UNIVERSITI PUTRA MALAYSIA

MATHEMATICAL MODELLING OF COMBINED INFRARED AND HOT AIR DRYING OF SLICED SWEET POTATO (Ipomoea batatas L.)

ONWUDE DANIEL IROEMEHA CHIKWENDU

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

July 2018

DEDICATION

With all my love, I dedicate this PhD thesis to my precious mum and to the blessed memory of my late dad.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Doctor of Philosophy

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July 2018

Chairman : Associate Professor Norhashila Hashim, PhD
Faculty : Engineering

Combined infrared and hot-air drying method has been identified to be able to improve both energy efficiency and quality of dried agricultural crops. However, being a novel drying technique, studies on its application to the drying of industrial crops such as sweet potato are still limited. Particularly, the drying conditions, combination strategies and modelling studies are not properly investigated. This research investigated the potential of combined infrared and hot-air in drying of sweet potato (*Ipomoea batatas L.*) slices. The combined computer vision (CV) and laser-light backscattering imaging was adopted to monitor the shrinkage and quality attributes. The specific energy consumption (SEC), colour and microstructural changes of sweet potato (*Ipomoea batatas L.*) based on experimental set-up of different combined IR and HAD strategies (Simultaneous IR and HAD, two-stage HAD + IR, two-stage IR + HAD, intermittent IR and HAD) were investigated. Mathematical models based on Lambert's equation of electromagnetics for single-phase and multiphase change during the combined IR and HAD of sweet potato were developed and evaluated, using finite element methods in both COMSOL and MATLAB software.

The combined IR and HAD resulted in 69.34 – 85.59% reduction in the SEC of HAD. The specific energy consumption during simultaneous IR and HAD, two-stage HAD+IR, two-stage IR+HAD, and intermittent IR and HAD varied between 174.10-310.93 MJ/kg, 95.80-177.48 MJ/kg, 56.30-68.36 MJ/kg, 99.61-149.18 MJ/kg, respectively. The intermittent IR and HAD was demonstrated to be the most suitable combination strategy based on the combined effect of total drying time, shrinkage, SEC and total colour change. The moisture and temperature distribution results of the single-phase model for simultaneous and intermittent IR and HAD of sweet potato agreed well with experimental drying data. The multiphase simulations results indicated that the model could adequately describe the underling drying mechanism

of combined IR and HAD. The water and vapour fluxes due to gas diffusion and gas pressure resulted to increased drying efficiency of combined IR and HAD. The understanding of these phenomenon could be used to improve food quality and increase energy efficiency. The automation and optimization ability could also be increased.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

MATEMATIK TERHADAP GABUNGAN PENGERINGAN INFRAMERAH DAN OLAKAN UDARA PANAS UNTUK KEPINGAN UBI KELEDEK (*Ipomoea batatas* L.)

Oleh

ONWUDE DANIEL IROEMEHA CHIKWENDU

Julai 2018

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Kaedah gabungan inframerah dan pengeringan secara udara panas telah dikenalpasti mampu untuk meningkatkan kecekapan tenaga dan kualiti keluaran pertanian kering. Walau bagaimanapun, sebagai satu teknik pengeringan novel, kajian berkaitan penggunaannya terhadap pengeringan industri tanaman seperti ubi keledek adalah masih terhad. Khususnya, kinetik pengeringan, keadaan pengeringan, strategi gabungan dan kajian pemodelan tidak dikaji secara teliti. Kajian ini menyelidik potensi teknik gabungan inframerah dan udara panas untuk pengeringan kepingan ubi keledek (*Ipomoea batatas L.*). Gabungan visi komputer (CV) dan pengimejan penghamburan cahaya laser telah diguna pakai untuk memantau proses pengecutan dan sifat kualiti. Kinetik pengeringan, penggunaan tenaga yang tertentu (SEC), warna dan perubahan mikrostruktur ubi keledek berdasarkan penyediaan eksperimen dengan strategi gabungan inframerah (IR) dan pengeringan udara panas (HAD) berbeza (IR dan HAD serentak, dua-peringkat HAD + IR, dua peringkat IR + HAD, IR dan HAD secara selang seli) telah dikaji. Teori pemodelan berasaskan persamaan Lambert tentang elektromagnetik untuk perubahan fasa tunggal dan perubahan fasa yang berbilang semasa gabungan IR dan HAD ubi keledek dibangunkan menggunakan kaedah unsur terhingga dalam perisian COMSOL dan MATLAB. Gabungan IR dan HAD menghasilkankan pengurangan 69.34-85.59% SEC HAD. Penggunaan tenaga yang tertentu semasa IR dan HAD serentak, HAD + IR dua-peringkat, dua peringkat IR + HAD, dan IR dan HAD berselang seli berbagai-bagai dengan masing-masing antara 174.10-310.93 MJ/kg, 95.80-177.48 MJ/kg, 56.30-68.36 MJ/kg, 99.61-149.18 MJ/kg. IR dan HAD yang berselang seli telah menunjukkan sebagai strategi gabungan paling sesuai berdasarkan kesan gabungan jumlah masa pengeringan, pengecutan, SEC dan jumlah perubahan warna. Keputusan pengagihan lembapan dan suhu model fasa tunggal untuk IR dan HAD serentak dan berselang seli keledek adalah selari dengan data pengeringan secara eksperimen. Keputusan kesahihan selanjutnya

