UNIVERSITY OF NAIROBI

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DEPARTMENT OF ENVIRONMENTAL AND BIOSYSTEMS ENGINEERING

Modelling and Optimization of Forced Convection Cooling and Hot-Air Drying for the Preservation of the purple-speckled Cocoyam Cultivar

By

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A thesis submitted for examination in partial fulfilment of the requirements for the award of the degree of **Doctor of Philosophy in Environmental and Biosystems Engineering**, in the Department of Environmental and Biosystems Engineering of the University of Nairobi

2021

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-ii-

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Dedication

To my dear wife Esther for your unrelenting love, prayers and encouragement for the whole duration of my studies.

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Abbreviations, Greek symbols, subscripts and superscripts

Abbreviation	**Meaning**
a*	Colour ratio between green and red
a_w	Water activity
A	Lag factor, dimensionless
AOAC	Association of Official Analytical Chemists
b*	Colour ratio between blue and yellow
B	Blanching pretreatment
Bi	Biot Number, dimensionless
BI	Browning Index
B+SM	Blanching and sodium metabisulfite pre-treatment
CCC	Concordance Correlation Coefficient
CFD	Computational Fluid Dynamics
CI	Confidence interval
CIE	International Commission on Illumination
D	Diameter
DI	Desirability index
db	Dry-basis
DM	Dry Matter
DR	Drying rate
DT	Drying time
E_s	Specific energy demand
ΔE	Total colour difference
Fo	Fourier Number, dimensionless
h	Convective heat transfer coefficient
$J_0()$	Bessel function of the first kind, order 0, dimensionless
$J_1()$	Bessel function of the first kind, order 1, dimensionless
k	Thermal conductivity, $W.m^{-1}. K^{-1}$
kNN	k-Nearest Neighbours
L	Length, m
L*	Lightness
LCL	Lower confidence limit
LOA	Limits of Agreement
L.LOA	Lower limit of agreement

LV	Latent Variable
M	Mass
MA	Moving Average
MAPE	Mean Absolute Percentage Error
MC	Moisture Content
MR	Moisture Ratio
MSC	Mean Scatter Correction
n	Sample size
N	Control pretreatment
Nu	Nusselt Number, dimensionless
p.a.	Per Annum
PC	Pore circularity
PCA	Principal Component Analysis
PCR	Principal Component Regression
PLSR	Partial Least Squares Regression
PPA	Percentage pore area
Pr	Prandtl Number, dimensionless
Q	Energy, (kJ)
r_o	Initial radius, m
Re	Reynolds Number, dimensionless
RF	Random Forests
RMSE	Root Mean Squared Error
RPD	Residual Prediction Deviation
RSA	Radical Scavenging Activity
RTD	Resistance Temperature Detector
S	Characteristic length, m
SDG	Sustainable Development Goal
SEM	Scanning Electron Microscopy
SMDAPE	Symmetric Median Absolute Percentage Error, %
SVM	Support Vector Machines
RR	Rehydration Ratio
RSM	Response Surface Methodology
t	Time
T	Temperature

TAA	Total Antioxidant Activity
TFC	Total Flavonoid Content
TPC	Total Phenolic Content
UCL	Upper confidence limit
U.LOA	Upper limit of agreement
VIP	Variable Importance in Projection
Vis-NIR	Visible to Near-Infrared
V_s	Volumetric Shrinkage
wb	Wet-basis
WI	Whiteness Index

Greek Symbols	**Meaning**
Ω	Temperature difference, dimensionless
λ	Eigen value, dimensionless
α	Thermal diffusivity, $m^2.s^{-1}$
∞	Ambient
ρ	Density, $kg.m^{-3}$
μ	Dynamic viscosity, ($kg.m^{-1}. s^{-1}$)
ϑ	Velocity, $m.s^{-1}$

Subscripts	**Meaning**
1	One-term approximation
a	Air
c	Cylinder
co	Core
T	Total
skn	Under the skin
s	Slab
sc	Short cylinder

ABSTRACT

Purple-speckled cocoyam (*Colocasia esculenta (L.) Schott*) is a tuber crop cultivated and consumed in tropical and subtropical regions of the world for food. Whereas cocoyam significantly contributes to the food and nutrition in regions of the world where it is grown, its uptake and commercialization are hampered by seasonality and poor storability in the fresh form due to the high moisture content of the tubers. This study set out to establish the flow of raw materials, post-harvest handling operations and key actors as cocoyam tubers move from the farm to storage or processing plants to the final consumer. The study identified the challenges in post-harvest preservation, value addition and storage of fresh tubers. The results of the baseline survey informed investigations into forced convection cooling and hot-air drying as potential methods for post-harvest preservation, value addition and storage.

The baseline survey was undertaken in Meru and Nairobi City counties to collect information on the structure and functioning of the cocoyam value chain. An assessment of the on-farm storage methods for fresh tubers revealed incidences of tuber rot due to poor control of storage environmental factors including temperature, relative humidity and air circulation. Open sun drying on tarpaulins was also utilised for on-farm preservation but extensive preservation and value addition was undertaken in agro-processing plants that produced puree and blended flours from a variety of crops. The purees and blended flours were processed further into porridge flour and baked goods. The solar greenhouse drying operation in the production process was constrained by daily weather changes which influenced drying temperature, relative humidity and wind speed. The compounded effect of this and non-uniform slice and chip sizes resulted in variations in drying rates, increased drying time and adverse changes in product quality. These findings informed investigations on hot-air drying to establish the optimal settings to improve the drying rate, drying and the retention of product quality.

In this study, forced convection cooling of whole purple-speckled cocoyam tubers under various levels of air velocity (0.5, 0.7, 0.9 $m \cdot s^{-1}$), tuber size (small, large) and tuber orientation to airflow (across, along) was investigated. The cooling time was found to be significantly influenced by the air velocity ($p < 0.0001$) and the tuber size ($p < 0.0001$) but not the orientation of tubers to airflow. Moreover, the energy removed from the corms was significantly influenced by the tuber size ($p < 0.0001$) but not the air velocity and the orientation of tubers to airflow. A prediction model based on transient heat transfer was developed to predict forced convection cooling time and the amount of field heat to be removed.

The drying behaviour of cocoyam and the effect of drying temperature (40 °C, 60 °C and 75 °C), slice thickness (4 mm, 7 mm and 10 mm) and pre-treatments (blanching in boiling water for 3 min, blanching in boiling water for 3 min followed by dipping in 0.1 per cent sodium metabisulfite for 5 min) and control samples were investigated. The process criteria and quality criteria considered included the total drying time, rehydration ratio, colour difference, browning index and specific energy consumption. The drying process exhibited a two-stage falling rate behaviour with kinetics best modelled by the Two-term Exponential, Peleg and Midili models. Non-pretreated cocoyam slices performed better than pretreated slices in terms of decreased drying time, total colour change (ΔE), browning index (BI) and specific energy consumption (E_s) except rehydration ratio (RR) at all process settings. At the parameter space investigated, numerical optimisation results revealed that the most suitable drying conditions were at a drying temperature of 75 °C, slice thickness of 4 mm and without pre-treatment, which yielded a composite desirability index of 0.78. These settings resulted in a drying time of 109 min, ΔE of 2.4, BI of 9.96, RR of 0.7 and E_s of 6,119.3 kJ/kg.

Hyperspectral Imaging, HSI (400 – 1700 nm) and chemometrics were successfully implemented to develop models to predict changes in quality attributes of purple-speckled cocoyam slices subjected to hot-air drying. The quality attributes considered included; moisture attributes, colour attributes, chemical attributes and structural attributes. In this study, 19 optimal wavelengths in the spectral range 400 – 1700 nm were selected using PLS-BETA and PLS-VIP feature selection methods. Prediction models for the studied quality attributes were developed from the 19 wavelengths. Excellent prediction performance ($RMSE_P < 2.0$, $r^2_P > 0.90$, $RPD_P > 3.5$) was obtained for MC, RR, V_S and a_w. Good prediction performance ($RMSE_P < 8.0$, $r^2_P = 0.70 – 0.90$, $RPD_P > 2.0$) was obtained for PC, BI, CIELAB b*, chroma, TFC, TAA and hue angle. Additionally, PPA and WI were also predicted successfully. An assessment of the agreement between predictions from the non-invasive hyperspectral imaging technique and experimental results from the routine laboratory methods established the potential of the HSI technique to replace or be used interchangeably with laboratory measurements.

In conclusion, this study has generated information on the structure and functioning of the cocoyam value chain in Kenya. It is hoped that this information will inform policy and guide future interventions aimed at improving production, post-harvest loss reduction and value addition. The information generated on forced convection cooling provides an understanding of the cooling behaviour of whole cocoyam tubers and is significant for the design and optimisation of forced convection cooling systems to precool tubers immediately after harvest and for long-term storage. Moreover, information on the drying behaviour and changes in quality attributes as presented provides critical input in the design and optimization of hot-air drying equipment for cocoyam tubers.

List of publications

This thesis constitutes research work contained in manuscripts either published, accepted for publication, submitted for publication in peer-reviewed journals or presented in scientific conferences and academic meetings. These are listed as follows;

1. **Papers and Manuscripts**

- Ndisya, J., Gitau, A., Mbuge, D., Arefi, A., Bădulescu, L., Pawelzik, E., Hensel, O., & Sturm, B. (2021). Vis-NIR Hyperspectral Imaging for Online Quality Evaluation during Food Processing: A Case Study of Hot Air Drying of Purple-Speckled Cocoyam (Colocasia esculenta (L.) Schott). *Processes*. 2021; 9(10):1804. https://doi.org/10.3390/pr9101804
- Ndisya, J., Mbuge, D., Kulig, B., Gitau, A., Hensel, O., & Sturm, B. (2020). Hot air drying of purple-speckled Cocoyam (Colocasia esculenta (L.) Schott) slices: Optimisation of drying conditions for improved product quality and energy savings. *Thermal Science and Engineering Progress*, *18*, 100557. https://doi.org/10.1016/j.tsep.2020.100557
- Ndisya, J., Mbuge, D., Roman, F., Gitau, A., Sturm, B., & Hensel, O. (2021). Simulation of unsteady-state heat transfer during forced convection cooling of whole Cocoyam (Colocasia Esculenta (L) Schott) tubers. *[manuscript submitted to Journal of Food Process Engineering]*.

2. **Conference papers**

- Ndisya, J., Gitau, A., Mbuge, D., Arefi, A., Bădulescu, L., Pawelzik, E., Hensel, O., & Sturm, B. (2021). Tropentag 2021: Towards shifting paradigms in agriculture for a healthy and sustainable future 14.09.2021 – 16.092021, Stuttgart, Germany
- Ndisya, J., Gitau, A., Roman, F., Mbuge, D., Kulig, B., Hensel, O. and Sturm, B (2021). Influence of air velocity and corm size on cooling behaviour. 5th CIGR International Conference 10.11. – 14.11.2021, Québec City, Canada.
- Ndisya, J., Mbuge, D.O, Kulig, B., Gitau, A.N, Hensel, O. and Sturm, B. (2019). Investigation of the drying behaviour of Cocoyam (Colocasia esculenta (L.) Schott). 15th RuForum Annual General Meeting 02.12 – 06.12.2019, Cape Coast, Ghana.

3. **Conference posters**

- Ndisya, J., Mbuge, D.O, Gitau, A.N, Kulig, B., Hensel, O. and Sturm, B. (2019). A scoping study of the Cocoyam (Colocasia esculenta (L.) Schott) Value chain in Kenya: Production, post-harvest handling and consumption behaviour. 15th RuForum Annual General Meeting 02.12 – 06.12.2019, Cape Coast, Ghana.

Table of contents

List of tables

List of figures

CHAPTER ONE: INTRODUCTION

1.1 Background

Food security is a subject of great global importance and by definition is attained 'when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life' (FAO, 1996). However, the combined effect of global climate change and the growing global population makes global food security complex and increasingly challenging (Poppy et al., 2014). Among many contributing factors, food loss and waste continue to threaten food security (van Gogh et al., 2017). Root and tuber crops have been touted as the next frontier in the achievement of food security especially in developing nations (Karya & Otsanjugu, 2019). This is because root and tuber crops have been proven to be resilient to both biotic and abiotic stresses in the face of climate change (Taylor et al., 2018). Moreover, root and tuber crops, are only second in importance to cereals as food crops in developing nations but provide more energy per day than cereals (Lebot, 2009; Q. Liu et al., 2014).

Cocoyam is a nutrient-dense tuber crop grown in the tropics and sub-tropics for food (Fern, 2018). Its uptake and commercialisation are however hindered by poor storability when fresh (Ndisya et al., 2020). Immediately after harvesting, the tubers undergo rapid rot or sprouting when stored under ambient conditions (Lewu et al., 2010; Opata & Ogbonna, 2015). As compared to other root and tuber crops including sweet potato, potato and cassava, limited post-harvest technologies and techniques have been developed for cocoyam (Lewu et al., 2010). Recent studies on the preservation of cocoyam tubers have mainly focused on the production of dried products and their derivatives (Aboubakar, Njintang, Scher, & Mbofung, 2009; Afolabi, Tunde-Akintunde, & Adeyanju, 2015; Kumar, Sharma, & Singh, 2017; Alcantara, 2013; Ndisya et al., 2020; Zhang et al., 2017). Traditionally, cocoyam tubers are either harvested for immediate consumption or left buried in the farm as a way of storage until needed (Opara, 2003). Moreover, infield storage not only ties-up land that could be used for a new crop but also affects the quality of the tubers. Infield storage beyond the optimal maturity age is associated with tuber rot (Modi, 2007; Wang & Higa, 1983) and decline in the quality of starch (Himeda et al., 2012). Documented improved storage methods include storage in traditional low-cost structures and pits (Opara, 1999), ventilated stores (Thompson, 2003) and refrigerated storage (Opara, 2003). These methods have registered widely varying degrees of success chiefly due to varying simplicity, performance and affordability. But none of these achieves the same level of success as refrigeration (Opara, 1999).

Maize and legumes are the leading smallholder staple crops relied upon for a year-round supply of food in Kenya (Kätterer et al., 2019; Mucheru-Muna et al., 2010). The effects of climate change are already being experienced in various ways in Kenya. Previous studies have predicted country-wide reduction in the production of key staples, increase in prices due to scarcity of the staples and lower accessibility to food which translates to a high incidence of malnutrition as a result of climate change (Herrero et al., 2010). Kenya is facing a widescale invasion by fall army-worms which in 2017 destroyed an estimated 70 per cent of the maize crop (World Vision Kenya, 2017) estimated to be 5million bags in quantity and 135 million Euros in value (Andae, 2019a). In 2019, maize production is projected to further reduce by 10million bags and the area under cultivation by 0.7million hectares due to recurring droughts (R. Shaw, 2019). The situation is exacerbated by declining soil fertility as a result of inadequate soil fertilisation (Kätterer et al., 2019). This has forced the Kenyan government to import food from the region and from outside Africa (Andae, 2019b).

