoids, minerals, phenolic compounds, dietary fiber, carbs, and many other nutrients (Chilakala *et al.*, 2021). The complete composition of the edible portion of mango fruit can be seen in Table 2.2.

Figure 2.2 Varieties of mangoes in the market.

Table 2.2 Content of nutrients, vitamins, minerals, and carotenoids in *Mangifera indica*

Mangifera indica* L** ***Nutrition value per 100 g	
Energy	60 Kcal
Fruit composition	**Quantity**
Carbohydrates	14.98 g
Protein	0.82 g
Fat	0.38 g
Fiber	1.6 g
Vitamins	
Vitamin C	36.4 mg
Vitamin B	1.12 mg
Vitamin A	1082 IU
Minerals	
Potassium	168 mg
Phosphorus	14 mg
Calcium	11 mg
Magnesium	10 mg
Sodium	1 mg
Carotenoids	
β-Carotene	446 µg
α-Carotene	17 µg

Source: USDA (2018)

2.3. Pineapple

The pineapple (*Ananas comosus*) is one of the most popular tropical fruit shipped worldwide. Pineapple is commonly consumed as fresh fruit, but it can also be processed and cooked. Vitamin A, vitamin B, vitamin C, magnesium, calcium, potassium, citric acid, thiamin, copper, riboflavin, pyridoxine, copper, and ferulic acid are among the vitamins and minerals found in pineapple (Farid Hossain, 2015). Pineapple ranked second of importance tropical fruit in world production. The leading producer of pineapple is Costa Rica, followed by China, India, and Thailand. Thailand is the number one exporter and producer of processed pineapple worldwide (Altendrof, 2019). Pineapple production in the world in 2012 - 2016 can be seen in Table 2.3.

Table 2.3 Pineapple production in the world in 2012 – 2016.

Pineapple production					
	2012	2013	2014	2015	2016 *estim.*
(thousand tonnes)					
World total	24,082	24,527	25,439	25,928	25,740
Asia	10,973	10,928	11,165	11,399	10,944
India	1,500	1,571	1,737	1,984	1,964
China	1,679	1,800	1,889	1,989	1,993
Thailand	2,400	2,068	1,915	1,734	1,681
Indonesia	1,782	1,883	1,835	1,730	1,396

Source: Altendorf (2017)

Thailand has 27 varieties of pineapple. The most popular one is the *Pattavia* variety. *Pattavia* is famous because it is quickly grown in many areas in Thailand. The flavor of Pattavia is mixed between sweet and sour. Pattavia is classified into two grades in Thailand market, which are *Keaw* 1 and *Keaw* 2. Those grades have distinct preferences. *Keaw 1* has a highly juicy and sweet flavor with slight acidity, but *Keaw 2* has a less juicy and sweet flavor with a bit of acidity. For most Thai people, *Keaw 1* is the preferred option (Dittakan *et al.*, 2018).

Figure 2.3 Varieties of pineapples in the market.

2.4.Dehydrated products

Fresh agricultural products such as fruit, vegetables, and spice are mostly preferred because of their nutrients, health benefits and natural flavor. However, perishable products which have a short life because of their high water content can cause them prone to microbial spoilage, chemical and enzymatic reactions. This seems to be a challenge to the food industry to preserve perishable products. Drying is one of the most popular preservation methods, which extend the shelf life, improve storage and distribution handling by reducing the costly cooling system requirements (Li *et al.*, 2020; Yu *et al.*, 2020). Nonetheless, drying can affect its qualities compared to the fresh one. The heat from drying causes nutrients degradation, shrinkage and discoloration (Zhang *et al.*, 2015). Therefore, the quality properties of dehydrated products are important to be monitored, such as hardness, TSS, SO_2 content, a_w and MC.

There are various types of dehydration in food processing that produce different characteristics of the products. Drying primarily utilizes heat to vaporize the moisture in the food (Cruz *et al.*, 2015). Solar drying is a very cheap drying method but produces bad product quality due to exposure to the environment causing food spoilage before the targeted moisture content is achieved (Guiné, 2010). Drying using a hot air oven is considered one important food preservation by drying the product in chamber with trays or moving belts inside the tunnels. However, convective drying, which is considered can be damaging the quality of products. Microwave drying, which combines convective and microwave radiation, is considered due to its time efficiency, low energy usage, and excellent product quality. This approach is an efficient way to postharvest agricultural products' processing (Pu *et al.*, 2016). Elimination of water from food products without using heat has been done by freeze-drying. Under specific pressure and temperature parameters, the water is first frozen and subsequently sublimated. This method produces high-quality products, but it is slower and more expensive than other methods (Wang *et al*., 2016). One of the most efficient dehydration methods for the perishable product such as fruit and vegetable is osmotic dehydration. Osmotic dehydration works as a pretreatment process before continuing to the drying process. Some solutions immersed in the food, which is a different kind of sugar, are one of the most popular ways for pretreatment in the food industry. It also provokes the water to come out from the food membrane and total soluble solids interchange (Nahimana *et al*., 2011). Solutions that can be used as osmotic agents such as sugar solution primarily as sucrose but fructose, glucose and its mixtures are also possible to be used in fruit products; meanwhile, salt solutions such as sodium chloride are mainly used for vegetable products (Barman & Badwaik, 2017).

Osmotic dehydration also is known as partially removing water. Fruit and vegetable have semi-permeable cell membranes and permits water to flow through them faster than sugar does. During the osmosis process, a tiny amount of fruit acid is extracted with water. This process is dynamic so that the water and acid are removed slowly while sugar penetration is increasing along the processing time. The amount of sugar content increased in final products and it affects the sensory quality. The osmotic dehydration process produces sweeter and fewer water products. The process has many benefits, such as production safe, low energy consumption, and reduction of drying temperature and time (Sagar & Kumar, 2010). The research results of (Sagar & Suresh Kumar, 2005) found that guava slice has higher sugar concentration (60 %) and temperature (60 °C) increased the water loss from the produce and solid gain into the osmosed guava slices with osmotic dehydration.

Figure 2.4 Commercial dehydrated products.

2.5. Quality properties

Food quality provides a variety of quantitative attributes, including color, moisture content, texture, and more elusive aspects like aroma and flavor (Gowen, 2012). Food quality determines the acceptance of the products by consumers. Consumer preference is different from one and another. Codex made regulations for food quality to meets consumer preferences also safe for them. Each food industry also has its regulation to make uniform products and their uniqueness. Variance from the specified standard can have a negative influence on the physical characteristics of food. For example, too dry components may impact the final product's uniformity (Appoldt & Raihani, 2017). For dehydrated fruits, the main quality properties are hardness due to shrinkage in the drying process. TSS shows sugar amount in the dehydrated fruits, SO2 content, which is the prevention of discoloration, a_w and MC as the parameters of the success drying process, which also as shelf-life parameters.

2.5.1. Hardness

Texture, described as the sensory expression of food structure and how this structure reacts to applied forces, is the intersection of all a product's mechanical, geometric, and surface qualities, as felt by mechanical, tactile, visual, and auditory receptors. Furthermore, when a force is applied to the product, texture can be linked to deformation, disintegration, and flow (Paula & Conti-Silva, 2014). Hardness is one of the textural attributes that affect the consumer acceptance of products. Besides affecting the mouthfeel of the products, texture also affects the release of the flavor profile and other properties that create the sensory experience as a whole (Seisun & Zalesny, 2021). The hardness transformation is related to the drying process, which lowered the moisture content and changes the physical and structural of the product (Marzec *et al.*, 2010).

2.5.2. TSS

TSS is correlated with the flavor of a dehydrated product and is commonly determined for quality evaluation. TSS is highly correlated with sweetness and sourness, which is important as sensory acceptance of consumers (Ashebir *et al.*, 2009). The drying of fruits affects the total soluble solids content. Workneh *et al.* (2014) reported that TSS of dried pumpkin dried by sun-drying has lower TSS content than oven drying. Sun-drying has longer intact with the sample and causing losses of some volatile oils, esters and readily oxidizable substances like ascorbic acid. Therefore, it is crucial to monitor thermophysical properties for choosing the drying method such as heat transfer, thermal conductivity and glass transition temperature (Gundurao *et al.*, 2011).

2.5.3. SO_2 content

SO_2 is one chemical used for fruit and vegetable preservation. SO_2 acts as anti-browning agents for both in drying process or the storage. Besides that, the advantages of SO_2 are: an antioxidant preventing oxidative degradations, an inhibitor of some enzymes such as oxidases, proteases, and peroxidases, an antimicrobial agent preventing the growth of especially yeasts and molds, and plasmolyzing cells, which facilitates drying (Türkyılmaz *et al.*, 2013). The most popular way to use SO_2 is as pretreatment, which can prevent the product's discoloration during drying by fumigation. Another way is by added by some salt. The taste of dehydrated fruit will be affected if the residue of SO_2 is high (Hassan, 1977). However, the use of SO_2 is regulated by Codex because it can be causing allergy, and sulfite can be causing asthmatic reactions in sensitive individuals (Vally & Misso, 2012). The maximum amount of SO_2 based on Codex in dried apricots is 2000 mg/kg (Codex, 1981).