menunjukkan bahawa model yang dibangunkan dalam kajian ini menjelaskan secukupnya mekanisme pengeringan secara gabungan IR dan HAD. Fluks air dan wap yang disebabkan oleh penyebaran dan tekanan gas menghasilkan peningkatan kecekapan pengeringan secara gabungan IR dan HAD. Pemahaman tentang fenomena ini boleh digunakan untuk meningkatkan kualiti makanan dan meningkatkan kecekapan tenaga. Keupayaan automasi dan pengoptimuman juga dapat ditingkatkan.

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I certify that a Thesis Examination Committee has met on 6 July 2018 to conduct the final examination of Onwude Daniel Iroemeha Chikwendu on his thesis entitled "Mathematical Modelling of Combined Infrared and Hot Air Drying of Sliced Sweet Potato (*Ipomoea batatas* L.)" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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I hereby confirm that:

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This is to confirm that:

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M_0	Initial moisture content *(kg water/ kg dry solid)*
M_e	Equilibrium moisture content *(kg water/ kg dry solid)*
M or M_t	Moisture content at any time *t (kg water/ kg dry solid)*
D; D_{eff}; D_{efft}	Effective moisture diffusivity *(m^2 s^{-1})*
E_a	Activation energy *(kJ/mol)*
t	Time *(s)*
r	Radius of cylinder
z	Direction of thickness
h^*	Half thickness sample *(m)*
D_{efy}; D_s; D_{effs}	Effective diffusivity with shrinkage *(m^2 s^{-1})*
V	Sample volume *(m^3)*
V_0	Initial volume of sample *(m^3)*
R^2 *or* r^2	Coefficient of determination
r ; R	Correlation coefficient
SSE	Sum square error
$RMSE$	Root mean square error
$RMSEP$	Root mean square error of prediction
x^2	Reduced chi-square
MBE	Mean bias error
w	Width (mm) or Width of emitter *(mm)*
h; z	Thickness *(mm)*
L	Length *(mm)* or Length of emitter *(mm)*
A	Area *(mm^2)*

T	Temperature *(°C)*
T_a	Ambient temperature *(°C)*
V	Air velocity *(m/s)*
RH	Relative humidity *(%)*
P_d	Power density *(W)*
P	Power intensity *(W/m^2)*
I	Solar intensity *(kW/m^2)*
FIR	Far infrared radiation
IRD	Infrared dryer
IR	Infrared radiation
HAD	Hot-air drying
CHAD	Convective hot-air drying
CD	Convective drying
IR-HAD; IR-CHAD	Simultaneous infrared and hot-air drying
HAD+IR	Two-stage sequential hot-air and infrared drying
IR+HAD	Two-stage sequential infrared and hot-air drying
IIR+HAD; IIRCD	Intermittent infrared and hot-air drying
SEM	Scanning electron microscope
$w.b$	Wet basis
$d.b$	Dry basis
$ANOVA$	Analysis of variance
SEC	Specific energy consumption *(MJ/kg)*
PR	Pulse ratio
DR	Drying rate *(kg/kg min)*
t_{on}	Total infrared "on" time (s)