A study by Transform Nutrition Research Programme Consortium (2011) found Kenyan diets to be mainly formulated from staple foods with a very limited range of micronutrients. This makes the country particularly susceptible to a phenomenon called 'hidden hunger'. Hidden hunger presents itself in the form of deficiency of vital micronutrients either as a result of inadequate food intake or intake of sufficient food but poor in micronutrients (Biro & Menon, 2014). An assessment of global hidden hunger indices by Muthayya et al. (2013) found Kenya to score an 'alarmingly high' index at 51.7, only second to Niger in the African continent indicating a severe deficiency of multiple micronutrients in Kenyan diets. The severity of hidden hunger is becoming more entrenched in modern African societies with the increase in the rate of rural to urban migration and abandonment of agriculture by the youthful generation. Evidence from Tanzania suggests that people migrating to urban areas neglect the consumption of traditional staple foods in favour of convenient and easy to access foods that are often unhealthy (Cockx et al., 2019). The same situation is also true for Kenya (Peters et al., 2019).
The Kenyan Government recently launched the Big Four Agenda policy document that provides the key areas of focus of government development from 2018 and beyond. Pillar Number 1 of the Big 4 agenda aims at improving the food security situation in the country by providing incentives for post-harvest technologies for value addition and decreasing overall post-harvest

losses to 15 per cent (Presidential Delivery Unit, 2021). Moreover, the right to food is anchored on Article 43 (1) (c) in the bill of rights of the Kenya Constitution 2010 which states that ‘every person has a right to be free from hunger and to have adequate food of acceptable quality’. The Kenya Vision 2030 document and its associated Medium-Term Plans (MTPs) is the blueprint of the country’s development priorities. Among other things, the document provides the overall direction for agricultural policy reforms aimed at improving the food security situation by the year 2030. This research, therefore, aims to contribute to the realization of the new development objectives towards the attainment of food security in Kenya.

There is a renewed interest in the production of traditional crops, including root and tuber crops in Kenya driven by a steadily increasing demand and a push by the government because they are often resistant to droughts, pests and diseases (NAFIS, 2011). Traditional crops provide a vital source of food and nutrition especially in the arid and semi-arid regions of Kenya (Muthoni & Nyamongo, 2010). Despite the potential of traditional crops to combat food insecurity and malnutrition, they remain largely neglected and underutilised in Kenya (FAO, 2009). Cocoyam in particular receives minimal attention from official research and is largely left out by government extensions services (FAO, 2017). Cocoyam is widely grown in West African countries such as Nigeria and Cameroon (Grimaldi & van Andel, 2018), but in Kenya, it is mainly grown by small-holder farmers for subsistence use (Munguti et al., 2012). Cocoyam has been shown to yield high quality starch per acre of land (Pereira et al., 2015), various micro-nutrients (Alcantara et al., 2013) and medicinal value (Grimaldi & van Andel, 2018). These aspects make cocoyam a nutritionally superior crop as compared to cereals.

General information on agronomy, production and post-harvest handling of various cocoyam varieties grown around the world are available in the literature (Agbor-Egbe & Rickard, 1991; Bamidele et al., 2015; Deo et al., 2009; Kaushal et al., 2015; Ndisya, Gitau, Roman, et al., 2021a; Pérez et al., 2007). However, information on the current structure and functioning of the Kenyan cocoyam value chain is unavailable. Additionally, direct linkages between the information available in the literature to the specific requirements of food processors and consumers in Kenya are not fully explored. This study sets out to map the cocoyam value chain in Kenya and to identify the actors and enablers in the cocoyam value chain; to establish production methods, quantities and post-harvest losses; postharvest handling operations, value-addition methods applied to cocoyam and technology gaps and viable interventions to improve postharvest handling and value-addition. These findings informed investigations on forced convection cooling and hot-air drying as methods for preservation, value addition and long-term fresh storage. It is hoped that the information and knowledge generated from this study will be of importance in promoting the adoption and marketability of cocoyam to improve food security, nutritional diversity, farmer incomes and alleviate rural poverty in accordance the SDG 1 (Ending poverty in all its forms everywhere), SDG 2 (Zero hunger) and SDG 12 (Sustainable consumption and production patterns) (United Nations, 2019a).

1.2 Problem statement and justification

The significance of roots and tubers, including cocoyam, is only second to cereals in many developing countries after cereals (Lebot, 2009). In comparison to cereals, root and tuber crops provide more energy per day (Q. Liu et al., 2014). Estimations of the evolution of global trade in food items for the current century placed emphasis chiefly on grains, oil crops and animals (Scott et al., 2000). Nevertheless, with the global population projected to surpass 8.5 Billion over the next decade (United Nations, 2019b), the amount of carbohydrates required to feed the population will surpass the production capacity of cereal farms (Lebot, 2009). For this reason, the significance of roots and tubers relative to mainstream food crops is projected to increase (Scott et al., 2000).

In as much as cocoyam supplements the carbohydrates and micronutrients consumed in the tropics and sub-tropics (Alcantara et al., 2013; Pereira et al., 2015), its full adoption hindered by its seasonal availability and low shelf life due to the high moisture content of the tubers (Rashmi et al., 2018). The wet-basis moisture content of cocoyam tubers is estimated to be 60 – 83 per cent contingent on growth conditions and maturity (Rashmi et al., 2018). Immediately after harvesting, the tubers undergo rapid rot or sprouting when stored under ambient conditions (Lewu et al., 2010; Opata & Ogbonna, 2015). Traditionally, cocoyam tubers are either harvested for immediate consumption or left buried in the farm as a way of storage until required (Opara, 2003). However, infield storage not only ties up land that could be used for a new crop but also affects the quality of the tubers. Infield storage beyond the optimal maturity age is associated with tuber decay and degradation of starch quality (Himeda et al., 2012; Modi, 2007; Jaw Wang & Higa, 1983). Therefore, cocoyam tubers must be harvested on time and preserved immediately to avoid spoilage and food losses. As compared to other root and tuber crops such as sweet potato, potato and cassava, limited post-harvest technologies and techniques have been developed for cocoyam (Lewu et al., 2010).

Existing studies have suggested that the shelf life and quality of rots and tubers and their products can be enhanced by techniques such as forced convection cooling and hot-air drying. Documented improved storage methods for fresh tubers include traditional low-cost structures and pits (Opara, 1999), ventilated stores (Thompson, 2003) and refrigerated storage (Opara, 2003). These methods have registered widely varying degrees of success chiefly due to varying simplicity, performance and affordability. But none of these achieves the same level of success as modified environment storage. Forced convection cooling is a technique commonly applied to improve the storage conditions of agricultural products in place of the comparatively expensive refrigeration methods (lal Basediya et al., 2013). Cooling preserves the natural quality of products by suppressing physiological, biochemical, and microbiological processes (Dehghannya et al., 2010). However, poorly designed cold storage can allow biotic and abiotic stress in the stored products and consequently result in loss in weight and degradation of the quality of the stored products. Therefore, proper design and control of cold storage can extend the shelf life and preserve the quality of fresh agricultural produce thereby making it available and nutritious for consumption long out of season.

Hot-air drying is popular both as a method of preservation and as an initial step in value-addition (Adeboyejo et al., 2021; Afolabi et al., 2015; Macmanus C. Ndukwu et al., 2017). Hot-air drying reduces the moisture content of food to hinder spoilage microorganisms and to slow down biochemical activity. Nonetheless, destruction of nutrients, flavour, visual appearance and bioactive compounds, texture and structure can occur in poorly controlled of hot-air drying processes (Prabhakar & Mallika, 2014). Additionally, hot-air drying is costly as a result high energy consumption accounting for 15 – 25% of industrial energy use. (Kemp, 2012; C. Kumar et al., 2014; Menon et al., 2020; Qu et al., 2021). Therefore, proper control of the hot-air drying processes can not only preserve product quality but also conserve energy (Kondakci & Zhou, 2017; Sturm, 2018).

1.3 Objectives

1.3.1 Overall objective

To model and optimize forced convection cooling and hot-air drying for the preservation of the purple-speckled cocoyam cultivar.

1.3.2 Specific objectives

i). To assess the preservation methods and technologies applied to cocoyam cultivars in Kenya.

ii). To model and optimize convective cooling of purple-speckled cocoyam at different process settings.

iii). To model and optimize hot-air drying of purple-speckled cocoyam at different process settings

1.4 Research questions

This study sought to answer the following research questions;

i). Which preservation methods and technologies applied to the cocoyam cultivars in Kenya?

ii). What are the optimal settings for forced-convection cooling of cocoyam tubers?

iii). What is the influence of drying settings on energy use during hot-air drying and on the quality attributes of dried cocoyam products?

iv). What are the optimal settings for hot-air drying settings of cocoyam tubers?

1.5 Scope of the study

The scope of this study is limited to the cocoyam tubers of the variety *Colocasia esculenta (L.) Schott* commonly referred to as 'Nduma' in Kenya. In this study, the scope of investigations was limited to an assessment of current preservation and value-addition techniques applied to cocoyam in Kenya; mathematical and numerical modelling of forced convection cooling processes and hot-air drying and the changes in quality attributes of whole cocoyam tubers and cocoyam slices.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter introduces the cocoyam crop and puts it into the global perspective of food security. The chapter provides a comprehensive review of preservation methods utilised to extend the shelf life of fruits and vegetables. Forced convection cooling and hot-air drying are then presented as viable preservation methods for fruits and vegetables and the analysis is narrowed down to root and tuber crops. Conventional and novel techniques for modelling and optimisation of forced convection cooling processes and hot-air drying to preserve product quality and improve energy efficiency are also presented.

2.2 Global food security perspectives

Food security is a subject of great global importance. This is because access to food of adequate quantity and quality is vital to the existence and survival of humankind. According to the World Food Summit 1996, food security is attained 'when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life' (D. J. Shaw, 2007). Presently, an estimated 12 per cent of the global population representing 928 million people were severely food insecure in 2020 with a large percentage of the people (700 million) in the developing world (FAO et al., 2021). Moreover, 149.2 million (22.0 per cent) of children under the age of five years suffered from stunting and a further 45.4 million children (6.7 per cent) were wasted (FAO et al., 2021). With the world population projected to increase to 9.7 billion people by 2050, an estimated 70 per cent more food than is consumed today will be needed to feed the world (Cole et al., 2018). Furthermore, the increased demand for food will occur alongside new challenges including a less predictable planet due to climate change, increased global wealth and urbanisation, quality-conscious consumers, ageing populations and increased chronic illnesses and connected global value chains that are susceptible to various risks (Cole et al., 2018; Hajkowicz & Eady, 2015). In this scenario, feeding the world sustainably will be a grand challenge (Cole et al., 2018).

In spite of the progress achieved by virtue of the sustainable development goals (SDGs) initiatives to end hunger, attain food security and improve nutrition, several challenges and opportunities are still being experienced (United Nations, 2019a). Small-holder farmers in a majority of rural areas still endure in food insecurity and malnourishment in spite of owning some resources to produce adequate staples (Sibhatu & Qaim, 2017). Moreover, the demand for convenient and healthy food such as processed fruits, vegetables is anticipated to increase fostered by the growth of urban areas and increasing incomes for urban inhabitants in developing countries (Satterthwaite et al., 2010; Shrestha, Crichton, et al., 2020).

2.3 Food security situation in Kenya

Maize and legumes are the leading smallholder staple crops relied upon for a year-round supply of food in Kenya (Kätterer et al., 2019; Mucheru-Muna et al., 2010). The effects of climate change are already being experienced in various ways in Kenya. Previous studies have predicted country-wide reduction in the production of key staples, increase in prices due to scarcity of the staples and lower accessibility to food which translates to a high incidence of malnutrition as a result of climate change (Herrero et al., 2010). Recently, Kenya faced a widescale invasion by fall army-worms which destroyed an estimated 70 per cent of the maize crop (De Groote et al., 2020; World Vision Kenya, 2017) estimated to be 5million bags in quantity and 135 million Euros in value (Andae, 2019a). In 2019, maize production further reduced by 10 million bags and the area under cultivation by 0.7million hectares due to recurring droughts (R. Shaw, 2019). The situation is exacerbated by declining soil fertility as a result of inadequate soil fertilisation (Kätterer et al., 2019). This has forced the Kenyan government to import food items such as grains and cereals from the region and from outside the continent (Andae, 2019b; Munda, 2021). This has seen a steady rise in the country's food import bill and the resultant household expenditure on food items (Munda, 2021).

Recent nutrition studies in the Sub-Saharan Africa region have established that found Kenyan diets to be mainly formulated from main staple foods with a very limited range of micronutrients (Keding, 2016). This makes the country particularly susceptible to a form of malnutrition called 'hidden hunger'. Hidden hunger presents itself in the form of deficiency of vital micronutrients either as a result of inadequate food intake or intake of sufficient food but poor in micronutrients (Biro & Menon, 2014). An assessment of global hidden hunger indices by Muthayya et al. (2013) found Kenya to score an 'alarmingly high' index at 51.7, only second to Niger in the African continent indicating a severe deficiency of multiple micronutrients in Kenyan diets. The severity of hidden hunger is becoming more entrenched in modern African societies with an increase in the rate of rural to urban migration and abandonment of agriculture by the youthful generation. Evidence from Tanzania suggests that people migrating to urban areas neglect the consumption of traditional staple foods in favour of convenient and easy to access foods that are often unhealthy (Cockx et al., 2019). The situation is also the same in Kenya (Peters et al., 2019).

2.4 Role of root and tuber crops in Kenya

The significance of roots and tubers, including cocoyam, is only second to cereals in many developing countries after cereals (Lebot, 2009). In comparison to cereals, root and tuber crops provide more energy per day (Q. Liu et al., 2014). Previous forecasts of the global demand, supply and trade in food for this century focused mainly on grains, oilseeds, and livestock (Scott et al., 2000). However, with the world population expected to exceed 8.5 Billion by 2030 (United Nations, 2019b), the demand for carbohydrates will exceed the production potential of areas set aside for the production of cereals (Lebot, 2009). In this scenario, the importance of root and tuber crops relative to other major crops is predicted to increase (Scott et al., 2000). This is especially the case in the face of climate change whose direct effects in the form of limited food access and utilization and indirect adverse effects on household and individual nutrition and incomes are already being felt (Wheeler & von Braun, 2013).

There is a renewed interest in the production of traditional crops, including root and tuber crops in Kenya driven by a steadily increasing demand and a push by the government because they are often resistant to droughts, pests and diseases (NAFIS, 2011). Traditional crops provide a vital source of food and nutrition especially in the arid and semi-arid regions of Kenya (Muthoni & Nyamongo, 2010). Despite the potential of traditional crops to combat food insecurity and malnutrition, they remain largely neglected and underutilised (CGIAR, 2020; FAO, 2009). Cocoyam in particular receives minimal attention from official research and is largely left out by government extensions services (FAO, 2017; Talwana et al., 2009). Cocoyam is widely grown in West African countries such as Nigeria and Cameroon (Grimaldi & van Andel, 2018), but in Kenya, it is mainly farmed by small-holder farmers for subsistence use (Munguti et al., 2012). Cocoyam has been shown to yield high-quality starch per acre of land (Pereira et al., 2015), various micro-nutrients (Alcantara et al., 2013) and medicinal value (Grimaldi & van Andel, 2018). These aspects make cocoyam a nutritionally superior crop as compared to cereals. Despite being an underutilised crop, opportunities for increasing production, value addition to the tubers and extending their shelf-life abound (CGIAR, 2020).

2.5 Cocoyam

2.5.1 Taxonomy and global distribution

Cocoyam (*Colocasia esculenta* (L.) Schott) is a perennial crop grown in the tropics and sub-tropics for food (Fern, 2018). According to Kokwaro (2015), two cocoyam varieties are belonging to the *Araceae family* are grown in the East-African region. Cocoyam (Old) is the

Colocasia esculenta (L) Schott also known as eddoe, dasheen or Taro (Lim, 2015; Rubatzky & Yamaguchi, 1997). Cocoyam (new) is the *Xanthosoma sagittifolium* (L) Schott also known as Malanga, Tannia or Yautia (Lim, 2015; Rubatzky & Yamaguchi, 1997). The naming of the crop is specific to a location in the world where it is grown. Cocoyam is important as a staple crop in the Pacific Islands, Asia and Africa (Akwee et al., 2015; Otekunrin et al., 2021). Within the East-African region, cocoyam is cultivated in Kenya, Tanzania, Rwanda and Burundi (Akwee et al., 2015; Munguti et al., 2012; Otekunrin et al., 2021; Talwana et al., 2009). In Kenya, the crop is locally known as 'Nduma' grown throughout the country where moisture is readily available (Akwee et al., 2015). The traditional growing areas include the Central, Rift-valley and Nyanza of Kenya.