2.5.4. a_w

The a_w in fresh products for example meats, seafood, most dairy products, fruit, and, vegetable have water activity close to 1, which is the maximum water activity in foods meanwhile a_w in dehydrated foodstuffs indicates the amount of water accessible for microbiological spoilage and water-mediated loss of physicochemical quality during storage. It is commonly employed as a critical measure to assess dehydrated foodstuffs' stability and shelf life (Feng *et al.*, 2021). The a_w relates to moisture content, so sometimes it is hard to differentiate which one is affecting the characteristics of food, such as microbial growth. The microbe grows in food material is caused by the free water on the surface of the food material. It also corresponds to a statement by W.J. Scott in 1952, who introduced the concept of water activity. The concept says that it was not moisture content related to microbe growth rate but water activity.

2.5.5. Moisture content

Water is one of the main contents in agricultural products, which is high perishable products. Water or moisture content in fresh fruit and vegetable can contain up to 95% of water. Concentrated and sweetened products have the water content lowered. The texture, weight, flavor, appearance, and shelf life of foodstuffs are affected by moisture content. Free, absorbed and bonded water are the three types of water found in food. Food pores and intergranular gaps both contain free water. The absorbed water is water accumulated on the surface of macromolecules (starches, pectin, cellulose, and proteins), resulting in colloidal systems. Hydrogen bonding and van der Waals forces are responsible for this absorption. The chemical and spatial qualities of the materials surrounding by water determine the properties of bound water. Water attached to the surfaces of food components at hydrophilic/hydrophobic interactions can be classified as weakly or tightly bound (Coultate, 2009; Kasaai, 2014). Due to the attempts to quantify the quantities of total forms of water in ineffective foods, the moisture content is commonly determined by measuring the quantity of free water. As a result of the drying process, not all kinds of water in foodstuffs evaporate, leaving largely bonded water in the food structure (Garrido *et al.*, 2015).

2.6. Near infrared hyperspectral imaging

Nondestructive is qualities checking method in agricultural products. The benefit of the nondestructive method is that we could know the quality without cutting or destroying the products. NIRS is one of the most popular instruments used in the nondestructive method in agricultural products. NIRS has been used to evaluate quality traits of purple passion fruit (Maniwara *et al.*, 2019), intact mango fruit dry matter content (Sun *et al.*, 2020), apple fruit quality (Pissard *et al.*, 2021), flesh firmness measurement of peach fruit (Uwadaira *et al.*, 2018) and detection of fungal infections on citrus fruit (Lorente *et al.*, 2015). However, there is more advanced technology about NIR. NIR can collaborate with HSI. HSI shows the spectral information of the scanned image at each pixel. This information is something that neither conventional imaging nor spectral spectroscopy can do separately. NIR-HSI is frequently utilized in agriculture, military reconnaissance, geological research, weather prediction, and other applications (Chen *et al.*, 2018). In the agricultural and food process field, NIR-HSI has been used in cherry fruit (Li *et al.*, 2018), cakes (Sricharoonratana *et al.*, 2021), tapioca starch (Khamsopha *et al.*, 2021), limes (Teerachaichayut & Ho, 2017) and hens' eggs (Suktanarak & Teerachaichayut, 2017). It indicates that the application of NIR-HSI is an interesting topic for monitoring and evaluating the quality of various kinds of fresh or processed food products.

2.6.1 Data acquisitions

Whisk-broom imaging, push-broom imaging, and area scanning are three standard techniques to create a hyperspectral picture. Line scanning is particularly well suited to conveyor belt systems widely used in food processing lines for food quality monitoring and safety inspection since it employs continuous scanning in one direction (Leiva-

Valenzuela *et al.*, 2013). The generated hyperspectral picture of a food sample is a stack of sub-images of the sample taken at discrete, contiguous, spectral narrow bands, allowing for the acquisition of a complete reflectance spectrum for any part of the sample being imaged (Nakauchi *et al.*, 2012). Regardless of the acquisition method, the hyperspectral imaging system's output is a three-dimensional (3-D) form (spatial-spatial-spectral) known as a spectral cube, data cube, spectral volume, or simply hypercube. Two additional pictures were used to fix a hypercube image with dimensions of x, y and λ consisting of two spatial dimensions (x, y) and one spectral dimension (λ). With the assistance of white and dark hyperspectral pictures, the acquired image should be adjusted in the spatial and spectral domains. An internal white reference was used to generate the white picture. When the light source was switched off and the camera lens was covered entirely with a non-reflective opaque black cap, the dark image was captured. This adjustment was made to minimize the effect of lighting, detector sensitivity, and geometry (ElMasry *et al.*, 2013).

2.6.2 Data analysis

The scanning results from the NIR-HSI system included both the sample and background spectra. The background data was eliminated using principal component analysis (PCA), leaving only the region of interest (ROI) (Barbin *et al.*, 2012). Due to data resulted from NIR-HSI is contain both spectral and spatial data, it provides more redundant data and increasing the calculation's complexity. As a result, NIR-HSI has focused on decreasing spectral-domain redundancy and identifying representative spectral-spatial characteristics (Bioucas-Dias *et al.*, 2013). Chemometrics is a technique for breaking down data complexity, which involves statistical and mathematical techniques (Alamar *et al.*, 2016).

In most cases, the collected spectrum data contains noise and variability. Dealing with variability is one of the most challenging in handling hyperspectral imaging data, both conceptually and practically. Therefore, spectral pretreatment could reduce noise, improve the resolution of overlapping data, and minimize contributions from imaging instrument responses that are not correlated to variations in the imaged sample's characteristics (Vidal & Amigo, 2012). Smoothing (Savitzky-Golay), first derivative differentiation, second derivative differentiation, multiplicative scatter correction (MSC) and standard normal variate transformation (SNV) are examples of spectral pretreatments.

2.6.3 Data modeling

The framework's mathematics module is typically used to create data analysis algorithms and manipulate multivariate statistical procedures to manage complex data. The module's essential ability depends on the use of chemometrics to create reliable calibration models. Depending on the study's objectives, the sample type and the required accuracy, various kinds of acceptable multivariate chemometric schemes are available to develop calibration models that correlate spectral data (X-matrix) with quantitative data (Y-matrix) (M. ElMasry & Nakauchi, 2016). Particularly, PLSR is commonly used for establishing spectral data models. It can resolve the problem of variable multiplicity correlation and dimension reduction (Wang *et al.*, 2021). After spectral pretreatments, the best models were investigated by considering the lowest root mean square error of cross-validation (RMSECV) and the highest correlation coefficient of cross-validation (R_{cv}). The performance of the acquired models was tested with samples in the calibration set by considering the correlation coefficient of calibration (R_c) and the root mean square error of calibration (RMSEC). Their accuracy was tested with samples in the prediction set by samples considering R_p and RMSEP.

CHAPTER 3

Development of NIR-HSI and PLSR for Predicting Quality of Dehydrated Ginger, Mango and Pineapple

3.1 Abstract

The quality of any food product processed from fruit and vegetables can vary depending mainly on raw material quality and processing. NIR-HSI is a reliable and effective online monitoring method of food products and was therefore tested on dehydrated ginger, mango and pineapple. The quality parameters assessed were hardness, TSS, SO_2 content, a_w and MC. The models for hardness, TSS, SO_2 content, a_w and MC were established using PLSR. Spectral pretreatments were tested in order to get better precision of the models. For dehydrated ginger, smoothing pretreatment was used to create the calibration model of hardness, a_w and MC and original spectra for TSS and SO_2. For dehydrated mango, original spectra were used to create a calibration model of hardness and SO2 content, while TSS, a_w and MC using smoothing pretreatment. For dehydrated pineapple, original spectra were used to create a calibration model of hardness, SO2 content, and aw while TSS and MC used smoothing pretreatment. For the accuracy of the prediction models of dehydrated ginger for hardness, TSS, a_w and MC were achieved R_p of 0.80, 0.77, 0.78 and 0.71 respectively and RMSEP of 3.19 N, 2.72%, 0.007 and 0.77%, respectively. The R_p achieved for dehydrated mango hardness, TSS, SO_2 content, a_w and MC were 0.80, 0.86, 0,82, 0.86 and 0.81 respectively and RMSEP were 3.08 N, 2.18%, 58.57 mg/kg, 0.007 and 0.66% respectively. Dehydrated pineapple achieved R_p of 0.77, 0.80, 0.78, 0.74 and 0.77 respectively and RMSEP of 1.05 N, 1,89%, 24.29 mg/kg, 0.0051 and 0.87% respectively. Results showed that NIR-HSI has the possibility for determining hardness, TSS, a_w and MC of dehydrated ginger, mango and pineapple, also SO_2 of dehydrated mango and pineapple non-destructively and could possibly be used as part of the production process for online grading in dehydration.

3.2 Introduction

Ginger (*Zingiber officinale*) is a native of Asia where has been grown since ancient times and from where it has been exported to Europe in its dried form for centuries. *Z. officinale* is a perennial herb with a fleshy rhizome that is used as a spice, as a preserve and has medicinal properties. It is sold fresh, but also as preserved ginger, crystallized ginger and dried ginger. Ginger has many uses as a flavoring and traditional medicine because of its volatile and non-volatile compounds, including gingerols, shogaols and zingerone (Kiyama, 2020; Ren *et al.*, 2021). FAO estimated the total world production of ginger in 2019 as 4,081,374 tonnes. The major producers are India, Nigeria, China, Nepal, Indonesia and Thailand (FAO, 2019). Fresh ginger contains some 85-95% water and when dried ginger is produced, the process can affect its quality, including taste, texture, color, nutrient content and consumers acceptability (Lin *et al.*, 2020; Osae *et al.*, 2019).