t_{off}	Total "off" time of infrared radiation (s)
t_{tol}	Total time of drying *(h)*
d_e	Distance between IR emitter and sample *(cm)*
T	Temperature *(°C or K)*
v	Air velocity *(m/s)*
HA	Hot-air
SR	Shrinkage ratio
L*	Lightness index
a*	Redness index
b*	Yellowness index
$\triangle E$	Total colour change
D_{eff}	Effective moisture diffusivity *(m^2/s)*
SR	Shrinkage ratio
V_s	Volumetric shrinkage ratio
S_v	Degree of sample shrinkage *(%)*
A_b	Illuminated area
P	Perimeter
A_0	Initial surface area
P_0	Initial perimeter
A_{0b}	Initial illuminated area
ANN	Artificial neural network
E_1	Energy required for the infrared bulb emitter *(MJ),*
E_2	Energy required for the hot air *(MJ)*
M_w	Total moisture removed by drying *(kg)* or Moisture content (wet basis)

c	Moisture concentration (kg/m^3)
T	Temperature *(^oC)*
ρ	Density (kg/m^3)
C_p ; C_{ps}	Specific heat capacity of sweet potato (J/kgK)
k	Thermal conductivity (W/mK)
QIF	Volumetric infrared heat source *(W/m^3)*
q_{IF}	Heat absorbed by sweet potato *(W)*
α	Absorption coefficient
δ	Infrared penetration depth *(mm)*
P_0	Radiation heat transfer *(W)*
ε_{IF}	Infrared emitter emissivity
ε_s	Emissivity of the sweet potato
$F_{s,IF}$	View factor between the infrared emitter surface and sweet potato
$F_{IF,w}$	View factor between infrared emitter and the wall
$F_{w,s}$	View factor between sweet potato and the wall
σ	Stefan-Boltzmann radiation constant
T_{IF}	Temperature of the emitter *(^oC or K)*
T_s	Temperature of the sample surface *(^oC or K)*
R_t	Total thermal resistivity
m_0	Initial mass of sample *(kg)*
m_d	Mass of dried sample *(kg)*
h_c; h_T	Heat transfer coefficient *(W/m^2K)*
h_m	Mass transfer coefficient *(m/s)*
T_{air}; T_∞	Drying air temperature *(^oC or K)*

H_{vap}; h_{fg}	latent heat of evaporation (J/kg)
c_b	Bulk moisture concentration (kg/m^3)
C_p	Specific heat capacity (J/kgK)
k_p	Thermal conductivity of product (W/mK)
A_0	Initial surface area of sweet potato *(m^2)*
A	Surface area of sweet potato at time, *t* (m^2)
ρ_w	Density of water (kg/m^3)
ρ_s	Density of sweet potato (kg/m^3)
E_a	Activation energy (kJ/mol)
R_g	Universal gas constant (J/mol/K)
D_0	Diffusion integration constant (m^2/s)
ρ_a	Density of air (kg/m^3)
μ_a	Dynamic viscosity of air *(kg/ m.s)*
μ_w	Dynamic viscosity of water *(kg/ m.s)*
μ_v	Dynamic viscosity of vapour *(kg/ m.s)*
v	Drying air velocity *(m/s)*
k_a	Thermal conductivity of air *(W/ (K.m))*
C_{pa}	Specific heat capacity of air (J/kgK)
a_w	Water activity
ΔV	Sum of the gas, water and solid volume (m^3)
ΔV_g	Volume of gas (m^3)
ΔV_w	Volume of water (m^3)
ΔV_s	Volume of solids (m^3)
φ	Apparent porosity
S_g	Gas saturation

S_w	Water saturation
K_{evap}	Evaporation constant
M_v	Molecular weight of vapour *(kg mol^{-1})*
M_a	Molecular weight of air *(kg mol^{-1})*
M_g	Molecular weight of gas *(kg mol^{-1})*
P_{amb}	Ambient pressure *(Pa)*
P_w	Total flux of liquid water
R_{evap}	Liquid water evaporation to water vapour (kg/m^3s)
K_g	Intrinsic permeability of gas *(m^2)*
P_{vair}	Air vapour pressure *(Pa)*
D_{va}	Binary diffusivity (m^2/s)
C_{pv}	Specific heat capacity of vapour (J/kgK)
C_{pw}	Specific heat capacity of water (J/kgK)
$K_{th,s}$	Thermal conductivity of sweet potato (W/mK)
$K_{th,g}$	Thermal conductivity of gas (W/mK)
$K_{th,w}$	Thermal conductivity of water (W/mK)
W_v	Vapour mass fraction
MLP	Multi-layered perceptrons
CCD	Charge-coupled device
CV	Computer vision
PLS	Partial least square regression