2.5.2 Production, yields and economic value

Cocoyam thrives in wet tropical lowlands with temperatures of 20 – 30 °C, rainfall of up to 2500 mm p.a and soil pH of 5.5 – 6.5. (Anikwe et al., 2007; Onyeka, 2014). However, the crop also grows in artificial unflooded upland conditions away from the traditional wetlands (Adekiya et al., 2016; Anikwe et al., 2007; Tumuhimbise et al., 2020). This method enables farmers to grow cocoyam in moisture beds far away from wetlands with fewer water requirements thereby enabling them to expand their production boundaries (Otieno, 2017; Tumuhimbise et al., 2020). Like other crops, the yield of cocoyam varies with variety, location, soil type, and agronomic practices. As shown in Figure 2.1, Africa is the leading continent in the production of cocoyam followed by Asia in a distant second (FAO, 2021d). The world production of cocoyam as of 2019 is estimated to be 5.4 tonnes/ha (FAO, 2021b). The leading producers in the world in 2019 are Nigeria, Cameroon and China at 2.86, 1.91 and 1.90 million tonnes respectively (FAO, 2021c). However, in the East African region, the yields are higher at 6.5 tonnes/ha but the aggregate production is lower at 0.63 million tonnes in 2019 (FAO, 2021a). As shown in Figure 2.2, the average area under cocoyam production in Kenya in the duration 2009 – 2018 was 4278.23 Ha (MoALFC, 2019). However, the production steadily increased in the same duration from 16,872.00 tons in 2009 to 120,777.28 tons in 2018 (MoALFC, 2019). With the price per 50 kg bag of cocoyam tubers being KSh. 2,512.00, the economic value of cocoyam tubers produced in 2018 was KSh. 303.4 million or about USD 3 million[1].

[1]Official Central Bank of Kenya exchange rate on 28.12.2018: $1 = KSh. 101.81.

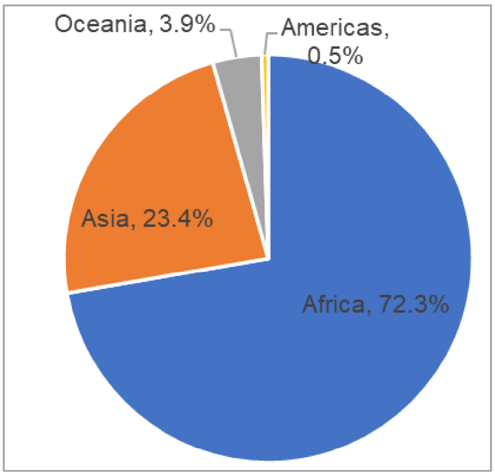


Figure 2.1: Production share of cocoyam by region in 2021 [Source: (FAO, 2021d)]

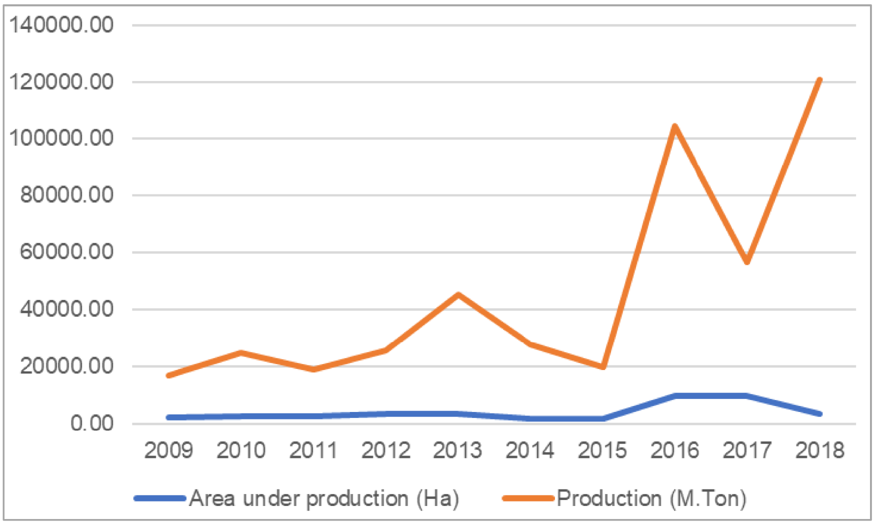


Figure 2.2: Cocoyam production and area under production in Kenya, 2009 – 2018 [Source: (MoALFC, 2019)]

2.5.3 Nutritional value and consumption

Table 2.1 provides macro- and micro-nutritional composition of the cocoyam variety grown in the East African region. Cocoyam tubers contain various macro and micronutrients (Alcantara et al., 2013; Pereira et al., 2015). Cocoyam tubers yield higher quality starch than potato, yam, cassava, sweet potato, rice and plantains (Pereira et al., 2015). The crop is rich in ascorbic acid, iron, phosphorus, zinc, potassium, copper and manganese (Alcantara et al., 2013). It also contains B-complex vitamins - thiamine, riboflavin, pyridoxine and niacin - at a quantity comparatively higher than in whole milk (Alcantara et al., 2013). Additionally, cocoyam is rich in diverse bioactive components that exert a strong antioxidant response making it popular not only as a food but also as an ethnomedical item (Eleazu, 2016; Pereira et al., 2015). These compounds may help to counteract free radicals that cause chronic health conditions (Balsano & Alisi, 2009; Ortega & Campos, 2019). In particular, the tubers contain anthocyanins (i.e., a component of flavonoids), particularly pelargonidin 3-glucoside, cyanidin 3-rhamnoside and cyanidin 3-glucoside (Ghan et al., 1977). These flavonoids are responsible for the pleasant pink to purple colour of the tuber flesh (Ghan et al., 1977; Moy et al., 1977). Cocoyam tubers provide a good carbohydrate base in the manufacturing of food for infants are a result of fine-sized starch grains which are easy to digest as compared to sweet-potato, cassava and yams (Adekiya et al., 2016; Otekunrin et al., 2021). In some regions, the leaves are also consumed as a vegetable or used as animal feed (Adekiya et al., 2016; Onyeka, 2014).

Table 2.1: Composition of the cocoyam grown along the Lake Victoria Basin (Ndabikunze et al., 2011)

Compound	Amount
Moisture content	68.7^{a}
Ash	2.69^{b}
Crude protein	3.8^{b}
Crude fibre	1.34^{b}
Fats	0.44^{b}
Carbohydrate	23.03^{b}
Potassium	715.39^{c}
Phosphorus	134.30^{c}
Copper	0.19^{c}
Iron	3.48^{c}
Zinc	4.32^{c}
Manganese	3.68^{c}
Calcium	68.67^{c}
Magnesium	83.76^{c}
Sodium	13.18^{c}

Superscripts: ^{a}-percent, ^{b}-g/100 g_{DM}, ^{c}-mg/100 g_{DM}

2.6 Forced convection cooling of food materials

2.6.1 Forced convection cooling for food preservation

Forced convection cooling is a common thermal treatment applied to fresh agricultural produce to remove field heat immediately after harvest and during storage to preserve product quality and extend the shelf life methods (Defraeye et al., 2014; lal Basediya et al., 2013). Forced convection cooling usually involves the provision of a low temperature and/or high humidity airstream to the storage environment of agricultural products (Kondjoyan, 2006). The objective is to provide the optimal storage conditions which retard physiological changes that could result in transpiration weight loss, degradation of colour, texture and nutritional quality and the growth of spoilage microorganisms and development of disease (Dehghannya et al., 2010; C.-J. Zhao et al., 2016).

The development of a forced convection cooling solution requires the knowledge of how the physical and thermophysical properties of the product interact with those of the cooling medium (Korese et al., 2017; van Gogh et al., 2017). Since forced convection cooling is chiefly a heat and mass transfer process, knowledge of the thermal properties of the product such as thermal conductivity, specific heat capacity and thermal diffusivity and physical properties such as bulk density and product dimensions are important in process design and engineering (Çengel & Ghajar, 2015; Sahin & Sumnu, 2006). These properties are dependent on the temperature, composition, and porosity of the product (Sahin & Sumnu, 2006). Thermal conductivity is an indicator of the ability of a product to conduct heat where products with high values of thermal conductivity are good conductors (Çengel & Ghajar, 2015). Thermal conductivity in food materials increases with an increase in moisture content in the food matrix (Sahin & Sumnu, 2006). The rate at which heat diffuses through a material is quantified by the thermal diffusivity which is a ratio between heat conduction and heat storage (Çengel & Ghajar, 2015). Materials with large values of thermal diffusivity exhibit a tendency to respond rapidly to temperature changes in the surrounding environment (Sahin & Sumnu, 2006). Specific heat capacity is the ability of a product to store heat energy (Çengel & Ghajar, 2015). Various analytical methods for the determination of thermophysical properties have been documented. However, models based on relative ratios of food components including protein, fat, ash, carbohydrate, fibre and water are suitable in the prediction of thermophysical properties (Choi & Okos, 1986; Sahin & Sumnu, 2006). Food component models have been utilised to predict thermophysical properties for sweet potato (Korese et al., 2017), berries (Costa et al., 2018), potato and carrot (J. Chen et al., 2014; Srikiatden & Roberts, 2008), mushroom (Tansakul & Lumyong, 2008) and black pepper (Ghodki & Goswami, 2017) among other products.

Forced-air convection cooling is the most popular method applied to extend the shelf life of fresh produce (Dehghannya et al., 2010). Previous studies have documented various forced convection cooling applications for precooling and storage of a wide variety of fruits and vegetables including sweet potatoes (Korese et al., 2017), apples (J.-W. Han et al., 2018; J. Han et al., 2017), citrus fruits (Defraeye et al., 2014; Hussain, Kamal, Alam, et al., 2021), peaches (Y. Chen et al., 2020), grapes (Dincer, 1995b), mushrooms (Salamat et al., 2020) and strawberries (Ferrua & Singh, 2009; Nalbandi et al., 2016; D. Wang et al., 2019) among other agricultural products. A properly designed forced convection cooling solution can enhance the storability of perishable products at the farm level to be consumed for an extended duration thereby improving household food and nutritional security. Transregional and transnational long-distance trade also benefit greatly from adequately cooled fresh food products (J. Han et al., 2017; Korese et al., 2017).

2.6.2 Food quality changes during fresh storage

Fruits and vegetables are living biological organisms that continue experiencing physiological changes including respiration, transpiration, and biosynthesis even after harvest (Kahramanoğlu, 2017; C.-J. Zhao et al., 2016). As a result, degradation in both quantity and quality continue after harvest until consumption (Kahramanoğlu, 2017). Quantitative degradation often results from the loss of weight as a result of losing organic materials and moisture (Kahramanoğlu, 2017; C.-J. Zhao et al., 2016). Qualitative changes in colour, shape, size, texture, flavour and nutritional content may also occur (Yahia et al., 2019). Since the quantity and quality cannot be improved after harvesting, adequate precautions must be taken before harvest while pretreatments at harvesting and proper storage after harvesting must be implemented to maintain quantity and quality (Yahia et al., 2019). Preharvest conditions influencing post-harvest quantity and quality include crop genetic factors, climatic factors and agronomic factors including pests, diseases and insects and the controls applied (Yahia et al., 2019).

Various biotic and abiotic factors significantly influence the post-harvest quantity and quality of fruits and vegetables. The biotic factors include insects, pests, rodents and fungi (D. Kumar & Kalita, 2017; Rajendran, 2005). The growth and proliferation of these microorganisms depend on the level of control of abiotic factors such as temperature, relative humidity, atmospheric composition, and light (Kahramanoğlu, 2017). This is especially the case where produce is kept in poorly designed facilities and in some cases where farmers keep produce in the houses they live within. The problem with infestation by insects and pests is that they not only deposit excreta on the food but are also capable of passing toxic pathogens on the food that could be poisonous (Robertson, 2005). Moreover, the presence of mycotoxin producing fungi in a food storage facility has been shown to cause loss of dry matter in addition to the degradation of product quality (R Kumar et al., 2007).

Temperature is the most important abiotic factor influencing the shelf life of agricultural products postharvest (James & Zikankuba, 2017; Kahramanoğlu, 2017). This is because temperature influences the product's physiological response and the rate of growth of microorganisms (Ding et al., 2006; James & Zikankuba, 2017; Q. Lin et al., 2017). Kahramanoğlu (2017) reports that for every increase in temperature by 10°C, the rate of deterioration increases by 2 – 3 times. Therefore, cooling of products after harvest is applied to remove field heat and manage storage temperature. Depending on the postharvest stage, commonly applied cooling methods may include hydro-cooling, ice toping, evaporative cooling, forced air cooling and vacuum cooling (James & Zikankuba, 2017). However, cooling of agricultural products should only be done to keep the temperatures within the optimal range. Reducing the temperatures below the product-specific minimum temperature often results to chilling injury and freeze-thaw damage (Jha et al., 2019; Kahramanoğlu, 2017). The associated symptoms of these mechanisms of damage include skin discolouration, necrotic pitting, loss of rigidity, increased susceptibility to decay and changes in odour and flavour (Jha et al., 2019; Kahramanoğlu, 2017). The ideal storage temperatures range for a majority of tropical fruits and vegetables to avoid deterioration due to both low and high temperatures is 5 – 15 °C (El-Ramady et al., 2015; Kahramanoğlu, 2017). However, the temperature should be customized to the requirements of specific products.

Fresh fruits and vegetables contain a high moisture content of about 80 – 95% by weight making them immediately susceptible to weight loss after harvest (Kahramanoğlu, 2017). For this reason, storage in a high relative humidity environment is highly recommended to prevent or slow down transpiration water loss (Díaz-Pérez, 2019; Xanthopoulos et al., 2017). Relative humidity in the range of 85 – 95% has been reported to slow down transpiration water loss in various products (Kahramanoğlu, 2017; Lufu et al., 2020; Xanthopoulos et al., 2017). However, elevated levels of relative humidity are also associated with the proliferation of microbes as well as the weakening of packaging material (Kahramanoğlu, 2017; Lufu et al., 2020). For optimal relative humidity conditions which reduce transpiration water loss without being too high to encourage microbial growth, Lufu et al. (2020) recommend that the environmental relative humidity should be kept as close as possible to the moisture content of the product during storage.

Product respiration is influenced not only by relative humidity but also by atmospheric composition in regards to gases and water vapour mediated by temperature (Kahramanoğlu, 2017). Postharvest respiration of fresh produce is influenced by the composition and concentration of oxygen, carbon dioxide and ethylene gas (Bhande et al., 2008; Kahramanoğlu, 2017). During respiration, fresh produce takes in oxygen from the environment to convert substrates such as carbohydrates and organic acids into mainly carbon dioxide, water and energy (Bhande et al., 2008; Ghosh & Dash, 2018). As previously discussed, the production of water during respiration not only causes the product to lose weight but provides a microbial friendly environment and weakens packaging materials (Kahramanoğlu, 2017; Lufu et al., 2020; Raudienė et al., 2017). The rate of product deterioration can be reduced by providing a low-temperature environment with a low concentration of oxygen and ethylene and a slightly elevated concentration of carbon dioxide (Bhande et al., 2008; Ghosh & Dash, 2018). Previous studies have documented various methods and technologies of providing such kind of environment using Modified Atmosphere Packaging (MAP) and Controlled Atmosphere Storage (CAS) (El-Ramady et al., 2015; Ghosh & Dash, 2018; Kahramanoğlu, 2017; Majidi et al., 2014).