Mango (*Mangifera indica* L.) is a tropical fruit that originated from Southeast Asia. Nowadays, mango is mainly produced by countries in the Indo-Burmese region, including India, Thailand, and Indonesia, because of cultivation development. Mango grows seasonally and is consumed a lot worldwide (Tiyayon & Paull, 2017). Mango is one of the essential fruits as seen based on its production value. The mango production value in 2017 was reported as more than half of total global major tropical fruit production (Altendorf, 2017). The producer of mango is mainly a developing country and still lacks on processing mango. Therefore, mango processing is needed to extend the shelf life of fresh mango. The mango is commonly processed into puree/pulp, nectar, juice, juice concentrate, and dehydrated mango (Evans *et al.*, 2017). These ways can also add value to the fresh mango, not only extending its shelf life.

The demand for pineapple (*Ananas comosus*) keeps increasing as it was ranked third in the production value of tropical fruit, following banana and citrus. Pineapple is classified as tropical fruit mostly planted in South America (Mohd Ali *et al.*, 2020). As of 2019, Costa Rica produced the most pineapple worldwide (3328.1 metric tons), followed by the Philippines (2746.86 metric tons), Brazil (2426.23 metric tons), Indonesia (2196.46 metric tons), the mainland of China (1727.61 metric tons), India (1711 metric tons) and Thailand (1679.67 metric tons) (Statistia, 2019). Pineapple is considered a seasonal fruit, highly perishable, and grown in limited places; therefore, preservation is essential to store it throughout the year and distribute it to more comprehensive places (Tunckal *et al.*, 2018). Pineapples are mainly processed into canned, frozen, juice and dehydrated pineapple to fulfill the longstanding demand.

TSS is highly correlated with sweetness and sourness, which is important as sensory acceptance of consumers (Ashebir *et al.*, 2009). Yi *et al.* (2016) reported that the change of pectin structure is associated with physicochemical and physical characteristics, for example, texture during drying processing, primarily because of heat treatment. The discoloration during drying could be prevented by pretreatment using SO_2, as Sen et al.

(2015) reported. SO_2 pretreatment also inhibits the growth of mold and yeast, as well as insect damage. The drying process of ginger is targeted to achieve moisture content around 15% and a_w around 0.6 (Lad *et al.*, 2019).

In a factory that produces dried fruit, the fresh fruit the provides the raw material can vary day-to-day. Therefore, the constant quality analysis is required. Traditionally quality analysis is on a sample basis of each batch, but this method is disruptive, time-consuming, labor-intensive and may require specific materials or chemicals. Therefore, a rapid and nondestructive method, analyses all the throughput can be more cost-effective and maintain high and consistent standards (Magwaza *et al.*, 2012; Nicolai *et al.*, 2007).

Of possible analytical methods that could meet these criteria, near infrared hyperspectral imaging (NIR-HSI) was selected. It is nondestructive and non-contact and allows collections of spatial and spectral data to predict product quality. NIR-HSI has previously been applied for quality analysis of cakes (Sricharoonratana *et al.*, 2021), tapioca starch (Khamsopha *et al.*, 2021), eggs (Suktanarak & Teerachaichayut, 2017), limes (Teerachaichayut & Ho, 2017), beef jerky (Achata *et al.*, 2021), jujubes (Su *et al.*, 2017) and cucumbers (Xu *et al.*, 2019). The optimum method is to analyze the information produced by the NIR-HSI instrument using a chemometrics method such as partial least square regression (PLSR) to extract the critical data and create a linear model prediction of the dependent variable from an abundant number of independent variables (Liu *et al.*, 2014). Therefore, predicting the textural attribute of hardness, the chemical attributes of TSS and SO_2 content, also physical attributes of a_w and MC of dehydrated ginger, mango and pineapple, which are critical attributes of dried products, were selected in this study. The NIR-HSI was tested for predicting the quality of dehydrated ginger, mango and pineapple non-destructively.

3.3 Materials and methods

3.3.1 Dehydrated ginger mango, pineapple preparation

The commercial dehydrated ginger cv. *Thai ginger*, mango cv. *Kaew* and pineapple cv. *Pattavia* samples that were used in the experiments were from various lots produced from Thai ginger in a fruit dehydration factory at Kanchanaburi Province, Thailand. Samples were inspected visual to ensure they were without flaws and of good appearance.

Figure 3.1 Sample of dehydrated ginger

Figure 3.2 Sample of dehydrated mango

Figure 3.3 Sample of dehydrated pineapple

3.3.2 Spectral Data Acquisition

Each sample was scanned in reflectance mode in the 935–1720 nm wavelength and consisted of 224 spectral bands using a push-broom-laboratory-based sisu CHEMA system that supported a hyperspectral camera (Specim Fx17, Spectral Imaging Ltd, Oulu, Finland) (Fig 3.4). Each sample was positioned on the moving table and passed through the camera's field of view with a positioning speed of 20 mm/s and scanning speed at 15 mm/s using a stepper motor. The positioning speed is when no significant overshoot occurs, meanwhile scanning speed is the speed when a continuous spectrum is formed for each spatial point. Six halogen lamps were used in the illumination unit. The samples and two references were taken in each scanning, one a dark reference which captured when the lid was on the camera during a closed shutter and the other a white reference using a spectralon bar.

Figure 3.4 NIR-HSI system unit

3.3.3 Physical and chemical qualities analysis

3.3.3.1 Hardness

The hardness of each sample was measured using a texture analyzer (TA-XT Plus, Stable Micro Systems Ltd., UK) with a 2 mm diameter cylinder probe, a crosshead speed of 1 mm/s, and a 25 kg load cell. When the probe was withdrawn from the sample, the same speed was used. To determine the hardness of each material, the maximum peak force during the first compression was observed, as previously reported by Link *et al.*, 2018.

3.3.3.2 TSS and SO_2 content

The TSS was measured, using the AOAC method (AOAC, 2000), by taking 5 g of samples of each batch of dehydrated ginger, adding 95 ml of deionized water, homogenizing using a homogenizer (IKA, T25 digital ULTRA-TURRAX®, Germany) and then filtering. The filtered solution was then tested using a digital refractometer (PAL-1, Atago Co., Ltd., Tokyo, Japan) and used for SO_2 content determination using the Ranganna (1986) with modification. Using a 0.02 N iodine solution, an iodometric titration was performed to measure SO_2. In an Erlenmeyer flask, 25 ml of sample was poured, followed by 10 mL of 1 N NaOH, and left to stand for 10 minutes. 1 ml of 1% starch solution was added to the solution as an indicator, followed by 10 ml of H_2SO_4, and it was then allowed to stand for 10 minutes. After that, 5 ml of H_2SO_4 was added and quickly titrated with 0.02 N iodine to a dark blue color. The amount of SO_2 content in the sample was calculated using Eq.1.

$$S0_2\ content\ (mg/kg) = \frac{V_{\mathrm{Iodine}}\ x\ N_{\mathrm{Iodine}}\ x\ 32\ x\ 1000}{V_{\mathrm{sample}}} \quad (1)$$

3.3.3.3 a_w

The determination of a_w was done by the AOAC method (AOAC, 2005) using an a_w meter (4TE, Aqualab©, USA). The a_w meter was calibrated at first using the calibration standard with a_w that is already known, which is distilled water. The a_w meter should have shown the water activity of distilled water value, which is 1.000 ±0.003. Determination of a_w was done by weighing 1 g of sample in an a_w-measuring cup. The cup with the sample was then put in the a_w meter. The value of a_w was displayed in a_w meter and it sounded "beep" when the measurement is done.

3.3.3.4 MC

Determination of moisture content was done following the AOAC method (AOAC, 2000) by drying aluminum can in an air oven with temperature 105 ºC overnight then cooled in a desiccator for 15 minutes the weight it (A). Sample amounting 1 g (B) was put in the aluminum can that already known its weight. The aluminum can and the sample were dried in an air oven with a temperature of 105 ºC until a constant weight was reached and cooled in a desiccator then weighed (C). MC was calculated using Eq.2.

$$MC(\%) = \frac{B-(C-A)}{B} X\ 100\% \quad (2)$$

3.3.4 Data analysis

The scanning results from the NIR-HSI system included both the sample and background spectra. The background data was eliminated using PCA leaving only the ROI. The ROI spectra of each sample were then averaged and used for the analysis. The acquired data of hardness, TSS, SO_2 content, a_w and MC were defined as dependent variables and the spectra of the sample as the independent variables. Those data were plotted into calibration and a prediction set. The spectral pretreatments including Savitzky-Golay smoothing, first and second derivatives, SNV, MSC and the combinations were applied and investigated in order to acquire the best conditions for developing PLS models for each parameter (Jannok & Piyamart, 2017). The calibration models for hardness, TSS, SO_2, a_w and MC were created using PLSR (Cheng & Sun, 2017). The determination of the best calibration model of each dependent variable was considered by the R_{cv} with the highest number, RMSECV with the lowest number and number of latent variables (LV) also observed. In order to measure the model's capability, both R_c and RMSEC were considered, which were acquired by validation of selected calibration models for dependent variables were tested with the samples themselves in the calibration set. Also, the calibration models were tested with the samples in the prediction set to test the model's accuracy considering the R_p and RMSEP.