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Sweet potato is the fourth most important food crop after the cereal wheat, rice and corn in global crop production. According to FAO statistics, the world output in 2016 was 105 million tons harvested on 8.6 million hectares of land with an average yield of 12.2 tonne/ha (FAO, 2018). In developing countries, Asia in particular has focused on sweet potato's potential for continued rapid expansion in the decades ahead (Singh, 2008; Walker et al., 2011). Opportunities for industries are a topic of added interest given the magnitude of future food requirements in the wake of rising incomes, growing urbanization, and the sheer numbers of Asian consumers (Scott and Suarez, 2012).

Most food and agro-allied industries around the world, including Malaysia, rely heavily on sweet potato slices to produce flour, starch, flake, crisps and chips. Sweet potato is rich in vitamins, minerals, antioxidant, dietary fibre and fatty acids which are important to human health (Andre et al., 2017; Lee & Lee, 2017; Nabubuya, 2012; Oladejo et al., 2017). The processing of sweet potato into flour, flake, starch and other bakery products is the most satisfactory method of creating a product that is not only functionally adequate, but also remains stable for an extended period without spoilage (Hanim et al., 2014). Sweet potato flour can also be used to produce cakes, muffins, cookies and noodles, extruded snacks and chiffons (Zainun et al., 2005). Overall, sweet potato can enhance human health, improve the revenue of farmers and processors, and ultimately generate wealth for a country. However, the efficient production of sweet potato and its products has been limited due to inadequate processing and preservation techniques (Yadav et al., 2006a; Yadav et al., 2006b). Therefore, adequate processing and preservation techniques for agricultural crops, sweet potato in particular, must be developed to reduce wastage, promote food security and improve product quality.

Drying is one of the oldest and important food processing and preservation method. It involves the removal of moisture from a material due to simultaneous heat and mass transfer (Hashim et al., 2014; Akpinar, 2006). Drying increases shelf life, reduces product weight and volume thereby reducing the cost of storage, packaging and transportation (Doymaz, 2005). Drying may also be the most important unit operation for most industrial processes (Onwude et al., 2016). However, it is the most energy intensive process that could consume up to 10-25% of total energy required in most industrial processes (Chua et al., 2000), and about 10-15% of the total energy demands of food and agro-allied industries in most developing countries (Klemes et al., 2008). Furthermore, drying affects the quality of dried products including discoloration, loss of flavour, textural changes, degradation of bioactive compounds, changes in shape and physical appearance (Erbay & Icier, 2009; Firouzi et al., 2017; Salarikia et al., 2016). Recently, novel hybrid drying technologies have emerged as potential methods to reduce the energy demands and improve the qualities of dried food and agricultural commodities.

The combination of infrared (IR) heating and hot-air drying (HAD) technique have been investigated as a viable method for obtaining high quality dried food stuffs, including fruits, vegetables and grains (Chayjan et al.,2014; Hafezi et al., 2015; Hebbar et al., 2004; Pekken et al., 2013; Tog, 2006). However, as the application of this drying technique on agricultural crops is still in its infancy, several aspects regarding to its effectiveness in order to encourage commercialisation and industrial acceptability have not yet been investigated and fully understood. Therefore, a comprehensive study that will include the potential of applying non-destructive monitoring approach, the most suitable combination strategy and the development of adequate theoretical model in oder to improve efficiency becomes indispensable.

Physical properties of agricultural crops, including moisture content, shrinkage and colour, are important quality parameters that affect the acceptability of dried agricultural products (Onwude et al., 2017). The monitoring of these physical properties of fruits and vegetables during drying is still carried out using conventional techniques.