Immediately after harvesting, various pretreatments can be applied to fresh produce to eliminate spoilage microbes from the field and to slow down deterioration as a result of physiological factors. The pretreatments include thermal pretreatments, chemical pretreatments and application of edible coatings on the surfaces among others. Application of putrescine and carnauba wax pretreatment to pomegranate fruits before storage at 3°C and 90 ± 5% relative humidity resulted in a lower respiration rate and a 65% lower occurrence of chilling injury symptoms (Barman et al., 2011). Pretreatment of potato slices with a high concentration of oxygen before storage at 4°C significantly reduced enzymatic browning and preserved texture, and antioxidant capacity (X. Liu et al., 2019). Composite chemical pretreatment of button mushrooms with disodium salt, calcium chloride, citric acid and sorbitol in different proportions resulted in the preservation of texture, colour, moisture content during storage at 4°C and 80% relative humidity for 12 days. Application of Chitosan as an edible coating on the surface of fresh Jackfruit bulbs in addition to pretreatments before extended controlled atmosphere storage at 6°C significantly reduced losses in total phenolics and ascorbic acid (Saxena et al., 2013). This review shows that pre-storage preparations and proper control of the storage environment can extend the shelf life and preserve the quality of fresh agricultural produce.

2.6.3 Energy consumption during cooling

Energy consumption is a significant consideration in the design of controlled atmosphere storage solutions for fruits and vegetables. This is especially critical in the light of recent environmental conservation efforts that are geared towards reducing the level of greenhouse gas emissions in the food industry (Crippa et al., 2021). Cooling services are responsible for about 15% of global greenhouse gas (GHG) emissions (Dong et al., 2021). Refrigeration services alone contribute to about 43% of the energy consumed globally in the retail sector to ensure uninterrupted cold chains (Crippa et al., 2021). Forced convection cooling is the most common postharvest practice applied to agricultural products after harvesting and involves forcing refrigerated or conditioned air through packed produce (O'Sullivan et al., 2017). In the design, operation and control of a forced convection cooling system, information on the cooling load is pertinent (Dincer, 2003). The cooling load consists of field heat in the produce, respiration heat and thermal gains from the environment due to poor insulating, lighting and equipment (Dodd & Bouwer, 2014).

The amount of heat removed from a product to its surroundings during cooling is equivalent to the change in the energy content of the product (Çengel & Ghajar, 2015). In forced convection cooling applications, the energy is influenced by the thermophysical properties of air and the product, product dimensions, surface condition and velocity of the airstream (Çengel & Ghajar, 2015). The estimation of energy consumption during forced convection cooling of agricultural products using mathematical models is dependent on the availability and accuracy of thermophysical data (Mukama et al., 2020). In cooling applications, the specific heat capacity and density are the most important properties influencing the heat content of the product (Hoffmann et al., 2018; Mukama et al., 2020). On the other hand, the density, thermal conductivity and dynamic viscosity of the air influence the rate of heat removal and therefore sizing and selection of heat transfer equipment (Hoffmann et al., 2018). Information on the surface heat transfer coefficient is important in the prediction of the total cooling time and therefore the expected cooling load. The surface heat transfer coefficient is in turn influenced by the velocity of air, dimensions and the surface condition of the product (Çengel & Ghajar, 2015). The foregoing review shows that careful selection of forced convection cooling settings can optimise the utilisation of energy resources during forced cooling settings.

2.7 Hot-air drying of food materials

2.7.1 Hot-air drying for food preservation and value-addition

Moisture removal through drying is an historically popular food preservation method that dates back to the pre-historic period (Michailidis & Krokida, 2014; Nummer, 2002). The modern drying process is considered to be not only a preservation method but also a step towards value addition (Ramos et al., 2003). Drying involves the removal of moisture from the food matrix to not only increase the shelf-life but also to facilitate easier packaging, transportation and storage (Michailidis & Krokida, 2014; Ratti, 2001). As the moisture in the food material is reduced, the rate of biochemical reactions also decreases the proliferation of spoilage microbes is prevented (Alp & Bulantekin, 2021; Bourdoux et al., 2016; Michailidis & Krokida, 2014). Drying is particularly useful in extending the availability of seasonal foods and in periods of surplus production in the farms (Duan et al., 2016; Michailidis & Krokida, 2014; Orsat et al., 2008). Drying is also applied to ensure that high-value foods such as baby foods, nutraceuticals, distinguished organoleptic foods and special end-use foods include military, outdoor and performance sports food retain their nutritional quality (Adhikari et al., 2021; Ratti, 2001).

A large body of studies, publications, patents and technologies on the drying of food have been documented. The technologies and methods include hot-air drying, microwave drying, freeze-drying, spray drying, osmotic dehydration, sonic drying, heat pump drying, infrared drying, sun drying and solar drying, vacuum drying, supercritical drying and pulse drying among others (Michailidis & Krokida, 2014; Sagar & Suresh, 2010). Vacuum and freeze-drying are commonly applied to dry heat-sensitive products because moisture removal proceeds at temperatures below 30°C for the former and sub-zero temperatures for the latter (Lewicki, 2006). The products from the two processes are comparatively of very good quality but the shelf-life depends on specific post-drying processes and the equipment involved is expensive (Lewicki, 2006).

Drying of food products with hot-air is a popular method that accounts for 85% of industrial drying processes (Mujumdar, 2006; Onwude, Hashim, & Chen, 2016). This is attributed to the ready availability, simplicity and affordability of hot-air dryers (R. Zhao & Gao, 2016). Hot-air drying involves exposing a food material to a continuous flow of heated air to remove moisture. Since hot-air drying only exposes the product to air, the process of naturally safe, non-toxic, hygienic and rapid (Onwude, Hashim, & Chen, 2016). A large body of information is available on the hot-air drying of a wide variety of fruits and vegetables (Castro et al., 2018; W.-P. Zhang et al., 2021), seeds and grains (Barrozo et al., 2014; Hemis et al., 2015; Vega-Gálvez et al., 2010), nuts (L. Chen et al., 2021; Tarigan et al., 2007), meat (Aykın Dinçer, 2021; Muga et al., 2020), roots and tubers (Ndisya et al., 2020; Ojediran et al., 2020; Vera et al., 2021), aromatic plants and spices (M.C Ndukwu et al., 2021; Orphanides et al., 2016) for preservation and value-addition. Hot-air drying can extend the shelf life of food materials by at least a year (Onwude, Hashim, & Chen, 2016).

2.7.2 Food quality changes during hot-air drying

All methods of drying have the potential to impart undesirable changes to the food material being dried. Adverse changes in the sensory, textural, structural and nutritional attributes influence the quality of food materials and the acceptability by consumers (Koç et al., 2013; Michailidis & Krokida, 2014; Onwude, Hashim, & Chen, 2016; Varela et al., 2006). Despite being the widely utilised method for dehydration of food products, destruction of natural pigments and flavours, degradation of nutrients, structural damage to food materials and high energy consumption can occur with hot-air drying (D. Kumar et al., 2014; Qing-guo et al., 2006). To conserve product quality and improve the drying efficiency, hot-air drying processes must be optimised and adjusted to suit the requirements of specific products and drying equipment (Ndisya et al., 2020; Sturm, 2018).

Hot-air drying is associated with higher drying temperatures and in some instances longer drying times (D. Kumar et al., 2014; Qing-guo et al., 2006). As a result, this negatively affects the heat and oxygen-labile physical and biochemical properties of the product being dried (Qing-guo et al., 2006). The retention of vitamin C is commonly utilised as an indicator of nutrient loss during drying processes utilising heat (Khraisheh et al., 2004; Qiu et al., 2020; Sablani, 2006). This is because the vitamin is water-soluble and prone to leaching in liquid media, highly heat-labile, sensitive to pH and light and easily oxidized by ascorbic acid oxidase (Jun Wang et al., 2017). Igwemmar et al. (2013) reported a loss in vitamin C of 49.91 – 64.71% in various vegetables subjected to heating for 30 minutes. A loss of vitamin C content greater than 50% was observed in probiotic orange powders after convective hot-air drying (Barbosa et al., 2015). Hot-air drying was also observed to result in the lowest vitamin C retention in sour cherries as compared to hybrid microwave-convection drying (Horuz et al., 2017).

Colour is one of the most important quality attributes in the food processing industry because it influences consumer perceptions, choices and preferences (Nurkhoeriyati et al., 2021; Pathare et al., 2013). This is because consumers associate colour and other visual attributes to taste, nutritional value, hygiene, shelf life and personal gratification (Sturm et al., 2014; Sturm & Hensel, 2017). Thermal processing of food products is associated with degradation of pigments such carotenoids, chlorophylls and anthocyanins, enzymatic and non-enzymatic browning all which result in colour change (Fernandes et al., 2011; Sturm & Hensel, 2017). The colour changes are influenced by drying temperature and duration, pretreatments and product-specific factors such as cultivar and chemical content (Fernandes et al., 2011). Doymaz (2017) observed changes in colour (CIE L*, a* and b*) in carrots subjected to hot-air drying at temperatures above 50°C. This was attributed to oxidative reactions enhanced by drying temperature whose combined effect causes degradation of carotenoid pigments and nonenzymatic browning (İ. Doymaz, 2017). Similar observations were made for bananas (Seyedabadi et al., 2019), lemon balm (Argyropoulos & Müller, 2014), pomegranate (Süfer & Palazoğlu, 2019) and cocoyam (Ndisya et al., 2020).

Drying processes cause changes to food at the microstructural level thereby affecting macroscopic characteristics such as density, porosity and volume and this influences the overall texture and structural characteristics (Porciuncula et al., 2016; Ramos et al., 2003). Depending on the product being dried, these changes can be desirable or undesirable. For products like potato flakes, breakfast cereals and instant dry milk powder, the porous structure created by drying is a desirable attribute to consumers (Bonazzi & Dumoulin, 2011). Additionally, an increase in hardness during drying can be beneficial in preventing product damage during further processing and transport (Süfer & Palazoğlu, 2019). The heat applied during hot-air drying processes causes water to migrate in liquid form from the product centre to the surface where it is removed by evaporation (Bonazzi & Dumoulin, 2011; Lewicki, 2006). With the movement of water from the material, damage and disruption of the cellular walls ensue and the result manifests as changes in shape and size of the material (Bonazzi & Dumoulin, 2011; Ramos et al., 2003). In particular, food products dried using convective hot-air drying are characterised by low porosity and high density as compared to freeze-dried products (Porciuncula et al., 2016). Süfer (2019) reported an increase in shrinkage and hardness with drying temperature during hot-air drying of pomegranate arils. Hot-air drying was observed to cause adverse changes in textural and structural characteristics such as shrinkage, hardness, springiness, cohesiveness and chewiness in cabbage as compared to freeze-drying (Rajkumar et al., 2017). Moreover, adverse changes in hardness, shrinkage, surface roughness and microstructural features were observed in hot-air dried nectarine slices (Ashtiani, Sturm, Nasirahmadi, et al., 2018).

Flours and convenience meals including instant snacks are often made from dried foods (Krokida & Philippopoulos, 2005). In order to recover the original properties, moisture is often reintroduced into dried foods using various liquid media. Therefore, the degree of moisture reuptake can be utilised as a quality index to assess the extent of structural damage imparted to the material during drying (Ashtiani et al., 2018; Lewicki, 1998). A low degree of moisture reuptake usually indicates extensive damage to the material making the material to be of poorer quality (Rajkumar et al., 2017; Ratti, 2001). The degree of moisture reuptake is highly influenced by the drying method utilised(Krokida & Philippopoulos, 2005). Ratti (2001) reports that the rehydratability of hot-air dried food materials is about 4 – 6 orders of magnitude lower as compared to freeze-dried food materials. This is attributed to extensive shrinkage and case hardening associated with hot-air drying (Benseddik et al., 2018; Ratti, 2001). Rajkumar (2017) observed a considerably lower rehydration ratio in hot-air dried cabbages as compared to freeze-dried cabbages. This is because freeze-drying induces a porous structure in the product as a result of the sublimation of frozen water (Bonazzi & Dumoulin, 2011).

While it is impossible to prevent the occurrence of adverse quality changes during hot-air drying, the application of various pretreatments and optimisation of drying settings can yield more acceptable products. Various physical and chemical pretreatments have been shown to enhance the drying rate and therefore reducing the residence time of food products in hot-air dryers. The reduction in residence time is a beneficial factor in preventing adverse changes in quality attributes that are negatively affected by prolonged exposure to heat and oxygen (Lyu et al., 2020; Riaz et al., 2009; Tripathi & Giri, 2014; Xianquan et al., 2005). Thermal blanching is the most commonly applied pretreatment before drying food products (Lewicki, 2006). Thermal blanching is mainly applied to inactivate the activity of oxidation enzymes such as polyphenol oxidase (PPO) and peroxidase (POD) which cause browning of food products (İ. Doymaz, 2017; Seyedabadi et al., 2019; Shrestha, Kulig, et al., 2020; Sturm & Hensel, 2017; Xiao et al., 2017). Blanching has also been shown to increase drying rate, reduce drying time and improve quality outcomes. Doymaz (2014) observed faster hot-air drying of broccoli after pretreatment by hot water blanching. Similar observations have been made for seedless grapes (Bai et al., 2013), paprika (Orikasa et al., 2018) and white cabbage (Tao et al., 2019). Despite the beneficial uses of thermal blanching, the application of heat during the process has been shown to negatively influence process outcomes and product quality attributes in some instances. Hot-water blanching was observed to increase the drying rate and therefore the drying time in purple-speckled cocoyam (Ndisya et al., 2020) and celeriac slices (Nurkhoeriyati et al., 2021) at the blanching and drying settings considered. As a result of the increased drying time, quality attributes including colour and bioactive compounds (Ndisya et al., 2020; Nurkhoeriyati et al., 2021). All factors considered many studies have reported positive process and quality outcomes with the blanching before hot-air drying but by ensuring that the blanching process is correctly controlled. Previous studies have also reported the use of chemical pretreatments and novel methods such as ultrasound, pulsed electric fields, high-pressure pretreatment and cold plasma pretreatment before food drying with varying degrees of success (Deng et al., 2019; Tao et al., 2019; Witrowa-Rajchert et al., 2014; Won et al., 2015; X.-L. Zhang et al., 2019).

Physicochemical analyses have established high phenolic composition in cocoyam (Yemenicioglu et al., 1999). The presence polyphenol oxidase enzyme (PPO) enhances the predisposes the crop enzymatic browning during hot-air drying (Ndisya et al., 2020). Browning reactions during hot-air drying can be controlled by the application of different pretreatments before drying. Pretreatment of cocoyam slices using a maltodextrin solution and freezing before intermittent microwave vacuum-assisted drying was observed to improve the drying and quality outcomes (Z. Zhang et al., 2017). Improvements in the physical, nutritional, functional and pasting quality of cocoyam flour was attained by precooking cocoyam flour in boiling water for ten minutes (Kumar et al., 2017). Application of ascorbic acid and sodium metabisulphite to banana, cinnamic acid, citric acid and malic acid to mushroom, citric acid and sulphites to in cashew apple successfully controlled enzymatic browning (Queiroz et al., 2011; Ünal, 2007; Zhou et al., 2016).

Besides product pretreatments, drying settings pose a great influence on the drying rate, drying time and quality attributes of the product being dried. Previous studies utilising hot-air drying have confirmed that increasing the drying temperature, air velocity and reducing the relative humidity and product dimensions result in increased drying rate and reduced drying time (Aral & Beşe, 2016; Hashim et al., 2014; Kaleta & Górnicki, 2010; Ndisya et al., 2020; W.-P. Zhang et al., 2021). However, setting the drying temperature and air velocity at their highest and the relative humidity and product dimensions at their lowest possible settings may not necessarily improve outcomes related to the product quality attributes. For instance, settings for the drying temperature and relative humidity often involve a delicate balancing act to optimize the drying rate and time without degradation of product quality. On one hand, high drying temperatures and low relative humidity increases the drying rate and reduce the drying time but this may quickly degrade proteins, bioactive compounds and colour (Demiray et al., 2013; Koné et al., 2013; Timm et al., 2020). On the other hand, lower drying temperatures and higher relative humidity may prevent oxidative reactions that may destroy chemical compounds but extends the residence time in the dryer which as well has a negative influence on some chemical compounds (Jun Wang et al., 2017).