All of the data were statistically analyzed using the Unscrambler software (CAMO, version 9.7, Osla, Norway) and UmBio Evince HSI analysis software (Prediktera Evince, version 2.7.5, Sweden).

3.4 Results and Discussions

3.4.1 Spectra of dehydrated ginger, mango and pineapple

The ROI from all of the samples achieved in the wavelength range between 935-1720 nm was averaged and used to establish the calibration models for dehydrated ginger, mango and pineapple (Fig. 3.5). The second derivative was performed in order to enhance resolution, identify and overcome overlapping peaks (Zheng *et al.*, 2014) (Fig. 3.6). As a result, peaks were clearly visible, corresponding to organic molecules' vibrational activity (Posom *et al.*, 2020). The averaged second derivative spectra showed clear peaks in the negative bands around at 964 nm which corresponded to absorption peak of water (Williams, 2019), the peaks around 1195 and 1590 nm were corresponded to absorption peak of glucose, meanwhile the peak around 1433 nm corresponded with sucrose's peak (López *et al.*, 2017) and the peak at 1364 nm corresponded to the absorbance bands of SO_2 (Rongtong *et al.*, 2018) indicating that water, sugar and SO_2 in dehydrated ginger, mango and pineapple could be detected.

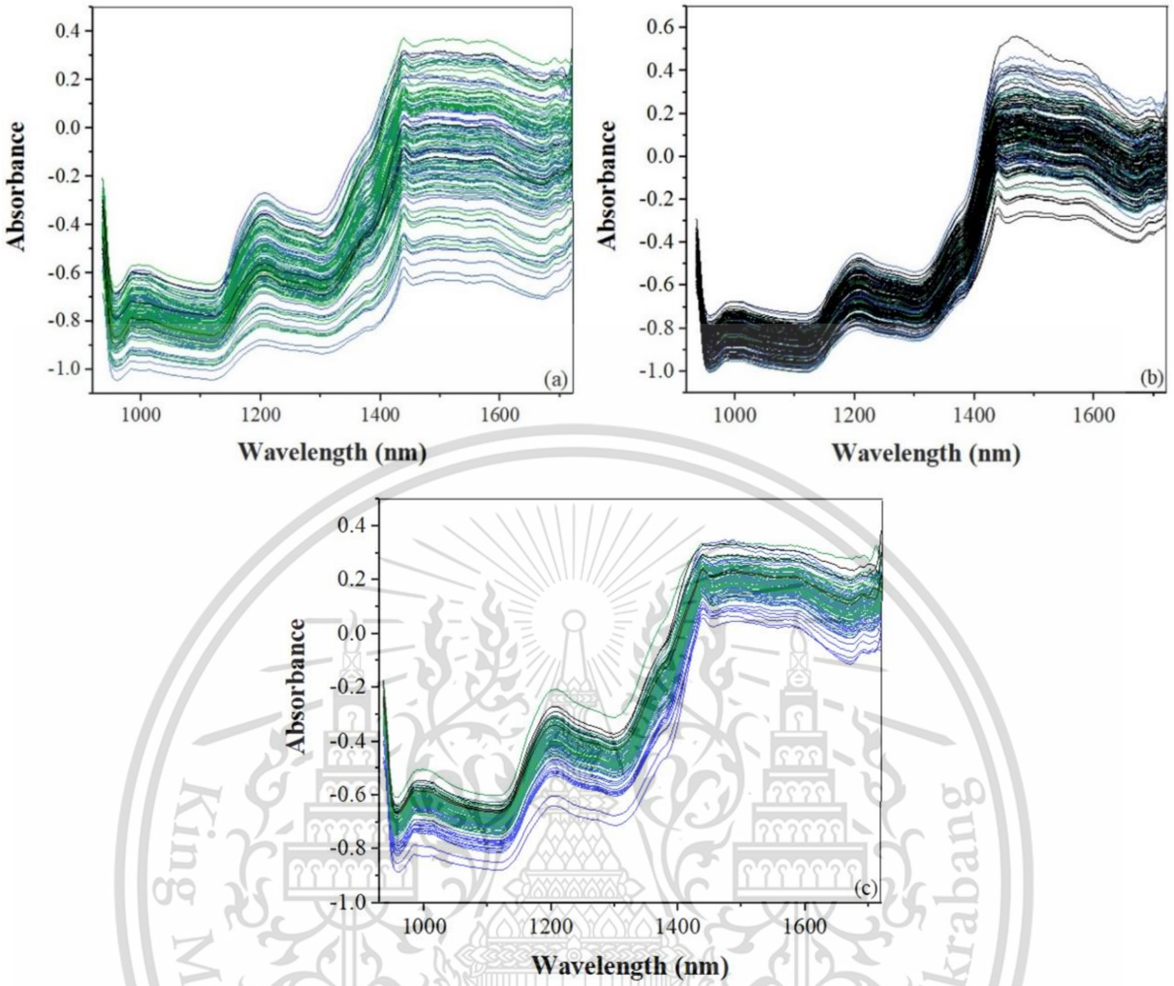

Figure 3.5 The average spectra of ROI from dehydrated gingers (a), mango (b) and pineapple (c).

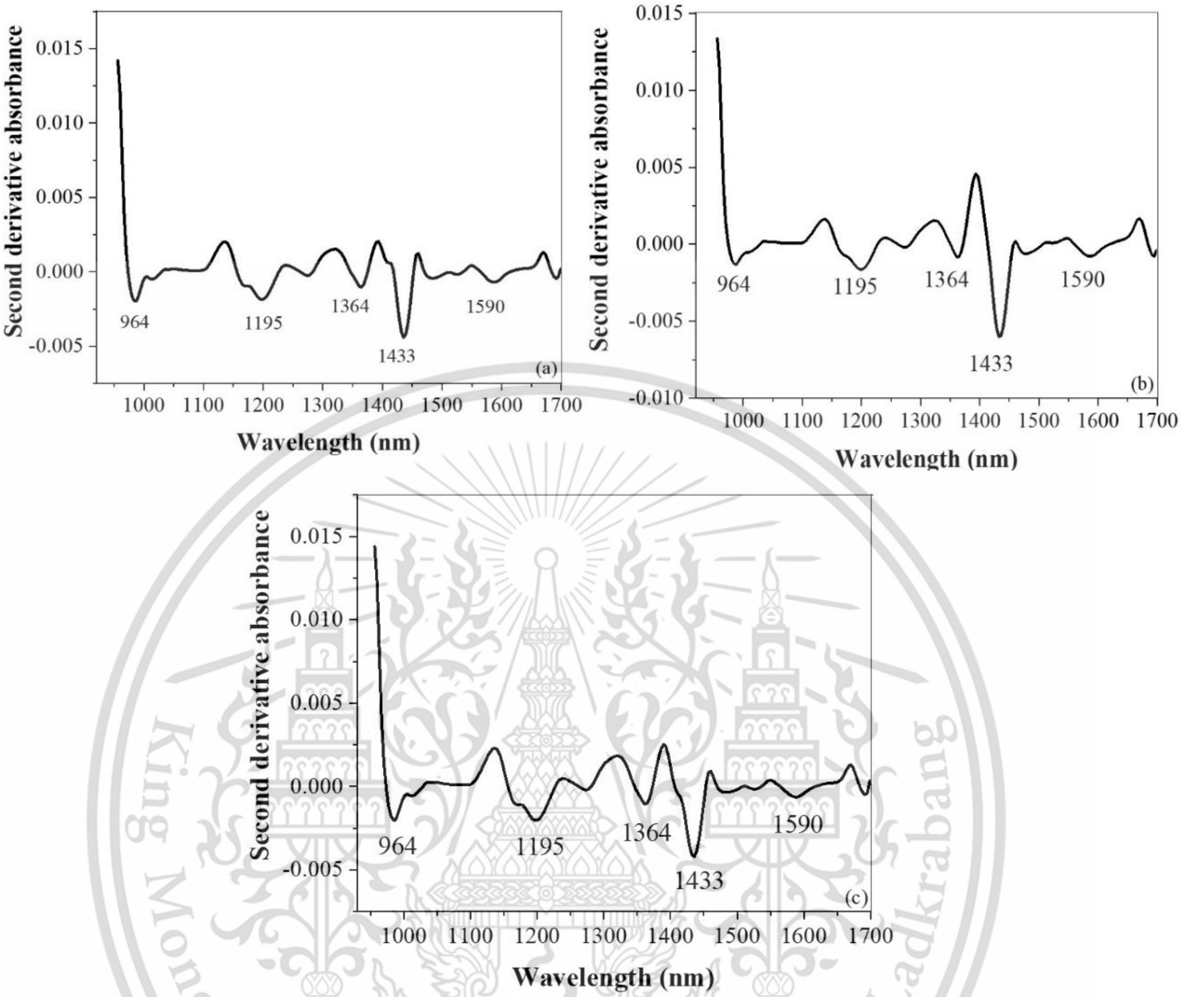

Figure 3.6 Average second derivative spectra of dehydrated ginger (a), mango (b) and pineapple (c).