Conventional method of monitoring the drying process of most fruits and vegetables includes measuring the changes in sample weight using weighing balance. This approach is erroneous as the sample may lose or gain some moisture content due to heat loss or gain in the surrounding. Besides, alternative practice involving contact measurements, like the use of colorimeter still lack the accuracy to explain the overall quality in varying samples during drying. More so, the quality of the final product is affected by changes in the textural and structural properties. These changes, which is caused by shrinkage of samples, is determined by analyzing the sample size and change in volume (Yadollahinia & Jahangiri, 2009), which is often done destructively. The shrinkage values obtained using these destructive methods could affect the accuracy and efficiency of the drying process in terms of optimization and modelling, as they are required drying parameters. Therefore, monitoring the shrinkage and changes in color parameters during drying process will need a more efficient, non-destructive and rapid equipment to overcome the problem. Consequently, inspection systems for fruits and vegetables during drying by using the backscattering imaging system couple with computer vision becomes a viable alternative for conventional methods.

Computer vision (CV) has increasingly been applied in most post-harvest processes, including drying. It has been used as a non-destructive method for detecting various quality properties of different agricultural crops, such as ripeness, colour, moisture content, shrinkage, firmness and soluble solids contents (SSC) (Hashim et al., 2010; Mohd Ali, Hashim et al., 2017). Although, CV may be suitable in monitoring the quality properties of agricultural commodities during several postharvest processes, it is inadequate in describing the changes in the tissue of agriculture crops during drying. Thus, the application of laser-light backscattering imaging system as a rapid and concise non-destructive monitoring technique becomes a viable option.

Laser-light induced backscattering imaging has recently been developed for monitoring changes in the quality parameters during the post-harvest processing of fruits and vegetables (Adebayo et al., 2016). This technique has the potential to provide a low-cost rapid evaluation for the drying process. The combination of computer vision and laser-light backscattering imaging technique provides an even more novel, rapid and objective medium of quality evaluation during drying. However, studies using these non-destructive imaging approach in monitoring the changes in shrinkage and colour parameters during drying of sweet potato slices do not exist.

Apart from the non-destructive monitoring of quality parameters during combined IR and HAD of sweet potato, the overall quality of the dried products also relies on the different modes of heat interaction such as simultaneous heating, intermittent heating and the two-stage sequential heating (Zhang et al., 2017b). This is because of the vast differences in internal and external properties of agricultural commodities, resulting in different degree of deterioration, discolouration, energy requirement, drying rate, shrinkage amongst others. It is therefore pertinent to determine the most appropriate infrared and hot-air combination strategies in order to improve the overall drying efficiency and enhance the quality of dried sweet potato slices. In these regards, the most suitable infrared and hot-air combination strategies have not been developed.

Mathematical modelling studies of the different combination strategies for IR and HAD of agricultural crops remain under-developed. In fact, there is no mathematical modelling study on the IR and HAD of sweet potato. The determination of mathematical modelling parameters regarding to changes in the physical properties of agricultural crops during drying is still carried out using conventional montoring techniques. There is no modelling study on the use of non-destructive method to monitor the changes in product's physical properties during IR and HAD. The development of physics-based theoritical models for IR and HAD of agricultural crops is essential to give a physical interpretation of the heat and mass transfer mechanism, improve the efficiency of the drying process, optimise the drying process and to improve the final product quality. Therefore, this study aims to develop a comprehensive study including mathematical models for IR and HAD of sweet potato slices.

1.2 Problem Statement

Conventional drying methods are widely used for preserving and processing of agricultural commodities in the industry. In particular, HAD method is most common for commercial and industrial processing of food. This drying technique is naturally harmless and non-toxic. However, it is energy demanding and could affect the quality of final product due to longer drying duration (Łechtańska et al., 2015; Zhang et al., 2017). Consequently, novel and innovative drying techniques have gained significant interest in recent years. IR and HAD of agricultural crops have been studied as one of the novel drying techniques with particular emphasis on its design, and drying kinetics. There are also few studies on its energy demand and effects of drying condition on product final quality. However, a comparative study on IR and HAD of agricultural crops is required. This is important in identifying the most suitable drying condition for optimising IR and HAD parameters.

Considering the complex nature of IR and convective heating, couple with the complexity of food product properties, an appropriate IR and HAD combination strategy is required for increased efficiency, reduced energy consumption and to improve quality of final product. In this regard, there is no known study on the performance of different IR and HAD combination strategies.