Regarding product thickness, products with large thicknesses require longer drying durations which result to lower retention of vitamin C as a result of longer exposure to hot air (Chin et al., 2015; P. H. S. Santos & Silva, 2008; Jun Wang et al., 2017). An increase in slice thickness was observed to cause a loss in the vitamin C content of hot-air dried kiwi fruit slices (Chin et al., 2015). Additionally, Ndisya (2020) reported a decrease in rehydration capacity with increasing slice thickness in hot-air dried purple-speckled cocoyam slices. The consensus for most food products on the influence of air velocity is that increasing air velocity has a remarked positive influence on both process and quality outcomes of hot-air drying processes especially at elevated drying temperatures (Kurozawa et al., 2014; Osorio-Arias et al., 2020; Sturm et al., 2012). In conclusion, to enhance the efficiency of the drying process and to preserve the quality characteristics of the product being dried, a proper selection of suitable pretreatments and drying settings is necessary. The pretreatments and process settings should also be tailored to the product under consideration.

2.5.4 Harvesting and postharvest handling

Cocoyam tubers are mature for harvesting when the leaves wither and turn yellow which is 4 – 6 months after planting (Opara, 1999). The timing of harvesting operations is of paramount importance in avoiding pre-harvest losses. Traditional and small-scale harvesting of cocoyam tubers in Kenya involves uprooting by hand (Naika, 2017), digging up with a hoe or machete (Oshunsanya, 2016; Wamucii, 2017) or by passing a plough close to the furrows and exposing the tubers. Mechanized harvesting methods have also been reported (Oshunsanya et al., 2018). During harvesting activities, there is a need for farmers to adopt the correct techniques and a heightened degree of caution to avoid injuring the tubers thereby increasing the likelihood of rotting (Wamucii, 2017). During the harvesting of cocoyam tubers, two wounds are inflicted on the tuber, one to trim the dry bottommost end and one at the petiole base to remove the foliage. For this reason, curing at 24 – 36°C at 85 – 95% or application of a fungicide has been shown to promote wound healing before storage (Opara, 1999; Owusu-Darko et al., 2014).

In the fresh form, cocoyam tubers are highly susceptible to sprouting and rotting making storability poor. This is due to a high moisture content of about 60 – 83% at harvesting (Ndisya et al., 2020; Rashmi et al., 2018). Therefore, the post-harvest losses related to cocoyam tubers can be as high as 25 – 45 per cent (FAO, 2012, 2019). Suitable storage conditions and preservation methods are thus required to prevent spoilage in its fresh form which leads to food loss. Traditionally, cocoyam tubers are left buried in the field and only harvested when immediately needed for consumption (Opara, 2003). However, infield storage not only ties up land that could be used for a new crop but also affects the quality of the tubers. Infield storage beyond the optimal maturity age is associated with tuber rot (Modi, 2007; Wang & Higa, 1983) and degradation of the quality of starch (Himeda et al., 2012). Documented improved storage methods include storage in traditional low-cost structures and pits (Opara, 1999), ventilated stores (Thompson, 2003) and refrigerated storage (Opara, 2003). These methods have registered widely varying degrees of success chiefly due to varying simplicity, performance and affordability. But none of these achieves the same level of success as refrigeration when the tubers are desired in their fresh form (Opara, 1999).

Drying is a popular preservation and value-addition method applied to chopped or sliced cocoyam tubers (Adeboyejo et al., 2021; Afolabi et al., 2015; Ndisya et al., 2020; Macmanus C. Ndukwu et al., 2017). A reduction in the moisture content of food to inhibit proliferation of spoilage microorganisms and to curtail biochemical activity can be attained through drying. Moreover, the reduction in weight and volume after drying decreases the packaging, storage, and handling costs (Ashtiani, Sturm, Nasirahmadi, et al., 2018; Prabhakar & Mallika, 2014). Traditionally, post-harvest preservation of fresh roots and tubers involves peeling them and drying them in open sunlight (Ukoba et al., 2018). Open-air sun-drying is weather-depended and exposes tubers to contamination with microbial elements and other foreign materials thereby causing loss of product quality and farmer incomes (El Hage et al., 2018; P. Singh et al., 2018; Udomkun et al., 2020). However, modern drying techniques including convective hot-air drying (Afolabi et al., 2014; Ndisya et al., 2020; Macmanus C. Ndukwu et al., 2017), osmotic dehydration (Olatidoye et al., 2016), microwave drying (Afolabi et al., 2014) have been applied in the preservation and value-addition of cocoyam.

2.7.3 Energy consumption during hot-air drying

Additionally, hot-air drying is costly as a result high energy consumption accounting for 15 – 25% of industrial energy use. (Kemp, 2012; C. Kumar et al., 2014; Menon et al., 2020; Qu et al., 2021). Production costs for food processing can be reduced by controlling the energy consumption of food drying operations (Motevali, Minaei, & Khoshtagaza, 2011; Qu et al., 2021). Moreover, this is in line with global efforts towards prevention of climate change through energy conservation (Kemp, 2012; Menon et al., 2020). More than 85% of industrial drying processes utilise convective hot-air drying (Moses et al., 2014; Mujumdar, 2006; Zarein et al., 2015). However, improperly controlled hot-air drying processes often involve a long drying time and therefore a high amount of energy is consumed (Moses et al., 2014; Onwude, Hashim, & Chen, 2016). During hot-air drying of pomegranate arils at drying temperatures between 45 – 70 °C and air velocity between 0.5 – 1.5 $m \cdot s^{-1}$, Motevali et al. (2011a) observed reduced energy consumption at the higher drying temperature and lower air velocity settings. Similar results were obtained after hot-air drying of mushroom slices (Motevali, Minaei, Khoshtaghaza, et al., 2011) and stinging nettle leaves (Alibas, 2007). This was as a result of the reduced drying time at such drying settings. However, Ndisya (2020) reported a quadratic effect of temperature of the energy consumption during hot-air drying of purple-speckled cocoyam slices. Drying energy demand was observed to be low at 40°C and 75°C but highest at 60°C (Ndisya et al., 2020). It was hypothesized that the accompanying decrease in drying time with an increase in the drying temperature beyond 60°C compensated for the higher energy requirements of heating the air (Ndisya et al., 2020). Although similar findings on the influence of air velocity were observed during hot-air drying of potato, garlic and cantaloupe, it was found in this case that an increase in the drying temperature caused a corresponding increase in energy consumption (Kaveh et al., 2018).

Pre-drying treatments have been shown to not only improve the quality of dried products but also to significantly improve energy efficiency in some instances. Microwave pretreatment was reported to reduce the drying time and energy consumption in hot-air drying of pomegranate arils as opposed to pure hot-air drying (Motevali, Minaei, & Khoshtagaza, 2011). Similar findings have been reported for Terebinth (Abbaspour-Gilandeh et al., 2021). Pretreatment of carrots with ultrasound in ethanol and ethanol were observed to reduce hot-air drying time by ~50% and the energy consumption by 42 – 62% (K. C. Santos et al., 2021). Tabibian et al. (2020) pretreated saffron with gliding arc discharge plasma and observed a reduction in the hot-air drying time by 54.05% and the energy consumption by 39.52%. Moreover, physical and chemical pretreatments were observed to reduce the energy consumption during hot-air drying of blackberry (Kaveh et al., 2020). However, Ndisya (2020) reported an increase in the drying time and energy consumption during hot-air drying of purple-speckled cocoyam slices after pretreatment by blanching and combined blanching sulphiting pretreatment. This was attributed to the formation of a hard case on the surface of the slices due to starch gelatinisation during the blanching phase (Ndisya et al., 2020). The hard case constrained moisture migration to slice surfaces for evaporation and therefore extended drying increased the energy requirements (Ndisya et al., 2020). It is clear from this review that hot-air drying settings and pre-drying treatments have a great influence on energy consumption during drying. Therefore, careful selection of hot-air drying settings can optimise the consumption of energy resources.

2.8 Non-invasive quality attribute measurements during food processing

Measurement for the purposes of quality control during food processing is an intricate and complex task requiring various inputs such as financial and qualified human resources (Ilyukhin et al., 2001). Conventionally, quality control measurements are executed offline in laboratories and the feedback implemented manually to the process (Ndisya, Gitau, Mbuge, et al., 2021). However, offline measurements with manual feedback can introduce measurement inconsistencies as a result of measurement bias and operator fatigue (Ndisya, Gitau, Mbuge, et al., 2021). As a result, shift in process settings and product quality may proceed unnoticed which ultimately influences the final product. Additionally, since majority of conventional laboratory tests are destructive, it may be difficult to trace the processing history of the product (Shrestha, Crichton, et al., 2020). Therefore, the modern process can highly benefit from timely and good quality control measurements by automating process monitoring and control (Ndisya, Gitau, Mbuge, et al., 2021; Raut et al., 2021; Slišković et al., 2011).

In recent times, the focus has shifted from conventional drying to smart drying of fruits and vegetables. Smart drying involves the utilisation of sensors, actuators and algorithms to monitor and control drying parameters to preserve product quality (Martynenko, 2018; Martynenko & Misra, 2020; Y. Su et al., 2015). Smart drying makes real-time measurements and dynamic control of drying conditions possible and cost-effective (Moscetti et al., 2017). When a large amount of historical data on the drying process is available, Machine Learning (ML) models can be built to evaluate or discover all possible physical relationships about the process (Ge et al., 2017; Martynenko & Misra, 2020). Machine Learning algorithms coupled with machine vision has been utilised for real-time monitoring of changes in product quality during drying (Martynenko, 2018; Martynenko & Misra, 2020).

Hyperspectral imaging (HSI) together with machine learning are contemporary techniques in the food industry for non-destructive evaluation of food quality (Ndisya, Gitau, Mbuge, et al., 2021). Recent advances in the techniques have been fostered by modernized instrumentation owing to advances in computing, sensors and data modelling techniques (Walsh et al., 2020). In contrast to classical Vis-NIR spectroscopy, HSI provides linkages between product properties and spatial information over a large number of wavelengths (Wu & Sun, 2013). HSI has found particular application in the evaluation of food quality attributes such as lipid profile in almonds and cocoa beans (Caporaso et al., 2021; Torres et al., 2021), soluble solids and texture in stone fruits (Benelli & Fabbri, 2020; Meng et al., 2021), fibre content in pasta (Badaró et al., 2021), microstructural changes in pork (Tian et al., 2020), sugar content in potatoes (Rady et al., 2020), micronutrients in wheat (N. Hu et al., 2021), colour and acid profile in hops (Sturm et al., 2020), colour, micronutrients and texture in apples (Arefi et al., 2021; Shrestha, Crichton, et al., 2020; Zude et al., 2006) among others. In the case of cocoyam, classical NIR spectroscopy in the region 350 – 2500 nm has been applied to evaluate carbohydrate content, cellulose, proteins, and minerals in 315 different cocoyam accensions (Lebot et al., 2011). Moreover, spectral information in the range 1100 – 2500 nm was utilised to evaluate changes in moisture, lipids, colour and texture in deep-fried cocoyam chips (Areekij et al., 2017).

HSI obtains data rich in quantity and quality because the spatial and spectral details collected provide much more information about target objects. The data is also highly correlated, making it very complex. Dimensionality reduction is therefore necessary before any valuable information is extracted using multivariate statistical techniques. Dimensionality reduction is achieved by projecting spectral data into a lower dimensional space or feature selection (or variable elimination). This removes redundant information, reduces computation requirements and improves prediction performance (Chandrashekar & Sahin, 2014). Principal Component Analysis (PCA) is commonly applied for orthogonal linear transformation of data into a lower dimension space (Qin et al., 2013). On the other hand, popular feature selection methods include Univariate feature selection, Genetic algorithms, Random Forests, Recursive Feature Elimination, PLS-BETA and Variable importance ranking among others (Alma & Bulut, 2012; Rong et al., 2019; Z. Wang et al., 2015). A wide range of machine learning techniques for predictive modelling after feature selection is available. The most common techniques include principal component regression (PCR), partial least squares regression (PLSR), support vector machines (SVMs) and artificial neural networks (ANNs) (Shang et al., 2014). The PLSR method is more popular for linear predictive modelling due to its relative simplicity, ability to model multiple variables and robustness in the presence of noise and missing data (Pirouz, 2006).

2.9 Modelling and optimisation of food cooling processes

2.9.1 Modelling of forced convection cooling

Forced-air convective cooling is the most popular and widely utilised method to extend the shelf life of fresh agricultural produce (Dehghannya et al., 2010; Kader, 2002). However, improper control of cooling temperature and distribution of the cooling air can result in non-uniform cooling that can cause temperature-induced damage in undercooled spots and chilling injury in the overcooled spots (Dehghannya et al., 2010; C.-J. Zhao et al., 2016). A myriad of experimental studies has been documented on forced convection cooling of fresh agricultural products. However, experimental studies are constrained by being expensive, time-consuming and labour intensive. Moreover, results derived from purely empirical studies are only relevant to the product under the unique experimental conditions and therefore are not helpful for optimisation of processes. Mathematical and numerical modelling of the forced convection cooling process is, therefore, suitable for optimisation of both the cooling efficiency and the energy efficiency (Dehghannya et al., 2010; C.-J. Zhao et al., 2016).

Heat transfer problems are classified as transient or steady where the temperature change is a function of time and location in transient state heat transfer problems and a function of only the location in steady transient state heat transfer problems (Çengel & Ghajar, 2015). Although steady-state heat transfer problems are easy to solve with simple mathematical analysis, truly steady-state conditions are rare in food process engineering (R. P. Singh & Heldman, 2009). Heat transfer problems in food process engineering very often occur in the transient state (Çengel & Ghajar, 2015; Earle & Earle, 2004; R. P. Singh & Heldman, 2009). Modelling approaches to forced convection cooling include the porous medium approach (single-phase and two-phase), lumped systems approach and computational fluid dynamics (CFD) (Dehghannya et al., 2010). A porous medium is defined as a solid matrix perfused by a series of interconnected voids which allows the movement of fluid across the domain (Badruddin et al., 2020; Dehghannya et al., 2010). An example of a porous medium is bulk agricultural products such as grains, tubers, fruits or vegetables stacked in storage with or without packaging

(Verboven et al., 2006). Heat transfer across a porous medium is considered as a mixed-mode process with thermal conduction in the solid matrix and thermal convection through the fluid permeating internal pores (Badruddin et al., 2020; Kang et al., 2019).

The porous medium approach is suitable for large stacks of products where computational resources are inadequate to allow modelling of objects and interstitial spaces individually and fluid flow characteristics can be described by space-averaged temperature, superficial velocity and heat transfer coefficient (Dehghannya et al., 2010; Verboven et al., 2006). The porous medium approach has been successfully applied to model heat and mass transfer during forced convection cooling of various agricultural products to investigate temperature distribution in produce as influenced by package vent configurations (Dehghannya et al., 2011), temperature evolution in products inside a bin (Alvarez & Flick, 1999, 2007) and products kept on a pallet in a cold room (Hoang et al., 2015). However, the drawbacks of the porous medium approach include; internal produce gradient is neglected which is debatable in the case of transient heat transfer (Dehghannya et al., 2010; Verboven et al., 2006). Moreover, for products kept in vented packages, the continuum assumption breaks down when the package-to-product diameter is below a certain threshold (Dehghannya et al., 2010; Pathare et al., 2012). Modelling of heat transfer in two-phase porous media also generates complex models whose parameters are difficult to assess thus degrading the accuracy of the estimations from the models (Dehghannya et al., 2010).