3.4.2 Calibration model for predicting quality indices of dehydrated ginger, mango and pineapple

The dehydrated ginger, mango and pineapple samples for creating the model of hardness (N=150, 235, 220), TSS (N=180, 100, 149), SO_2 content (N=104, 100, 140), a_w (N=240, 280, 150) and MC (N=104, 215, 294) were separated into calibration and prediction sets (Table 3.1, 3.2, 3.3). The samples for each quality indices of dehydrates samples in prediction set in the range of calibration set with a relative standard deviation between calibration and prediction set but SO_2 of dehydrated ginger was far. Different kinds of spectral pretreatments were applied to the spectra of samples in the calibration set in order to reduce noises' effects and shift in base line (Wu *et al.*, 2013).

The best calibration models for dehydrated ginger were achieved by applying smoothing pretreatment for hardness (R_{cv}= 0.74, RMSECV= 3.75 N), a_w (R_{cv}= 0.58, RMSECV= 0.0091) and MC (R_{cv}= 0.59, RMSECV= 1.16 %) and the original spectra were used for creating the models of TSS (R_{cv}= 0.75, RMSECV= 2.71%) and SO_2 content (R_{cv}= 0.26, RMSECV= 55.15 mg/kg). (Table 3.4). For dehydrated mango, the calibration models were created the best using original spectra for hardness (R_{cv}= 0.76, RMSECV= 3.66 N) and SO_2 content (R_{cv}= 0.67, RMSECV= 73.00 mg/kg) and smoothing pretreatment for TSS (R_{cv}= 0.68, RMSECV= 3.06%), a_w (R_{cv}= 0.881, RMSECV= 0.0069) and MC (R_{cv}= 0.76, RMSECV= 0.75%) (Table 3.5). Original spectra for hardness (R_{cv}= 0.70, RMSECV= 1.20 N), SO_2 content (R_{cv}= 0.74, RMSECV= 26.69 mg/kg) and a_w (R_{cv}= 0.721, RMSECV= 0.0053) resulted in the best calibration model of dehydrated pineapple, meanwhile smoothing pretreatment for TSS (R_{cv}= 0.76, RMSECV= 2.09%) and MC (R_{cv}= 0.689, RMSECV= 0.992%) (Table 3.6).

The calibration models that were created using the preprocessed spectra together with the PLSR were then tested in order to determine the accuracy by the samples in the prediction set for all quality indices. The models obtained acceptable results of dehydrated ginger for predicting hardness (R_p= 0.81, RMSEP= 3.26 N), TSS (R_p= 0.77, RMSEP= 2.72%), a_w (R_p= 0.78, RMSEP= 0.007) and MC (R_p= 0.71, RMSEP= 0.77%), meanwhile the poor results were obtained in calibration models of SO_2 content (R_p= 0.07, RMSEP= 50.98 mg/kg) (Table 3.7). The calibration model of dehydrated mango provided approximate accurate calibration results for predicting hardness (R_p= 0.80, RMSEP= 3.08 N), TSS (R_p= 0.86, RMSEP= 2.18%), SO_2 content (R_p= 0.82, RMSEP= 58.57 mg/kg) and a_w (R_p= 0.86, RMSEP= 0.007) and MC (R_p= 0.81, RMSEP= 0.66%) (Table 3.8). The calibration model of dehydrated pineapple showed a sufficient accurate accuracy for predicting hardness (R_p= 0.80, RMSEP= 3.08 N), TSS (R_p= 0.86, RMSEP= 2.18%), SO_2 content (R_p= 0.82, RMSEP= 58.57 mg/kg) and a_w (R_p= 0.86, RMSEP= 0.007) and MC (R_p= 0.81, RMSEP= 0.66%) (Table 3.9). Williams (2007) reported that the interpretation of R_p ranging from 0.81-0.90 is possible for screening and approximate calibration, Rp ranging from 0.71-0.80 might be used for rough screening; meanwhile, R_p below 0.70 shows the model has poor relation and should identify the reason and R_p lower than 0.50 is not possible to be used for NIR calibration model. Thus, in this study, NIR-HSI was not capable of predicting SO_2 of dehydrated ginger because the R_p was below 0.50. It may be possible that errors occurred during the experiment for many reasons, such as noises from scanning conditions and environments such as stray light. Stray light failed unintentionally onto the wrong pixels of a detector, resulting in inaccurate readings. Stray light might have been scattered randomly by errors in the grating or other optical components inside the instrument or by other errors in the instrument design (Zonios, 2010). Spectral pretreatments were used to correct the stray light. However, the results still showed poor correlations. The variation of the dehydrated ginger samples might be the other factor. The sample should have a good variation to create a good correlation. In this case, the repeated measurement from the start and controlling the scanning conditions are needed. Also, collecting the sample from different batches is considered. Unfortunately, due to the COVID-19 pandemic, the lab was closed and the laboratory work was not permitted.

The performance of calibration models of dehydrated ginger, shown by the scatter plots for hardness, TSS, a_w and MC (Fig 3.7 a, b, c, d). The hardness, TSS, SO_2 content, a_w and MC of dehydrated mango (Fig 3.8 a, b, c, d, e) and dehydrated pineapple (Fig 3.9 a, b, c, d, e). These figures show that the accuracy that was achieved by applying the calibration models to the samples in prediction set. These results showed that using NIR-HSI resulted in good performance and accuracy for predicting the hardness, TSS, a_w and MC of dehydrated ginger and hardness, TSS, SO_2 content, a_w and MC of dehydrated mango and pineapple, implies that it could be applied for use as a nondestructive online grading system for quality control during the production process for dehydrated fruits.

Table 3.1 The hardness, TSS, SO_2 content, aw and MC of dehydrated ginger in the calibration set and prediction set.

Item	Hardness (N)		TSS (%)		SO_2 content (mg/kg)		a_w		MC (%)	
	Calibration	Prediction	Calibration	Prediction	Calibration	Prediction	Calibration	Prediction	Calibration	Prediction
Number	100	50	120	60	70	34	154	76	70	34
Range	2.42 – 35.42	3.10 – 27.58	65-84	65-84	107 – 359.91	119.97 – 317.76	0.532-0.599	0.532-0.588	8.75 – 15.92	8.78 – 13.86
Mean	10.26	10.89	77.18	77.15	204.24	199.46	0.572	0.571	11.79	11.77
SD	5.22	4.95	4.08	4.10	56.95	51.11	0.011	0.012	1.46	1.05

Table 3.2 The hardness, TSS, SO_2 content, aw and MC of dehydrated mango in the calibration set and prediction set.

Item	Hardness (N)		TSS (%)		SO_2 content (mg/kg)		a_w		MC (%)	
	Calibration	Prediction	Calibration	Prediction	Calibration	Prediction	Calibration	Prediction	Calibration	Prediction
Number	157	78	67	33	67	33	187	93	144	71
Range	4.83-33.41	5.76- 28.36	62.67-85.33	63.00-84.00	356.67-875.45	405.3-794.39	0.486-0.547	0.488-0.546	7.86-14.63	8.56-13.43
Mean	18.57	18.43	78.21	77.98	602.30	602.30	0.5098	0.5097	10.95	10.91
SD	5.57	4.94	4.07	4.26	96.11	97.79	0.0145	0.0143	1.16	1.09

Table 3.3 The hardness, TSS, SO_2 content, aw and MC of dehydrated pineapple in the calibration set and prediction set.

Item	Hardness (N)		TSS (%)		SO_2 content (mg/kg)		a_w		MC (%)	
	Calibration	Prediction	Calibration	Prediction	Calibration	Prediction	Calibration	Prediction	Calibration	Prediction
Number	147	73	99	50	94	46	100	50	196	98
Range	3.40-12.51	3.62-10.85	74.00-88.67	74.67-88.00	210.76-389.09	210.76-356.67	0.567- 0.608	0.569- 0.604	10.29-16.92	10.40-16.65
Mean	6.84	6.76	80.98	80.80	285.46	283.68	0.588	0.588	13.45	13.45
SD	1.69	1.64	3.23	3.11	39.98	37.61	0.008	0.008	1.37	1.37

Table 3.4 Results of spectral pretreatment methods for PLSR models of dehydrated ginger for texture, TSS, SO_2 content, a_w and MC in the region of 935– 1720 nm.

Pre-processing techniques	Hardness (N)			TSS (%)			SO_2 content (mg/kg)			a_w			MC (%)		
	LV	R_{cv}	RMSECV	LV	R_{cv}	RMSECV	LV	R_{cv}	RMSECV	LV	R_{cv}	RMSECV	LV	R_{cv}	RMSECV
Original	6	0.73	3.82	**6**	**0.75**	**2.71**	**3**	**0.26**	**55.15**	15	0.52	0.0097	5	0.55	1.22
Smoothing	**7**	**0.74**	**3.75**	6	0.73	2.77	3	0.22	56.15	**14**	**0.58**	**0.0091**	**7**	**0.59**	**1.16**
1st Derivative	4	0.70	3.93	5	0.74	2.73	1	-0.01	57.83	10	0.50	0.0098	5	0.50	1.22
2nd Derivative	3	0.68	4.02	4	0.72	2.81	1	0.03	57.61	9	0.54	0.0094	4	0.49	1.22
MSC	6	0.73	3.83	5	0.75	2.74	1	-0.04	58.45	13	0.54	0.0095	5	0.50	1.24
SNV	5	0.73	3.84	5	0.75	2.73	3	0.18	56.84	15	0.53	0.0097	5	0.52	1.21
Smoothing + 1st Derivative	5	0.71	3.86	3	0.72	2.82	1	-0.17	60.92	6	0.49	0.0096	5	0.50	1.22
Smoothing + 2nd Derivative	3	0.69	3.98	4	0.72	2.84	1	-0.22	59.76	7	0.48	0.0097	4	0.47	1.25

Table 3.5 Results of spectral pretreatment methods for PLSR models of dehydrated mango for texture, TSS, SO_2 content, a_w and MC in the region of 935– 1720 nm.