Sweet potato, just like other vegetables undergo prominent changes ranging from physical to mechanical during the drying process. These changes include: porosity, textural, density, volume, colour, size and cellular changes amongst others. A common phenomenon associated with some of these changes is the shrinkage effect. Moreover, during the drying process, the colour of a product begins to change due to degradation in some phytochemical properties such as carotenoid content (Bualuang et al., 2017; Ong & Law, 2016; Yadav et al., 2006). All these processes that takes place in the product tissues during drying need to be properly understood and monitored in order to improve the drying process and also relevant equipment design. The evaluation of shrinkage and colour properties is currently carried out using conventional methods. There are few studies on the use of combined computer vision and laser-light backscattering imaging system as an accurate, rapid and affordable technique to monitor and evaluate the changes in product quality during drying of agricultural products (Udomkun, Nagle, Argyropoulos, Mahayothee, & Müller, 2016; Udomkun, Nagle, Mahayothee, & Müller, 2014). These studies did not consider the effect of sample thickness on shrinkage and only focused on the use of optical area and intensity parameters in predicting the shrinkage of papaya during drying based on multilinear regression technique. This statistical approach may also not provide adequate relationship between input parameters and shrinkage parameters and may be difficult to employ in in-line monitoring, control and optimisation of shrinkage phenomenon during drying. To the candidate's knowledge, studies on the use of combined CV and laser-light backscattering monitoring techniques for sweet potato during drying do not exist. In view of this, an extensive study on combined CV and laser light backscattering imagingsystem for monitoring the changes in physical properties of sweet potato during drying is required.

In practice, water loss in food and agricultural products are often described and modelled as a lumped process, which assume no internal water movement in the tissue (Nadi et al., 2012; De Smedt et al., 2002). Such empirical model offers no physical meaning in the actual water transport processes within the tissue. For this reason, Kucuk et al. (2014) recently criticized the use of empirical models in describing the drying process of agricultural crops. Thus, more advanced models, which will include the heat and mass transport of moisture in the tissue becomes indispensable.

Recently, a few researchers have developed heat and mass transfer models for infrared and infrared assisted drying (Jaturonglumlert & Kiatsiriroat, 2010; Salagnac et al., 2004). However, these models did not consider key drying phenomenon such as shrinkage and evaporation. For better understanding of the heat and mass transfer mechanism during combined IR and HAD, more robust mathematical model that will take cognisance of key drying factors as well as phase change and fluxes inside the product during drying is essential. However, such a model does not exist. In addition, there is no known heat and mass transfer model for the intermittent IR and HAD of agricultural crops. Therefore, a comprehensive mathematical model representing the physics behind heat and mass transfer mechanism for combined infrared and hot-air drying of sweet potato is needed. Thus, mathematical models considering single phase and non-equilibrium multi-phase change were developed in this study.

1.3 Objectives

The primary objective of this study is to investigate experimentally, the efficacy of combined infrared and hot-air drying of sweet potato slices and to develop a comprehensive mathematical model to describe the physics behind the heat and mass transfer process. In order to achieve the primary objective, the specific objectives of this study are:

i. To investigate the potential of computer vision and laser-light backscattering imaging system in evaluating the shrinkage of sweet potato during drying and to model the shrinkage of sweet potato slices during drying using artificial neural network (ANN).
ii. To investigate the potential of using computer vision and laser light backscattering imaging system in monitoring and predicting quality properties of sweet potato during drying.
iii. To determine the efficacy of convective hot-air, infrared, and combined infrared and convective hot-air drying methods for sweet potato.
iv. To evaluate the performance of different strategies for combined infrared and hot-air drying of sweet potato.
v. To evaluate a single-phase coupled heat and mass transfer model for describing the mechanism of simultanous combined infrared and hot-air drying of sweet potato.
vi. To model the single-phase transport process of sweet potato during intermittent infrared and hot-air drying.
vii. To develop a multiphase theoretical model for combined infrared and hot-air drying of sweet potato considering transport of liquid water, vapour and air fluxes.

1.4 Significance and scope of study

This study has investigated the application of computer vision couple with laser-light backscattering imaging system emitting at 658 nm wavelength in evaluating the changes in the physical properties of sweet potato (*Ipomoea batatas L.)* slices during drying. The imaging parameters were extracted based on an algorithm developed using MATLAB software (Version R2016a; Mathworks Inc., Natick, MA, USA). ANN and PLS were used in developing a correlation between the imaging parameters and the physical properties of shrinkage, moisture content, and colour of sweet potato (*Ipomoea batatas L.)* slices. This imaging technique provides an accurate and rapid means of determining shrinkage and colour parameters used in evaluating the drying process performance and also in developing mathematical models. The findings of this study are essential in optimising the drying parameters in order to improve product quality based on physical properties.