Recent advances in computing technology have made it possible to solve intricate heat and mass transfer problems giving an intuitive understanding of underlying phenomena with greater accuracy and speed (Zhong et al., 2016). The challenges of model development and solution associated with porous media models can be overcome by utilising CFD. With CFD, quantitative solutions of fluid-flow problems can be solved conservation mass, momentum and energy equations governing fluid motion (H. Hu, 2012). With Direct Numerical Simulation (DNS), a branch of CFD, complete time-dependent numerical solution of three-dimensional Navier–Stokes and local energy equations to glean insight on how local fluid flow behaviour influences the heat and mass transfer process (Dehghannya et al., 2010; Verboven et al., 2006). As compared to the porous medium approach, simplification of geometry and fluid properties with space-averaged values is not required (Dehghannya et al., 2010). Additionally, governing equations for heat and mass transfer can be solved for both laminar and turbulent flows (Dehghannya et al., 2010). Previous studies have utilised CFD to study forced convection cooling of packaging and post-harvest storage facilities for various agricultural products including; apples (J. Han et al., 2017; Hoang et al., 2015; Hussain, Kamal, & Hafiz, 2021), peaches (Y. Chen et al., 2020), pomegranates (Ambaw et al., 2017), straw berries (Ferrua & Singh, 2009), lettuce (X.-F. Wang et al., 2021), citrus fruits (Defraeye et al., 2013, 2015; Hussain, Kamal, & Hafiz, 2021), zucchini (M. Zhang et al., 2019), cashew apple (Brandão et al., 2020) and dates (Ghiloufi & Khir, 2019) among other products. However, CFD is computationally expensive and often requires commercial software which is out of reach for most common users. Additionally modelling and interpretation of CFD results requires skills and years of experience. For these reasons, the use of CFD for many low-value items may not always be economically justified (Defraeye, 2014).

In the special case where temperature varies with time but not with location, the heat transfer problem is referred to as a lumped system problem (Çengel & Ghajar, 2015). When the spatial variation of temperature is negligible and the state change is assumed to be purely temporal, lumped system analysis can be applied to study transient heat transfer (Çengel & Ghajar, 2015). In this case, the Biot number (Bi) is less than 0.1 and the material exhibits negligible internal resistance to heat transfer (Phongikaroon & Calabrese, 2005). Tegenaw, Gebrehiwot, & Vanierschot (2019) compared the results of simulations from CFD and lumped system models in simulating heat transfer. The lumped system model results matched those from the CFD model but required lesser computational effort. Lumped system analysis has been successfully applied to study heat transfer in various products including figs (Dincer, 1994), grapes (Dincer, 1995a), fish (Davey, 2015) and sweet potatoes (Korese et al., 2017). However, Biot numbers for most engineering systems are often several times larger than 0.1 and, therefore, the simple lumped system analysis is seldom applicable in such cases (Ranmode et al., 2019). This is because the spatial variation of temperature becomes significant (Çengel & Ghajar, 2015). However, various recent studies have successfully extended the validity of lumped system analysis to cases where $Bi > 0.1$.

Xu, Li, & Chan (2012) and Jian et al. (2015) derived and tested new equations for calculating effective heat transfer coefficients for simple infinite geometries of relevance to thermal energy storage applications for use when $Bi > 0.1$. The results obtained using this method compared well with the analytical solutions. When the effective heat transfer coefficients and the resulting Biot numbers are used in the place of the heat transfer coefficients and Biot numbers in the lumped models, the heat transfer problem can be solved directly using the lumped system analysis method (Xu et al., 2012). In this case, the characteristic dimension utilised to compute the effective Biot number and the Fourier number for the cylinder geometry is half the radius of the cylinder rather than the full radius as typically used in the exact analytical solution (Ranmode et al., 2019; Xu et al., 2012). Lumped system models can be used to study the temperature distribution and heat transfer in one-dimensional heat transfer problems associated with infinite geometries such as large slabs and long cylinders. However, when the geometries can no longer be considered to be infinite, heat transfer is multidimensional and the governing equations are constructed using a product solution approach (Çengel & Ghajar, 2015; Christensen & Adler-Nissen, 2015).

2.9.2 Modelling of quality changes during cold storage

In recent years, consumer demand for fresh, safe and high-quality food products has increased due to increased awareness of healthy and sustainable living (Johe & Bhullar, 2016; W.-H. Su et al., 2020). As a result, food producers are increasingly interested in the shelf life and potential changes in the quality of the food they produce while in storage to satisfy consumer interests (Giménez et al., 2012; Martins et al., 2008). Depending on the storage environment provided, changes in colour, nutritional composition, texture and flavour can occur (Tanner, 2016). Insects, pests, rodents, fungi and spoilage bacteria may also attack the stored produce (D. Kumar & Kalita, 2017; Rajendran, 2005). For this reason, food producers make use of various mathematical models to evaluate the shelf life and to predict the degradation kinetics of various food components. Shelf life is the time during which food products 'retain desired sensory, chemical, physical and microbiological characteristics when stored under the recommended conditions' (Giménez et al., 2012). Within the shelf life, a food product should satisfy consumer expectations on quality and safety (Martins et al., 2008). To assess the shelf life, real-time or accelerated shelf-life testing studies are conducted while assessing shelf-life objective indices related to select quality attributes (Limbo et al., 2010; Martins et al., 2008). The objective index selected is usually the quality attribute that is the first or earliest to indicate deterioration of the food product in storage. For food products in chilled/ cold storage, the indices include senescence, microbial growth, enzymatic reactions and mechanical damage to tissues (Calligaris et al., 2019).

When the objective index is selected, data collected during shelf life testing is modelled to describe the evolution of the objective index as a function of storage time (Calligaris et al., 2019). Modelling approaches applied for this task include kinetic modelling, RSM modelling and multivariate statistical modelling (van Boekel, 2008). The shelf life of refrigerated minced beef was successfully assessed using a zero-order kinetics model of 2-thiobarbituric acid complex (TBA values) which is an indicator of oxidative rancidity (Limbo et al., 2010). Changes in colour and pH during accelerated shelf-life testing of tomato paste were successfully modelled using a zero-order kinetics model (Ganje et al., 2016). Moreover, zero and first-order kinetic models were successfully utilised to predict change kinetics of colour, pH, water activity, texture (spreadability, hardness, adhesiveness, and viscosity index) during storage of Gouda cheese at 8°C (Weiss et al., 2018).

Recent advancements in computing technology have facilitated the emergence of computational shelf-life dating (CSLD). Computer-based models provide an opportunity to dynamically assess changes in multiple quality parameters to uncover underlying relationships between them which are often too complex to analyse by conventional laboratory analyses (Martins et al., 2008; Martynenko & Misra, 2020). NIR spectroscopy combined with partial least squares discriminant analysis (PLS-DA) were utilised for shelf-life discrimination of green asparagus kept in a cooled environment for different durations of time (Sánchez et al., 2009). A real time shelf-life estimation model correlating temperature and weight loss of lettuce in cooled transport and storage was developed using multiple non-linear regression (MNLR) (Torres-Sánchez et al., 2020). Additionally, artificial neural network (ANN) models were found to perform well in predicting product temperatures for shelf-life prediction of fresh fruits and vegetables (do Nascimento Nunes et al., 2014).

2.10 Modelling and optimisation of food hot-air drying processes

2.10.1 Modelling of thin-layer drying kinetics

Drying is a complex process involving simultaneous heat and mass transfer in the differential structures of different biological materials (Erbay & Icier, 2010). Additionally, physical, chemical, and biochemical changes occur during the drying process thereby influencing the drying kinetics (Erbay & Icier, 2010). Proper understanding of a material's drying kinetics is important in establishing the ideal drying conditions for the material and therefore the design and optimization of drying equipment (Onwude, Hashim, Janius, et al., 2016; Ratti, 2001). Drying kinetics describe the drying behaviour of a product and are therefore necessary to estimate the amount of time and energy required to dry a product Mathematical models are utilised to derive drying kinetics because pure experimental drying without a mathematical basis can negatively affect dryer efficiency, production costs and product quality (Onwude, Hashim, & Chen, 2016). Besides, experimental investigations under field conditions pose various challenges including limited experimental time due to short harvesting seasons and the large number of homogeneous products required for tests among others (Mühlbauer & Müller, 2020).

Various mathematical models have been proposed to estimate the drying kinetics of agricultural products. Thin-layer drying is a commonly applied method to dry fruits and vegetables (Das Purkayastha et al., 2013; Diamante et al., 2010). As opposed to deep bed drying, thin layer drying involves drying products as one layer of particles, slices or cubes (Jayas et al., 1991; Yi et al., 2012). Drying products as thin layers reduces drying energy requirements and moisture gradients (Torki-Harchegani et al., 2014). In the range of mathematical models available for describing drying kinetics, thin-layer drying models are popular because of their ease of use due to fewer model parameters to be evaluated (Erenturk et al., 2004). Thin-layer drying models can be classified as theoretical, semi-empirical or empirical models. Theoretical models are derived from Fick's second law of diffusion and clearly describe moisture transport during the falling rate period (Claumann et al., 2018; Mühlbauer & Müller, 2020). Semi-empirical models are derived from Newton's law of cooling and Fick's second law of diffusion (Claumann et al., 2018; Mühlbauer & Müller, 2020; Onwude, Hashim, & Chen, 2016). Examples of semi-empirical models include the Two-term model, Midilli model, Page model, Lewis/Newton model, Logarithmic model and Henderson/Pabis model (Mühlbauer & Müller, 2020; Onwude, Hashim, & Chen, 2016).

The challenge with theoretical and semi-empirical models is that the assumptions and simplifications needed to solve the models often lead to differences between predictions from the models and data derived from experiments (Mühlbauer & Müller, 2020). In contrast, empirical models are based purely on experimental data without an understanding of the underlying moisture transport phenomena and therefore fit well to experimental data (Bessenyei et al., 2018; Mühlbauer & Müller, 2020). Therefore, the parameters of empirical models have no physical meaning (Mühlbauer & Müller, 2020; Onwude, Hashim, & Chen, 2016). The most popular empirical models utilised in thin-layer drying modelling include Aghbashlo and others, Wang and Singh, Diamante and others, Weibull, Thompson, Da Silva and others and Peleg model (Onwude, Hashim, & Chen, 2016).

Selection of the category of thin-layer drying models suitable for specific fruits and vegetables often depends on complexity, assumptions and simplifications to be made, nature of the problem (i.e., purely mass transfer or combined heat and mass transfer) and the need to incorporate physical parameters such as temperature, velocity and relative humidity (Mühlbauer & Müller, 2020; Onwude, Hashim, & Chen, 2016). Selection of a specific thin-layer drying model from the wide range of models available usually involves fitting experimental data to a number of the models then assessing various statistical metrics (Onwude, Hashim, & Chen, 2016). The most popular metrics include the Root Mean Square of Error (RMSE), coefficient of determination (r^2), chi-squared statistic (χ^2), and Sum of Squared Errors (SSE) among others. Onwude (2016) reports that most of the semi-empirical models and a few empirical models are suitable in describing the drying kinetics of most fruits and vegetables. These models have been successfully applied to describe the drying kinetics of purple-speckled cocoyam (Peleg model, Two-term Exponential model, and Midili model) (Ndisya et al., 2020), tomato (Logarithmic model, Henderson–Pabis model) (Das Purkayastha et al., 2013), banana (Page and Logarithmic models) (P. S. Kumar et al., 2019), cassava (Page and Midilli models) (Argo et al., 2018) and pumpkin (Midilli-Kucuk model) (Benseddik, Azzi, Zidoune, & Allaf, 2018) among others.

2.10.2 Modelling of quality changes during hot-air drying

Retention of sensory, textural, structural and nutritional quality attributes during hot-air drying is a primary concern to food manufacturers because it influences acceptability by consumers. Therefore, various researchers have attempted to develop insight into the relationship between food quality attributes and the drying process through mathematical modelling (Tuly et al., 2021). Mathematical models provide an understanding of quality change kinetics and therefore guide in the design and optimisation of processing and storage conditions (Perussello et al., 2013; Tuly et al., 2021). Although the relationship between changes in quality attributes and settings of the drying process is complicated, various empirical models are available and customizable to specific products and drying conditions (Tuly et al., 2021). These models include Kinetic model, Weibull model, Thermal death time (TDT) model, Williams-Landel-Ferry (WLF) model, Artificial neural networks (ANN) models, Eyring-Polanyi model, response surface methodology (RSM) models, Fractional conversion model, Modified Gompertz model, Bigelow model and Biphasic model among others (Nadian et al., 2015; Ndisya et al., 2020; Parthasarathi & Anandharamakrishnan, 2014; Tuly et al., 2021; Valdramidis et al., 2012; van Boekel, 2008).

The kinetic model has been widely applied in literature mainly to describe the degradation kinetics of various quality attributes. Zero and first-order kinetic models were found suitable to describe the colour and beta-carotene changes during hot-air drying of apricots, carrot, pumpkin and cardamon (Albanese et al., 2013; Demiray & Tulek, 2015, 2017; Onwude et al., 2017). The Weibull model has also been widely utilised to describe nutrient, enzyme, microbial and chemical degradation kinetics because of the adaptability accorded by the shape constant (Tuly et al., 2021). The degradation kinetics of chlorophyll, vitamin B1, and the polyphenol oxidase enzyme (PPO) in spinach puree, distilled water and buffered potato homogenate at a temperature of 50 – 80°C were observed to follow the Weibull distribution (Corradini & Peleg, 2004). Similar findings were reported for ascorbic acid degradation kinetics during hot-air drying tomato and pineapple (Marfil et al., 2008; P. H. S. Santos & Silva, 2009), microbial inactivation in tangerine juice (Hashemi et al., 2019). Moreover, texture change kinetics (firmness, energy, cohesiveness, springiness, resilience, and chewiness) of pumpkin and apple slices during thermal treatment were successfully modelled with the fractional conversion model (E. M. M. Gonçalves et al., 2007; Martynenko & Janaszek, 2014).

While physics-based models have enjoyed wide utilisation and success in the analysis of drying processes, their utility is often hampered by limited prediction capability and versatility (Martynenko & Misra, 2020; Sarkar et al., 2020). As such their suitability for real-time process monitoring, control and optimization are limited (Martynenko & Misra, 2020). Machine Learning has widely been utilised to develop models to evaluate quality changes during hot-air drying. Near-Infrared spectroscopy (NIRS) and Partial Least Squares (PLS) regression models were successfully utilised to monitor drying behaviour and physicochemical changes in organic carrot during hot-air drying (Moscetti et al., 2017). Changes in colour attributes of mushroom slices during hot-air impingement drying were successfully modelled using a Bayesian extreme learning machine model (Z.-L. Liu et al., 2020). Moisture content changes in potato and sweet potato tubers during hot-air drying were successfully monitored using near/mid-infrared (NIR/MIR) hyperspectral imaging and various ML algorithms such as partial least squares regression (PLSR), support vector machine regression (SVMR), locally weighted partial least square regression (LWPLSR), and back propagation artificial neural network (BPANN)(W.-H. Su et al., 2020).

2.11 Summary of literature review

Table 2.2 summarises the gaps and opportunities for the advancement of knowledge established through a review of the literature.

Table 2.2: Summary of literature review

No.	Domain	Gaps and opportunities
1	Global food security	• The need for more food to feed the increasing global population. • Provision of adequate food in the face of climate change, increasing urbanisation, ageing food producers, quality-conscious consumers and fragile global value chains. • Solutions to increasing global incidence of hidden hunger, malnutrition and rural poverty.
2	The food security situation in Kenya	• Feeding the nation in the face of reducing farm productivity, declining soil fertility, climate change, recurring droughts and pest infestation. • The solution to the 'alarmingly high' incidence of hidden hunger. • Reducing overreliance on main staple foods with a limited range of micronutrients.
3	Role cocoyam in food security in Kenya	• Renewed interest in the production of traditional crops, including root and tuber crops in Kenya driven by a steadily increasing demand and a push by the national government. • Potential for upscaling of cocoyam to meet food and nutritional needs. • Increased production as a result of the adoption of upland production technology. • Poor storability in the fresh form and relatively few post-harvest technologies for cocoyam.
4	Forced convection cooling for food preservation	• The high popularity of forced convection cooling for precooling and long-term storage. • Potential to run forced convection cooling with renewable energy. • Wide applicability to many agricultural products. • Influence of food components on thermophysical properties.