Pre-processing techniques	Hardness (N)			TSS (%)			SO_2 content (mg/kg)			a_w			MC (%)		
	LV	R_{cv}	RMSECV	LV	R_{cv}	RMSECV	LV	R_{cv}	RMSECV	LV	R_{cv}	RMSECV	LV	R_{cv}	RMSECV
Original	**9**	**0.76**	**3.66**	8	0.62	3.20	**8**	**0.67**	**73.00**	9	0.865	0.0073	4	0.75	0.76
Smoothing	8	0.73	3.78	**11**	**0.68**	**3.06**	8	0.66	73.36	**9**	**0.881**	**0.0069**	**5**	**0.76**	**0.75**
1st Derivative	6	0.71	3.90	11	0.63	3.29	10	0.60	80.84	7	0.809	0.0085	8	0.72	0.81
2nd Derivative	5	0.70	4.00	9	0.67	3.10	11	0.56	84.63	12	0.693	0.0108	5	0.68	0.86
MSC	6	0.69	4.09	9	0.65	3.19	7	0.61	77.09	9	0.876	0.0070	4	0.75	0.76
SNV	6	0.69	4.02	7	0.61	3.31	7	0.63	74.81	9	0.876	0.0069	3	0.74	0.78
Smoothing + 1st Derivative	6	0.73	3.80	10	0.66	3.08	8	0.54	82.80	9	0.871	0.0071	5	0.73	0.80
Smoothing + 2nd Derivative	5	0.70	4.00	6	0.57	3.34	6	0.52	82.13	6	0.774	0.0092	5	0.72	0.81

Table 3.6 Results of spectral pretreatment methods for PLSR models of dehydrated pineapple for texture, TSS, SO_2 content, a_w and MC in the region of 935– 1720 nm.

Pre-processing techniques	Hardness (N)			TSS (%)			SO_2 content (mg/kg)			a_w			MC (%)		
	LV	R_{cv}	RMSECV	LV	R_{cv}	RMSECV	LV	R_{cv}	RMSECV	LV	R_{cv}	RMSECV	LV	R_{cv}	RMSECV
Original	**6**	**0.70**	**1.20**	7	0.74	2.18	**3**	**0.74**	**26.69**	**2**	**0.721**	**0.0053**	6	0.686	0.997
Smoothing	7	0.70	1.20	**8**	**0.76**	**2.09**	3	0.73	26.81	2	0.720	0.0054	**6**	**0.689**	**0.992**
1st Derivative	6	0.63	1.31	7	0.72	2.25	3	0.73	27.13	1	0.680	0.0057	6	0.687	0.995
2nd Derivative	5	0.57	1.40	8	0.68	2.41	3	0.72	27.64	3	0.651	0.0059	6	0.684	1.007
MSC	5	0.56	1.39	6	0.72	2.25	3	0.73	26.81	1	0.659	0.0058	5	0.689	0.994
SNV	7	0.64	1.29	7	0.73	2.20	3	0.74	26.78	1	0.656	0.0058	5	0.688	0.995
Smoothing + 1st Derivative	5	0.61	1.32	7	0.73	2.21	3	0.73	26.80	1	0.682	0.0056	4	0.680	1.004
Smoothing + 2nd Derivative	4	0.57	1.38	6	0.66	2.44	2	0.70	28.13	2	0.673	0.0057	4	0.669	1.021

Table 3.7 The results of PLSR model for dehydrated gingers' dependent variables in the calibration set and the prediction set.

Parameters	Pre-treatrment	LV	Sample set					
			Calibration			Prediction		
			N	R	RMSEC	N	R	RMSEP
Hardness	Smoothing	7	100	0.81	3.26 N	50	0.80	3.19 N
TSS	Original	6	120	0.79	2.45%	60	0.77	2.72%
SO_2 content	Original	3	70	0.38	52.20 mg/kg	34	0.07	50.98 mg/kg
a_w	Smoothing	14	154	0.79	0.006	76	0.78	0.007
MC	Smoothing	7	70	0.73	0.99%	34	0.71	0.77%

Table 3.8 The results of PLSR model for dehydrated mangoes' dependent variables in the calibration set and the prediction set.

Parameters	Pre-treatrment	LV	Sample set					
			Calibration			Prediction		
			N	R	RMSEC	N	R	RMSEP
Hardness	Original	9	157	0.84	3.06 N	78	0.80	3.08 N
TSS	Smoothing	11	67	0.87	2.07%	33	0.86	2.18%
SO_2 content	Original	8	67	0.86	49.13 mg/kg	33	0.82	58.57 mg/kg
a_w	Smoothing	9	187	0.90	0.006	93	0.86	0.007
MC	Smoothing	5	144	0.79	0.71%	71	0.81	0.66%

Table 3.9 The results of PLSR model for dehydrated pineapples' dependent variables in the calibration set and the prediction set.

Parameters	Pre-treatrment	LV	Sample set					
			Calibration			Prediction		
			N	R	RMSEC	N	R	RMSEP
Hardness	Original	6	147	0.78	1.04 N	73	0.77	1.05 N
TSS	Smoothing	8	99	0.85	1.71%	50	0.80	1.89%
SO_2 content	Original	3	94	0.77	25.30 mg/kg	46	0.78	24.29 mg/kg
a_w	Original	2	100	0.74	0.0052	50	0.74	0.0051
MC	Smoothing	5	196	0.73	0.94%	98	0.77	0.87%

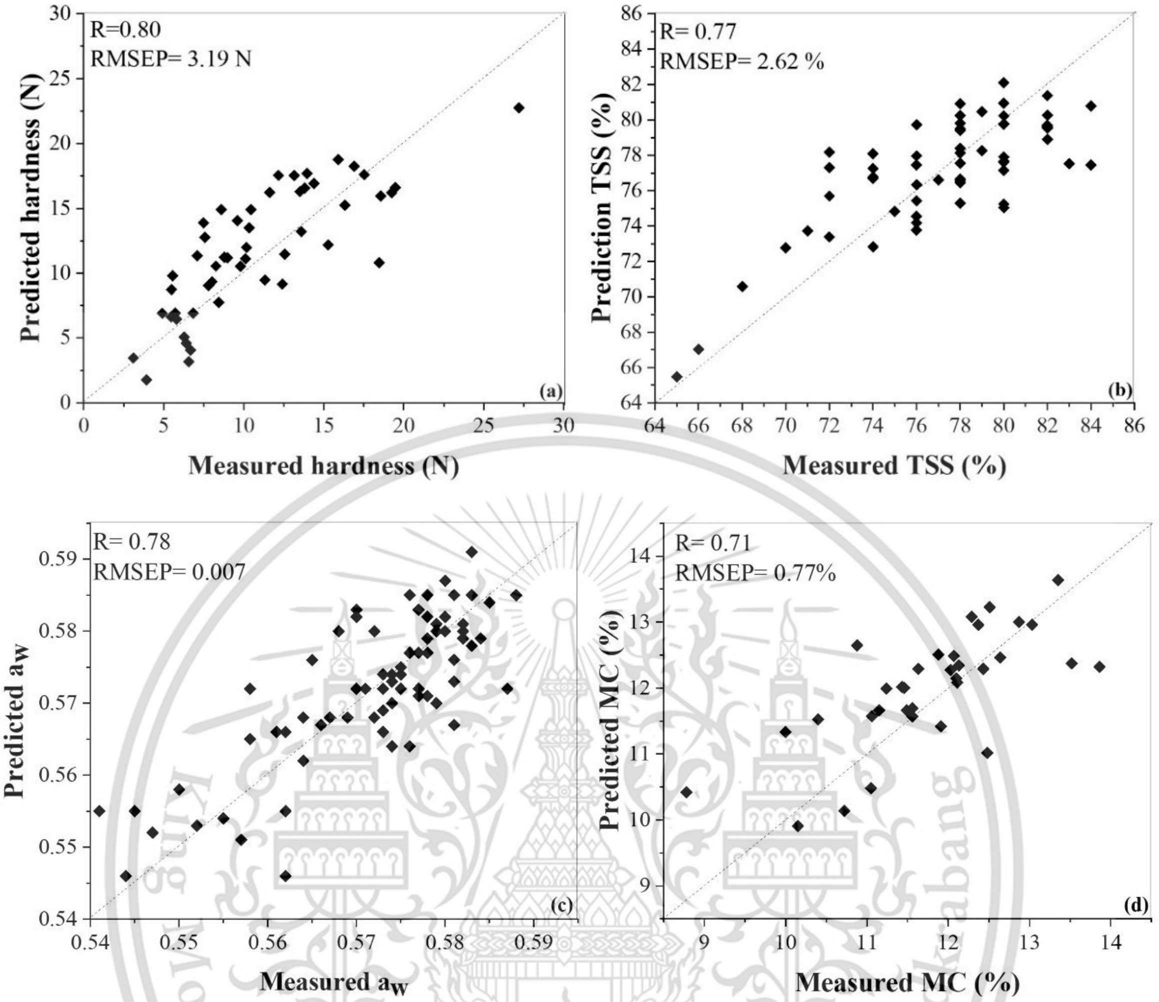

Figure 3.7 Measured and predicted hardness (a), TSS (b), a_w (c) and MC (d) in the calibration set of dehydrated ginger visualized in scatter plots.