The efficacy of combined IR and HAD for sweet potato (*Ipomoea batatas L.)* slices was also studied. This was done by comparing the performance of combined IR and HAD with those of HAD and IR alone based on physical properties of sweet potato slices. The drying parameters used were IR intensity of 1,100 and 1,400 W/m^2, drying air temperature 50 – 70 ºC, air velocity of 1.16 m/s and sweet potato slice thickness of 4-6 mm. The findings of this investigation are useful in selecting the most suitable drying parameters and thickness for mathematical model validation. The results of this study can also describe the comparative advantages of combined IR and HAD over other thermal drying methods.

The performance of simultaneous, intermittent and two stage combined IR and HAD strategies was investigated for sweet potato (*Ipomoea batatas L.)* with varying drying air temperature from 50 – 70 ºC, 1.2 m/s air velocity, IR intensity of 1100 W/m^2 and 4 mm sweet potato slice thickness. The essence was to identify the best combination strategy for reduced energy consumption and improve quality of final product, in terms of physical product attributes which are important factors for the industrial selection of an ideal drying approach.

This research also developed a novel and the only comprehensive mathematical model of combined IR and HAD, for better understanding of the heat and mass transfer process for sweet potato (*Ipomoea batatas L.)*. The model considered 3D and 2D electromagnetics for IR heating and different components of phase change during heat and mass transfer. The water fluxes, vapour fluxes, temperature distribution and re-distribution during the drying process were studied. Since these phenomena are the key to avoiding overheating during drying process, the developed models can therefore contribute immensely in improving the quality of dried products. In this study, the IR heating source were modelled based on Lambert's Law of radiation. The single-phase and multiphase model simulations were done using COMSOL commercial finite element engineering software, and MATLAB software (Version R2016a; Mathworks Inc., Natick, MA, USA) installed on a local computer (window 10, 12GB ram, core i5), respectively. The developed models and simulations are essential in the drying field, for all stake holders in the value chain of agricultural crop processing. These mathematical models are based of fundamental theories and therefore can be easily modified and adapted to any agricultural crop with little effort. The models developed in this study will also help future researchers in developing similar models for other food and agricultural processing systems, as well as their optimization. The implementation of these models in the food and agro-allied industries can also reduce the energy consumption, increase drying efficiency, improve final product quality and reduce the overall cost of production.

1.5 Thesis Layout

This thesis is organised into ten chapters. The background of the study, the knowledge gap, problem statement, research objectives, significance and scope of research are described in Chapter 1. Chapter 2 gives a comprehensive review of the study based on the study objectives. A review on sweet potato, non-destructive imaging methods, combined infrared and hot-air drying, and heat and mass transfer modelling is presented in Chapter 2. Furthermore, the chapter also presents key literature findings and gaps.

The potential of computer vision and laser-light backscattering imaging system in evaluating the changes in shrinkage, moisture content and colour properties of sweet potato during drying is presented in Chapter 3 and Chapter 4. Chapter 3 gives a detail study on the application of computer vision couple with laser-light backscattering imaging and artificial neural network (ANN) modelling in evaluating the shrinkage of sweet potato during drying. The evaluation of moisture content and colour changes during drying using combined computer vision and laser-light backscattering imaging parameters are presented in Chapter 4.

Chapter 5 and Chapter 6 presents the performance of IR and HAD as well as the different combination strategies for sweet potato. A comparative study of combined IR and HAD, IR, and HAD for sweet potato based on drying kinetics, specific energy consumption, effective moisture diffusivity, colour and microstructural changes is presented in Chapter 5. Chapter 6 gives a detailed study on the performance of simultaneous, intermittent and two-stage combined IR and HAD of sweet potato based on drying kinetics, drying time, shrinkage, specific energy consumption, colour and microstructural changes.