No.	Domain	Gaps and opportunities
		• Susceptibility of cocoyam tubers to physiological changes and biotic attacks during storage. • Selection of optimal forced convection cooling settings unique to cocoyam. • Optimisation of energy consumption during forced convection cooling.
5	Hot-air drying for food preservation and value-addition	• The high popularity of the hot-air drying methods as a preservation method and value addition step. • Potential to run hot-air drying with renewable energy. • Wide applicability to many agricultural products. • Controlling adverse changes in the sensory, textural, structural and nutritional attributes. • Selection of optimal drying settings unique to cocoyam. • Influence of pre-drying treatments on process and quality outcomes of cocoyam. • Optimisation of energy consumption during hot-air drying.
6	Quality attribute measurements during food processing	• Laboratory experiments often are destructive and costly. • Laboratory experiments are inappropriate for real-time process monitoring and control. • Opportunities accorded by recent advances in computing, instrumentation and data modelling techniques. • Background information provided by recent research and development in smart drying. • Applicability of computer vision technology in quality attribute measurements during hot-air drying.
7	Modelling and optimisation of food cooling processes and hot-air drying processes	• Availability of a wide selection of analytical, empirical, semi-empirical and numerical methods that can be adapted to modelling and optimisation of food cooling and hot-air drying processes.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Baseline survey

3.1.1 Introduction and study areas

A baseline survey was conducted to generate background information for this study. Crop production statistics for the duration 2012 – 2018 from the Ministry of Agriculture, Livestock, Fisheries and Cooperatives (MoALFC) show Kiambu, Murang'a and Meru counties to be the leading producers of cocoyam in Kenya. Based on these statistics in addition to information from literature and media reports of contract farming and a well-established cocoyam value-chain, Meru county was found to be the most suitable for the baseline survey. Moreover, Nairobi City County is a metropolitan county with a large population with varied cultural, educational and social identities. For this reason, the county was selected as a case of an urban area for this study. The objectives of the baseline survey were to;

i). Identify the actors and enablers in the cocoyam value chain.
ii). Establish the production methods, quantities and post-harvest losses
iii). Identify postharvest handling operations and value-addition methods applied to cocoyam
iv). Identify technology gaps and viable interventions to improve postharvest handling and value-addition
v). Consumption patterns and preferences.

Figure 3.1 provides a map of the area where the baseline survey was conducted. The study area, Meru County, is one of the 47 counties of Kenya located in the former Eastern region. The county lies between the latitudes $0^{o}6'$ North and $0^{o}1'$ South and the longitudes 37^{o}West and 38^{o} East. The county borders Isiolo County to the North, Tharaka Nithi County to the South East, Nyeri County to the South West, Laikipia County to the West and Isiolo County to the North. The county has a landmass area of 6,936 square kilometres and a total population of 1,545,714 (KNBS, 2019). Administratively, the county has 10 sub-counties namely: Imenti South, Meru Central, Imenti North, Buuri, Tigania East, Tigania Central, Tigania West, Igembe Central, Igembe South and Igembe North. The study area (i.e., Imenti Central sub-county) has five wards namely: Mwangathia, Abothuguchi Central, Abothuguchi West, Kibirichia and Kiagu. Meru County possesses a varied ecological landscape ranging from upper highlands in Imenti south to lower midlands in the areas bordering Laikipia and Isiolo counties. The county experiences a bimodal rainfall with an annual average of 1,250mm, temperatures between $8^{o}C$ and $32^{o}C$ (CoGM, 2018). An exception is the upper highland areas that experience an average annual rainfall of 2,500mm and the lower midland areas that receive an annual rainfall of 380mm (Hakizimana et al., 2017). Agriculture is the mainstay of the economy of Meru County. The major land use activity in the county is crop and livestock production (CoGM, 2018). The major crops produced include cash crops like Coffee, Tea, Macadamia and Khat and food crops like maize, beans, bananas, sorghum, millet, green grams, potatoes, cabbages, carrots and kales (CoGM, 2018).

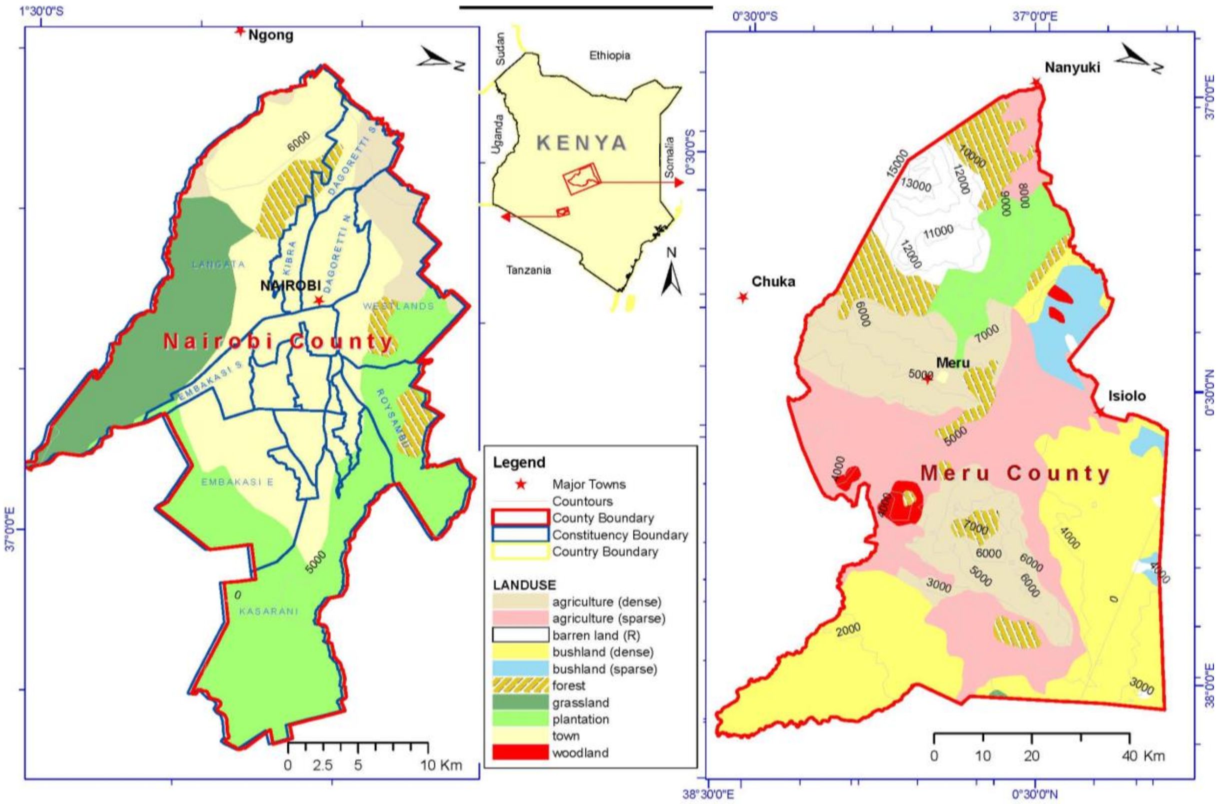


Figure 3.1: Geographic map of the study areas

On the other hand, Nairobi City County (NCC) is the third smallest county in Kenya with an area of 696.1 Km^2 lying between 36°45' East and 1°18' South (NCC, 2017). The county borders Kiambu county to the north and west, Kajiado county to the south and Machakos county to the east (NCC, 2017). The county is comprised of 17 sub-counties and a total population of 4,397,073 making it the most populous county in the country (KNBS, 2019). Being the capital city, NCC is the leading urban area with the main socio-economic activities being wage and self-employment (NCC, 2017). Low-level urban agriculture is practised in the peri-urban areas of the city to produce horticultural products for household consumption and commercial purposes (NCC, 2017). Being a population centre, NCC is a major trading centre with several markets trading in fresh produce (NCC, 2017). Among other items, these markets trade in diverse fresh products supplied from all over the country. For this study, six sub-counties were selected to study consumption patterns of cocoyam in an urban setting. The sub-counties selected included; Westlands, Lang'ata, Kasarani, Embakasi South, Starehe and Dagoretti South.

3.1.2 Baseline survey tools

A mixed-methods approach involving the collection of both qualitative and quantitative data was utilised. Qualitative data was collected through key informant interviews (Appendix 2.2), direct observation and secondary data. Quantitative data was acquired using household questionnaires. Two household questionnaires were utilised, one for urban consumers of cocoyam administered in Nairobi City County (Appendix 2.3) and a second one for rural farmers administered in Meru county (Appendix 2.4). The questionnaires also contained sections to collect qualitative information. Crop production and agribusiness statistics were obtained from government institutions. The complete list of stakeholders interviewed or consulted is provided in Appendix 2.1.

3.1.3 Sampling methodology for household interviews

A multi-stage sampling technique was applied in selecting respondents for the study. The first stage involved the selection of Meru County based on the factors discussed in sub-section 3.1.1. In the second stage, Imenti central sub-county, being a low-lying area with proven production of horticultural products including cocoyam was selected for the study. The third stage involved the application of homogeneous purposive sampling to select survey respondents from villages within the five wards of Imenti Central sub-county. Twenty-two (22) farmers were selected from each ward. Farmers were selected with the assistance of local provincial administration officers, agricultural officers and farmer group leaders. Only the farmers who grow cocoyam for subsistence consumption or commercial use and who voluntarily agreed to participate in the survey were selected.

The sample size of farmers was calculated using Cochran's method (Cochran, 1977). Nyariki (2009) described the calculation of a sample size application for household data collection for socio-economic research in agriculture where the characteristics of the population are unknown using Cochran's method;

$$n = Z^2 \cdot p \cdot q \cdot e^{-2} \quad (1)$$

Where: n = the desired sample size (households), Z = the critical value from a normal probability distribution at the desired level of confidence (i.e., 1.96 at the 95 per cent confidence interval), p = population variability (taken to be 0.5), $q = 1 - p$ (0.5), e = the acceptable margin of error for agricultural studies (i.e., 10 per cent or 0.1).

For this study, and providing a 10 per cent margin for nonresponse, Equation (1) provided a sample size of 106 households to be interviewed across Meru county and 106 households across Nairobi City county. An additional sample of 14 households in Meru county and 6 households in Nairobi City county was to pre-test the questionnaire before the actual survey. Therefore, the total sample size was 120 for Meru county and 112 for Nairobi City county. The household questionnaires were coded into ODK for convenient data collection using smartphones and for additional data validation using GPS coordinates. Five (5) and six (6) enumerators were recruited from the selected wards of Imenti central sub-county and sub-counties of Nairobi City county respectively with the assistance of local administration. The basis of enumerator selection was the possession of a minimum of a college diploma, a smartphone and good knowledge of the target ward or sub-county. The enumerators were trained and dispatched to the field to collect data under close field supervision.

3.1.4 Quality control and data analysis

During this study, triangulation was applied to crosscheck the data and information received from the different sources that included consultative meetings, household interviews, observation, benchmarking and literature review. At the end of every working day during data collection, a preliminary analysis was performed on the collected data to identify any gaps that required immediate remediation. The utilisation of ODK enabled the collection of telephone contacts and GPS coordinates that enabled the researchers to verify the actual households visited by the enumerators. The survey data was cleaned and validated before analysis and interpretation. Descriptive and inferential statistical analysis was performed on the quantitative data using the Python software (Python Software Foundation, Delaware, USA) and Microsoft Excel (Microsoft Corporation, Washington, USA). Qualitative data were examined and important information was deduced to support the results of quantitative analysis.

3.2 Convective cooling experiments and modelling

3.2.1 Materials

This study utilised cocoyam (*Colocasia esculenta (L.) Schott)* tubers harvested at maturity in December 2019 and carefully sorted by hand to select tubers without visible defects. The soil left on the surface of the tubers during harvesting was gently removed using a soft brush. The tubers were then trimmed at both ends to remove dried material formed on the previous scar at the bottom end and at the petiole base to remove the foliage. The tubers were then cured by placing them in open sunlight for about 8 hours until the wounded surfaces dried out following Opara (1999).

3.2.2 Experimental design and test apparatus

Experiments were conducted at three levels of air velocity (0.5, 0.7 and 0.9 m/s), two levels of tuber size (small, 173.32 ± 30 g and large, 466.98 ± 95 g) and two levels of tuber orientation to airflow (along, across) of cooling air. Cocoyam tubers were cooled in air at 90 ± 2 % relative humidity and 10 ± 0.2 ºC temperature from an initial temperature of 30 ± 2 °C at the core and 28 ± 2 °C under the skin of the tubers to a uniform final temperature of 12 ± 0.2 °C. A replicated full factorial experimental design was created using the Design-Expert software version 11 (Stat-Ease Inc., Minneapolis, United States) and utilised to conduct experiments. The experimental test apparatus included a VCL 400 climate chamber (Vötsch Industrietechnik GmBH, Reiskirchen-Lindenstruth, Germany) with a - 40 to +180 ± 0.5°C temperature range and relative humidity range of 10 to 98 ± 3%. To achieve control over air velocity, a test box fully insulated with glass wool was utilised. The test box was instrumented with an EBM-Papst 3218JH4 variable speed fan (EBM-Papst Inc., St. Georgen, Germany), PHYWE-07475 voltage controller (PHYWE Systeme GmbH, Göttingen, Germany), air inlet duct and plenum. The data collection mechanism consisted of Pt-1000 RTD sensors (Therma Thermofühler GmbH, Lindlar Germany) linked to an Agilent Keysight 34970A multi-channel data logger (Keysight Technologies, California, USA). For this study, the temperature sensors were placed approximately at the core of the tubers and about 2 mm below the skin of the tubers. The air velocity was measured at the sample location using a TA-5 thermal anemometer (Airflow Lufttechnik GmbH, Rheinbach, Germany). The complete experimental setup is presented in Figure 3.2.