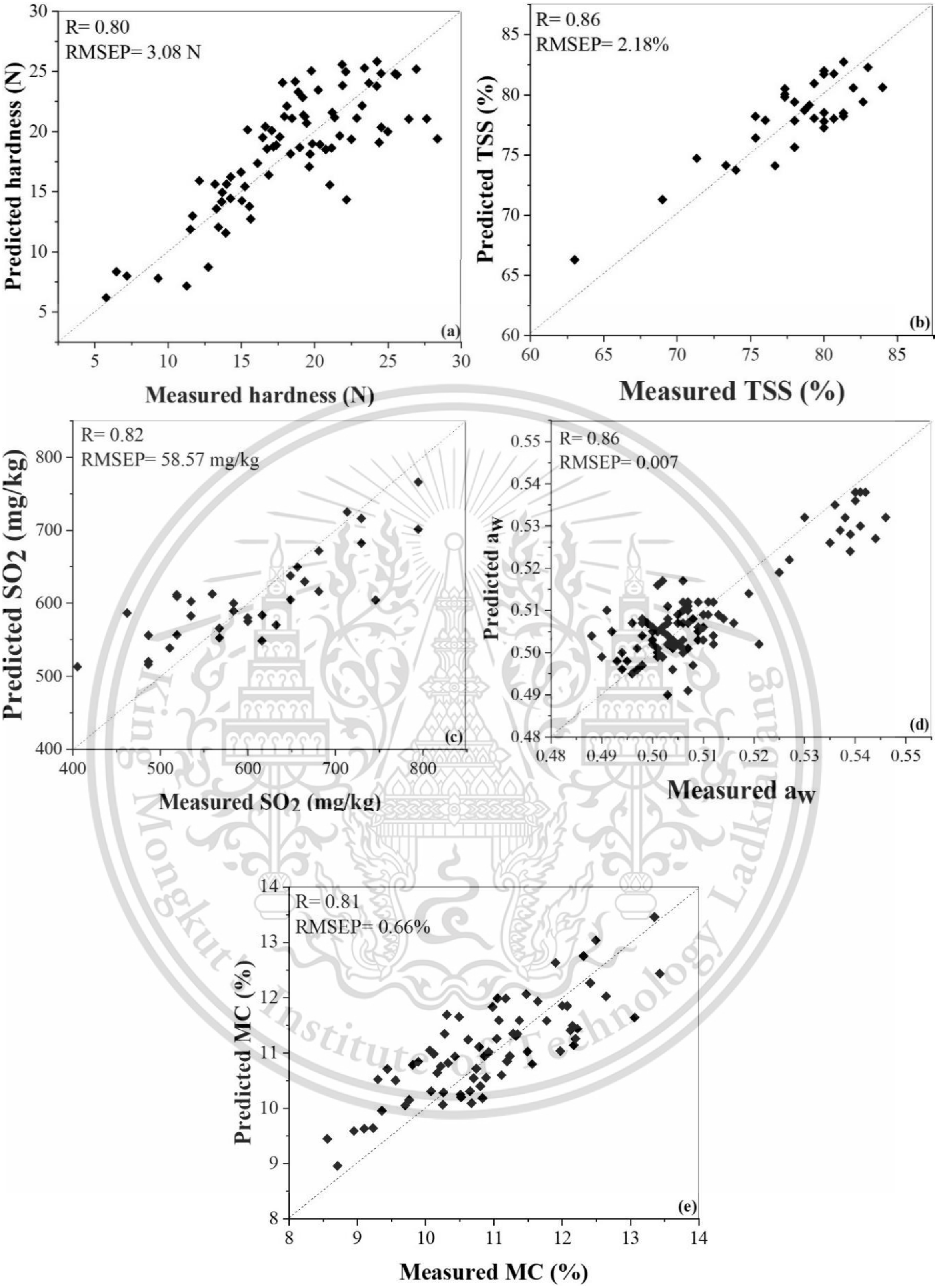

Figure 3.8 Measured and predicted hardness (a), TSS (b), SO_2 content (c), a_w (d) and MC (e) in the calibration set of dehydrated mango visualized in scatter plots.

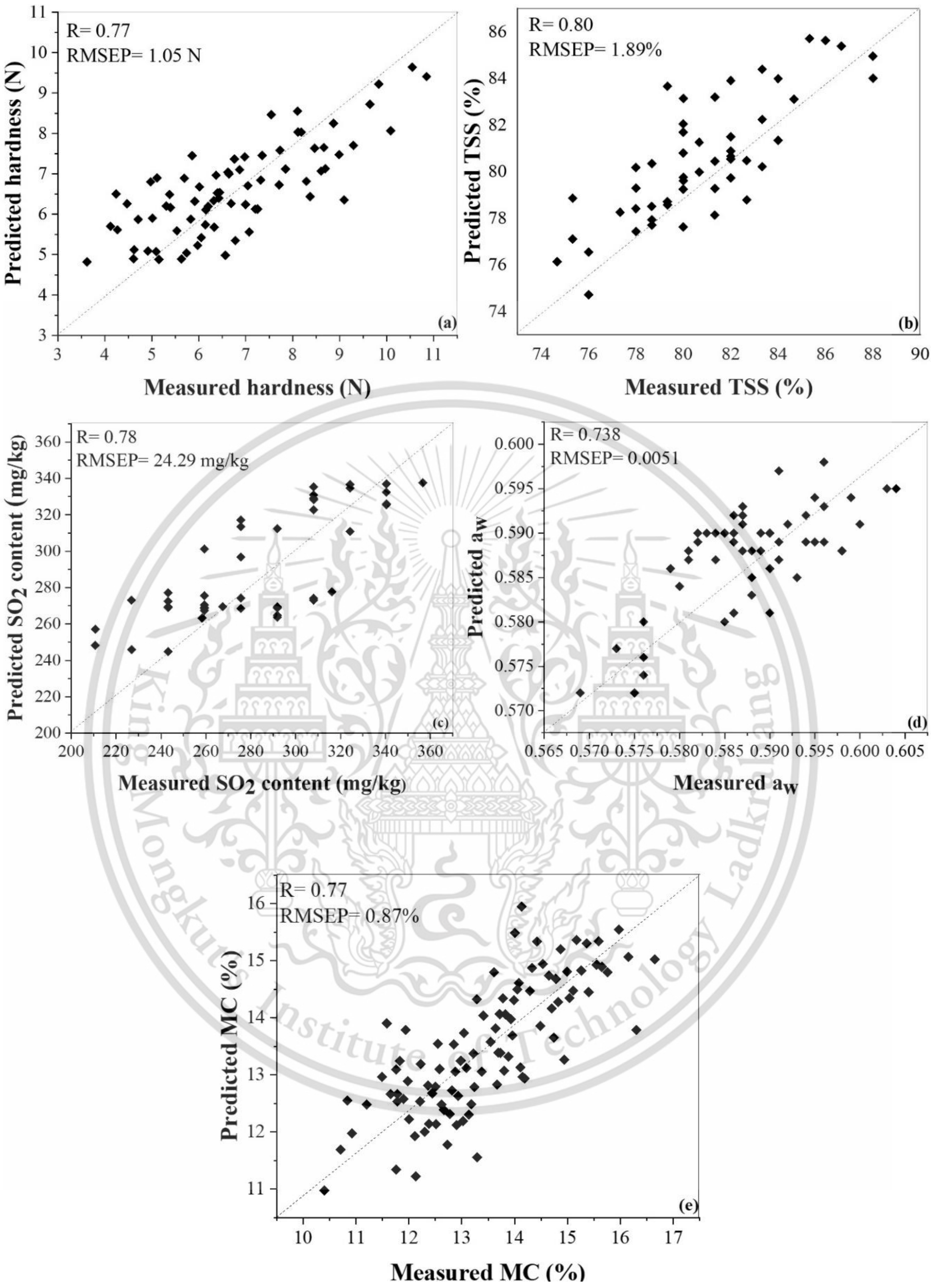

Figure 3.9 Measured and predicted hardness (a), TSS (b), SO_2 content (c), a_w (d) and MC (e) in the calibration set of dehydrated pineapple visualized in scatter plots.

3.5 Conclusions

The calibration models constructed using PLSR from average spectra with the smoothing spectral pretreatment of data from NIR-HSI equipment could be used to predicting the hardness and MC of dehydrated ginger; meanwhile, TSS using its original spectra. The calibration models of hardness and SO_2 of dehydrated mango were created by its original spectra; meanwhile, TSS, a_w and MC using smoothing pretreatment. For dehydrated pineapple, original spectra was used to create calibration model of hardness, SO_2 content and a_w, meanwhile TSS and MC using smoothing pretreatment. It was indicated that NIR-HSI had an acceptable performance and accuracy for predicting the hardness, TSS, a_w and MC of dehydrated ginger, mango and pineapple, also the SO_2 of dehydrated mango and pineapple, which could possibly be applied as a nondestructive, rapid and reliable quality control method in commercial manufacturing process line of dehydrated fruit factories. However, the calibration model of SO_2 for dehydrated ginger has a poor correlation, indicated that it obtained poor results in this experiment for predicting SO_2 of dehydrated ginger using NIR-HSI. Therefore, the results of SO_2 for dehydrated ginger that was different from other products may have the revised experiment and analyzed to get better results in the future.