The gradual development of comprehensive IR and HAD models are presented in Chapter 7-9. Chapter 7 gives detail study of the development and validation of a single-phase couple heat and mass model for simultaneous combined IR and HAD of sweet potato. A single-phase couple heat and mass model for intermittent combined IR and HAD of sweet potato is presented in Chapter 8. Chapter 9 presents the development and validation of multiphase couple heat and mass transfer models for both simultaneous and intermittent IR and HAD of sweet potato. The general conclusion and recommendations of this study is presented in Chapter 10. Chapters 2-9 contribute to individual publications for this study. An overview of the thesis Chapters is presented in Figure 1.1.

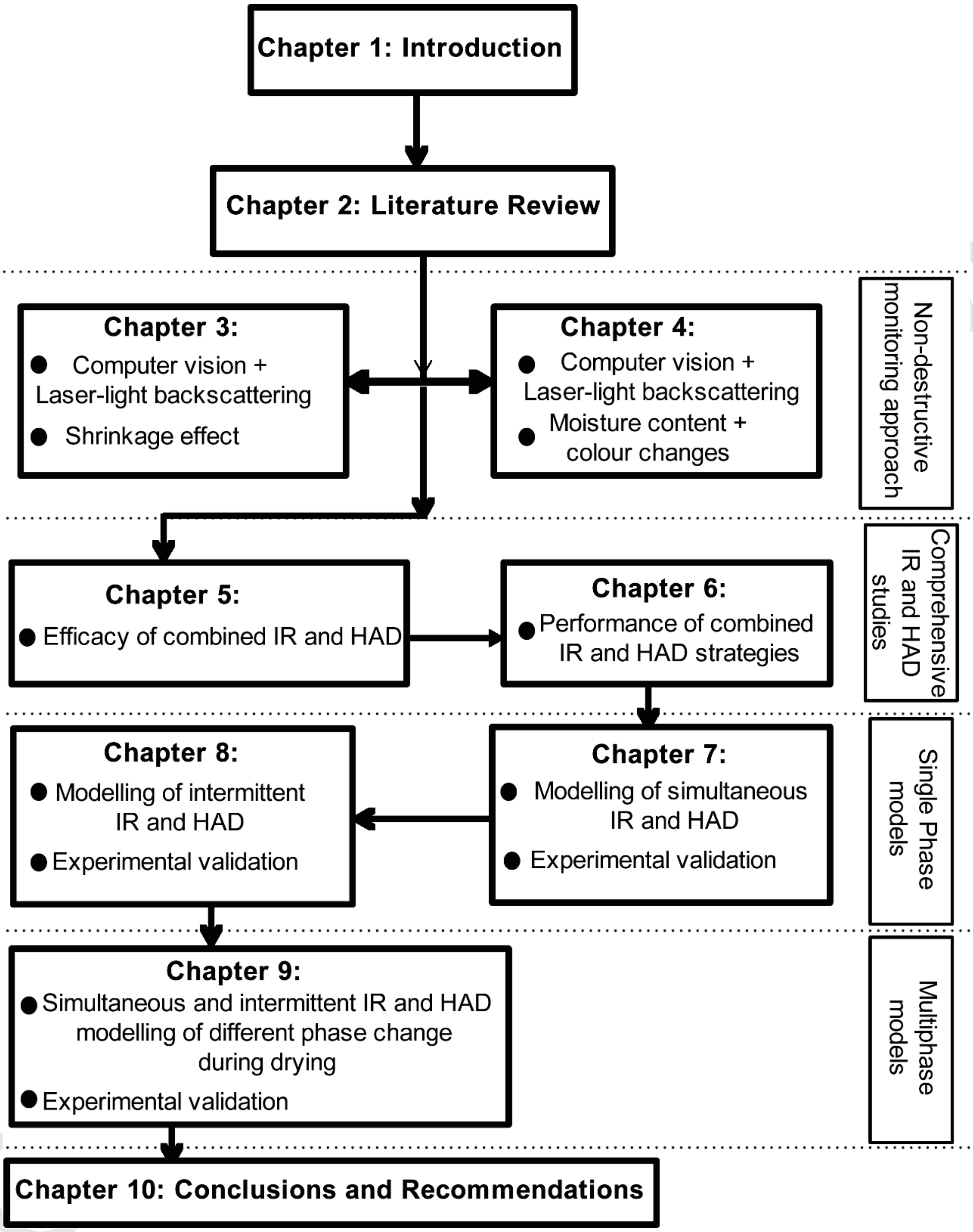

Figure 1.1 : Organisation of the thesis chapters

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