CHAPTER 4

SUMMARY AND RECOMMENDATIONS

4.1 Summary

The drying process impacted the textural attribute of hardness, the chemical attributes of TSS and SO_2 content, also the physical attributes of a_w and MC of final dehydrated fruits products. A simple system for analyzing is needed to check the quality of dehydrated products in large quantities non-destructively. The smoothing spectral pretreatment of data from the NIR-HSI system, could be used to predicting hardness, a_w and MC of dehydrated ginger, meanwhile TSS using its original spectra. The calibration models of hardness and SO_2 of dehydrated mango were created by its original spectra, meanwhile TSS, a_w and MC using smoothing pretreatment. For dehydrated pineapple, original spectra were used to create a calibration model of hardness, SO_2 content and a_w, meanwhile TSS and MC using smoothing pretreatment. These calibration models were created using PLSR and obtained sufficient accuracy to predict qualities of dehydrated ginger, mango and pineapple.

Therefore, NIR-HSI has the possibility to be applied for a nondestructive online quality control system in the production of dehydrated fruit. However, the calibration model of SO_2 of dehydrated ginger may get better results by revising experiments and analysis in the future.

4.2 Recommendations

To further explore the possibility of using NIR-HSI for predicting the qualities of dehydrated fruits, future studies should be focused on:

4.2.1 Scanning environment should be more controlled to minimize the effects or noises in the scanning results spectra, especially on SO_2 content quality indices.

4.2.2 The shelf life evaluation of dehydrated fruits using NIR-HSI.

4.2.3 The application of NIR-HSI on other types of dehydrated fruits samples.

4.2.4 Visualization of the distribution of dehydrated fruits quality indices by predictive images.

4.2.5 Other nonlinear modeling methods or combinations can be tried.

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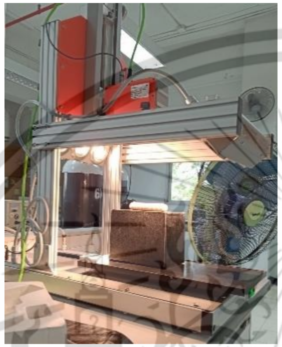
APPENDIX

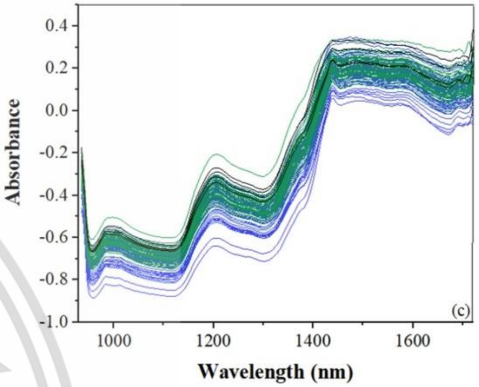
Appendix 1: Sample scanning and data acquisition

Dehydrated ginger, mango and pineapple



NIR-HSI scanning

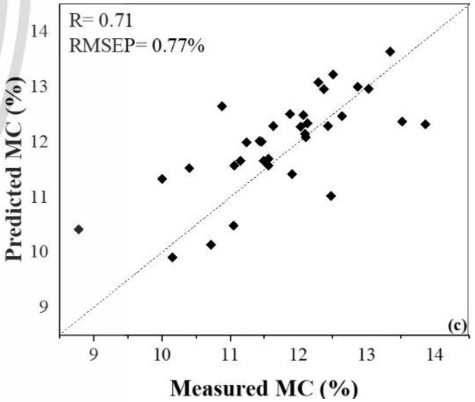
Evince analysis



Spectral data acquisition

Analysis of hardness,

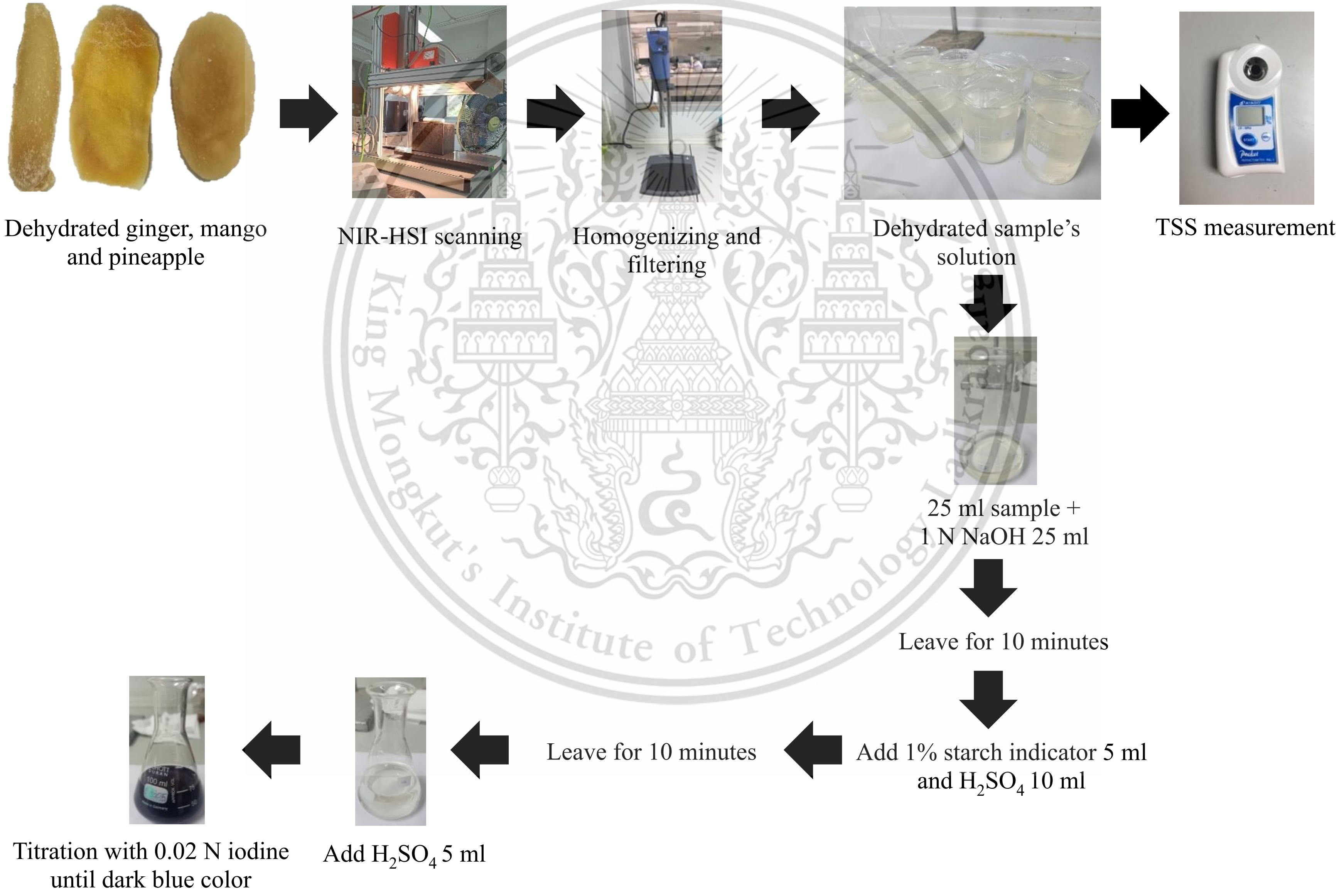
TSS, SO_2, a_w and MC



Prediction model acquisition

Appendix 2: Analysis of hardness, a_w and MC of dehydrated ginger, mango and pineapple.

Appendix 3: Analysis of TSS and SO_2 content of dehydrated ginger, mango and pineapple.



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Wayan Dipasasri Aozora was born on August 12th, 1996 in Bangli, Indonesia and grew up in Bogor, Indonesia. She graduated from Bogor Agricultural University with bachelor's degree in the major of Food Science and Technology in 2019. During her study, she was delegation of SUIJI (*Six University Indonesia Japan Initiation*) Japan summer course 2017 in Kochi University, Japan and she also joined an exchange student program in Mae Fah Luang University, Thailand (MFU) for five months, under *ASEAN International Mobility for Students (AIMS) Scholarship 2018*. She had a chance to continue her study at King Mongkut's Institute of Technology Latkrabang (KMITL), Thailand that supported by *KMITL - ASEAN Postgraduate Scholarship 2019*. She obtained her Master of Science degree (majoring in Food Science) in 2021 from KMITL, Thailand. During her study in Thailand, her research had been granted under *KMITL Research and Innovation Services (KRIS), [KREF126302]* with the project of predicting the quality of dehydrated fruit using near infrared hyperspectral imaging (NIR-HSI). She gained the lab-skills and knowledge related to the quality analysis of dehydrated fruit, data acquisition and data analysis of NIR-HSI, under the supervision of Assoc. Prof. Dr. Sontisuk Teerachaichayut at the School of Food Industry, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand.

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