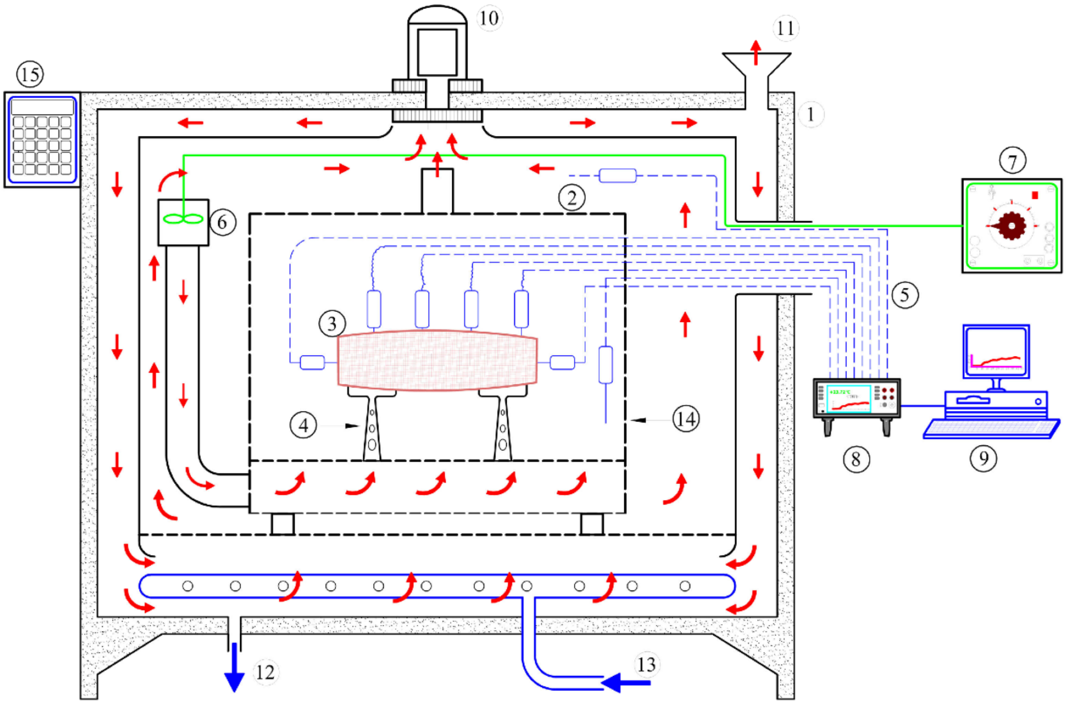


Figure 3.2: Experimental set-up for cooling experiments

(1. Vötsch VCL 400 Climate chamber, 2. RTD sensors, 3. Tuber, 4. Tuber support, 5. RTD wiring, 6. Ebmpapst Axial Suction Fan, 7. PHYWE Automatic Voltage/Speed regulator, 8. Keysight Data logger, 9. Logging computer, 10. Motor and Radial Blower Fan, 11. Vapour exhaust vent, 12. Condensate exhaust vent, 13. Distilled water inlet and humidifier, 14. Insulated test box, 15. Climate chamber control panel)

3.2.3 Key assumptions

The mathematical models for the solution of transient heat transfer equations for whole cocoyam tubers are based on the following assumptions: -

- The properties of the cooling air remain constant throughout the experiments;
- The range of air velocity (i.e. 0.5, 0.7, 0.9 $m \cdot s^{-1}$) is sufficiently subsonic (i.e. less than Mach 0.3) to guarantee incompressibility (Kundu et al., 2012);
- The flow domain wall condition is perfectly insulated to prevent thermal gains and losses;
- The thermophysical properties of cocoyam tubers can be adequately estimated using the models by Choi & Okos (1986);
- Each cocoyam tuber can be idealised as a short cylinder with an equivalent diameter as an average of the largest and smallest section diameters;
- Heat transfer in the domain occurs by internal conduction and surface convection only;
- For the air velocity range studied, the external surface of each tuber is fully surrounded by the cooling air (Zou et al., 2006).

3.2.4 Fluid and material properties

Table 3.1 provides the properties of air utilised in this study at standard atmospheric pressure (i.e., 101.325 kPa) and 10 °C air temperature.

Table 3.1: Air properties at 101.325 kPa and 10 °C (Rohsenow et al., 1998)

Property	Units	Value
Density (ρ)	$kg \cdot m^{-3}$	1.246
Specific heat capacity (C_{pa})	$kJ \cdot kg^{-1} \cdot K^{-1}$	1.006
Thermal conductivity (k)	$W \cdot m^{-1} \cdot K^{-1}$	0.02439
Dynamic viscosity (μ)	$kg \cdot m^{-1} \cdot s^{-1}$	1.778×10^{-5}
Kinematic viscosity (ϑ)	$m^2 \cdot s^{-1}$	1.426×10^{5}

The thermophysical properties of the cocoyam material were estimated from the models formulated by Choi & Okos (1986). The models provide a method to estimate properties as a function of major food constituents and temperature. The ratios of the constituents in cocoyam tubers are provided in Table 3.2 while the material properties are provided in Table 3.3.

Table 3.2: Proximate composition of cocoyam tubers ($g/100g_{DM}$) (Ndabikunze et al., 2011)

Moisture	Crude protein	Carbohydrate	Fat	Ash	Crude fibre
69.045±0.93	3.70±0.15	21.645±1.60	0.51±0.01	3.56±0.19	1.53±0.05

Table 3.3: Computed thermophysical properties of cocoyam tubers (Choi & Okos, 1986)

Property	Units	Temperature, T (°C)	
		10	30
Density (ρ)	$kg \cdot m^{-3}$	1125.96	1122.23
Specific heat capacity (C_p)	$kJ \cdot kg^{-1} \cdot K^{-1}$	3.347	3.359
Effective thermal conductivity (k_{eff})	$W \cdot m^{-1} \cdot K^{-1}$	0.414	0.414
Thermal diffusivity (α)	$m^2 \cdot s^{-1}$	1.099×10^{-7}	1.098×10^{-7}

3.2.5 Governing equations for transient heat transfer analysis

Transient heat conduction with a convective boundary was studied using the one-term solution of the Fourier series which is a reasonable approximation of transient heat transfer (Çengel & Ghajar, 2015). During the harvesting of a cocoyam tuber, two wounds are inflicted on the tuber, one to trim the dry bottommost end and one at the petiole base to remove the foliage. The geometry of the trimmed tubers therefore closely resembles a cylinder. Cylindrical geometries where L/D < 1.85 are known as short cylinders (Bharti et al., 2007; Zdravkovich et al., 1989). The tubers utilised in this study had an L/D of 1.62 ± 0.31 and therefore fit the description of short cylinders. The solution for the temperature at any point in the body of a short cylinder with transient cooling is computed by superposing the solutions of an infinitely long cylinder with a finite radius (r_o) and an infinitely large slab with a finite thickness (H = 2L) as shown in Figure 3.3.

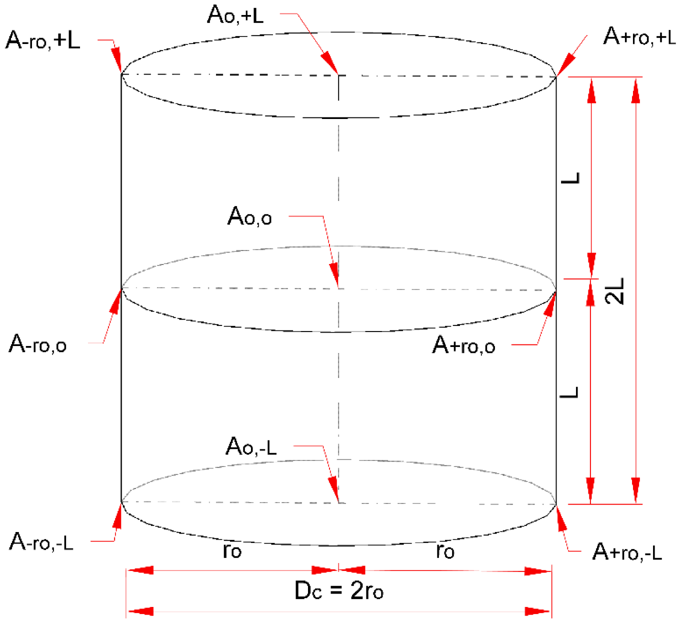


Figure 3.3: Dimension definitions of a short cylinder

For infinite cylinder and infinite slab geometries, the temperature history is calculated using Equation (2);

$$\Omega = \sum_{i=1}^{\infty} A_i \cdot e^{-\lambda_i^2 \cdot Fo} \tag{2}$$

where: Ω = dimensionless temperature difference, A_i = lag factor, λ_i = eigen value, λ_i^2 = Fourier exponent, Fo = Fourier number.

The Fourier number in Equation (2), also known as the dimensionless time, is determined using Equation (3);

$$Fo = \frac{\alpha_c \cdot t}{S^2} \tag{3}$$

where: α_c = thermal diffusivity of tubers ($m^2 \cdot s^{-1}$), t = total cooling time (s), S = characteristic length (m) which is half radius for the cylinder geometry and half-thickness for the slab geometry (Xu et al., 2012).

The Lag factor and the Fourier exponent are functions of the thermophysical properties of the product and are calculated from the Biot number. If their quantitative values are both greater than 1, then internal resistance to heat transfer in the tubers exists (Dincer & Genceli, 1994). For a product of a cylindrical geometry subjected to convective cooling, the convective heat transfer coefficient is determined as a function of Reynold's number (Re), Prandtl number (Pr) and the thermophysical properties of air provided in Table 3.1 using Equation (4) (Çengel & Ghajar, 2015);

$$h = 0.664 \cdot \left(Re^{0.5} \cdot Pr^{1/3}\right) \cdot \frac{k_a}{D} \tag{4}$$

where: h = convective heat transfer coefficient, Re = Reynolds number, Pr = Prandtl number, k_a = thermal conductivity of air, D = diameter of tuber (m).

The Reynolds number and Prandtl number are determined using Equation (5) and Equation (6) respectively.

$$Re = \frac{\rho_a \cdot \vartheta_a \cdot D}{\mu_a} \tag{5}$$

$$Pr = \frac{C_{pa} \cdot \mu_a}{k_a} \tag{6}$$

where ρ_a = density of air ($kg \cdot m^{-3}$), ϑ = cooling air velocity ($m \cdot s^{-1}$), μ_a = dynamic viscosity of air ($kg \cdot m^{-1} \cdot s^{-1}$).

The heat transfer coefficient in Equation (4) is translated into effective convective heat transfer coefficients for the slab and cylinder geometries using Equation (7) and Equation (8) respectively (Xu et al., 2012).

$$h_{eff.s} = \frac{1}{\frac{1}{h} + \frac{H/2}{3 \cdot k_{eff}}} \tag{7}$$

$$h_{eff.c} = \frac{1}{\frac{1}{h} + \frac{r_o}{4 \cdot k_{eff}}} \tag{8}$$

where $h_{eff.s}$ = effective convective heat transfer coefficient for slab geometry, $h_{eff.c}$ = effective convective heat transfer coefficient for cylinder geometry, k_{eff} = effective thermal conductivity of cocoyam tubers, H = thickness slab geometry, r_o = radius of cylinder geometry.

The effective Biot numbers are then determined as functions of the effective convective heat transfer coefficient, the characteristic length and the effective thermal conductivity of the cocoyam tubers using Equation (9) and Equation (10) following Xu et al. (2012).

$$Bi_c = \frac{h_{eff.c} \cdot \left(r_o/_2\right)}{k_{eff}} \tag{9}$$

$$Bi_s = \frac{h_{eff.s} \cdot \left(H/_2\right)}{k_{eff}} \tag{10}$$

where: Bi_c = effective Biot number for cylindrical geometry, Bi_s = effective Biot number for slab geometry.

The eigenvalue (λ_i) and the Fourier exponent (λ_i^2) are determined from the effective Biot numbers using Equation (11) and Equation (12) by applying an iterative procedure as discussed in section 3.2.6.

$$Bi_{i.c} - \lambda_i \cdot \frac{J_1(\lambda_i)}{J_0(\lambda_i)} = 0 \tag{11}$$

where: J_0 () and J_1 () are the Bessel functions of the first kind of order 0 and 1 respectively.

$$Bi_{i.s} - \lambda_i \cdot \tan(\lambda_i) = 0 \tag{12}$$

The calculated values of λ_i are then substituted into Equation (13) and Equation (14) to calculate the lag factors (A_i). The value of r_o in Equation (13) is equal to the radius of the tubers while r is the radius at any point of the tuber cross-section. In this study, the determination of the temperature history just under the skin of the tubers utilised $r = (r_o - t_s)$, where t_s = 2 mm is the thickness of the Tuber skin.

$$A_{1.c} = \frac{2 \cdot J_1(\lambda_{1.c})}{\lambda_{1.c} \cdot \left[J_0^2(\lambda_1.c) + J_1^2(\lambda_{1.c})\right]} \cdot J_0\left(\lambda_{1.c} \cdot \frac{r}{r_o}\right) \tag{13}$$

where: $A_{1.c}$ = lag factor for cylinder geometry, subscript $1.c$ = one-term approximate for cylinder geometry.

The value of L in Equation (14) is equal to half the height/length of the tuber (i.e., $L = 0.5H$) as shown in Fig. (2). The value of x is then the height at any point above or below the half-height of the tubers. Determination of the temperature history just at the surface of the trimmed ends of the tuber would be the case where $x = L$.

$$A_{1.s} = \frac{2 \cdot \sin(\lambda_{1.s})}{\lambda_{1.s} + \sin(\lambda_{1.s}) \cdot \cos(\lambda_{1.s})} \cdot \cos\left(\lambda_{1.s} \cdot \frac{x}{L}\right) \tag{14}$$

where: $A_{1.s}$ = lag factor for slab geometry, subscript $1.s$ = one-term approximate for slab geometry

Equation (13) and Equation (14) are then substituted into Equation (2) to obtain the dimensionless temperature differences for an infinite cylinder and infinite slab as given in Equation (15) and Equation (16).

$$\Omega_{1.c} = \frac{2 \cdot J_1(\lambda_{1.c})}{\lambda_{1.c} \cdot \left[J_0^2(\lambda_{1.c}) + J_1^2(\lambda_{1.c}) \right]} \cdot J_0 \left(\lambda_{1.c} \cdot \frac{r}{r_o} \right) \cdot e^{-\lambda_{1.c}^2 \cdot Fo} \tag{15}$$

$$\Omega_{1.s} = \frac{2 \cdot \sin(\lambda_{1.s})}{\lambda_{1.s} + \sin(\lambda_{1.s}) \cdot \cos(\lambda_{1.s})} \cdot \cos \left(\lambda_{1.s} \cdot \frac{x}{L} \right) \cdot e^{-\lambda_{1.s}^2 \cdot Fo} \tag{16}$$

The dimensionless temperature difference (Ω) for a short cylinder is obtained by calculating the product of the dimensionless temperature differences for an infinite cylinder and an infinite slab geometry using Equation (17).

$$\Omega_{1.sc} = \Omega_{1.c} \times \Omega_{1.s} \tag{17}$$

where: $\Omega_{1.sc}$ = one-term approximated temperature difference for short cylinder geometry.
The one-term approximated dimensionless temperature difference for a short cylinder is defined by Equation (18).

$$\Omega_{1.sc} = \frac{T_t - T_\infty}{T_i - T_\infty} \tag{18}$$

where T_t is the temperature at any point (r, x) in a short cylinder after a time, t, T_i = initial temperature of tubers (°C), T_∞ = temperature of cooling air (°C).

Rearranging Equation (18), the temperature at any point of a short cylinder after a time, t, can be calculated as:

$$T_t = \Omega_{1.sc} \cdot (T_i - T_\infty) + T_\infty \tag{19}$$

The amount of energy removed from each tuber at any time during the cooling process can be calculated using Equation (20) – Equation (46) (Çengel & Ghajar, 2015).

$$\left(\frac{Q}{Q_T} \right)_{s.c} = \left(\frac{Q}{Q_T} \right)_c + \left(\frac{Q}{Q_T} \right)_s \cdot \left[1 - \left(\frac{Q}{Q_T} \right)_c \right] \tag{20}$$

where Q = total amount of energy lost by the product to the surroundings after time, t (kJ), Q_T = total energy content of the material (kJ)

The second term on the right side of Equation (21) represents the energy ratio for an infinite cylinder and is a function of the dimensionless temperature difference for an infinite cylinder ($\Omega_{0, c}$) and the eigenvalue (λ_1) as given in Equation (19).

$$\left(\frac{Q}{Q_T} \right)_c = 1 - 2 \cdot \Omega_{0,c} \cdot \left(\frac{J_1(\lambda_1)}{\lambda_1} \right) \tag{21}$$

The second term on the right side of Equation (22) represents the energy ratio for an infinite slab geometry and is also a function of the dimensionless temperature difference for an infinite slab ($\Omega_{0,s}$) and the eigenvalue (λ_1) as given in Equation (19).

$$\left(\frac{Q}{Q_T}\right)_s = 1 - \Omega_{0,s} \cdot \left(\frac{\sin \lambda_1}{\lambda_1}\right) \quad (22)$$

The total energy content of the material is calculated using Equation (23).

$$Q_T = \rho \cdot V \cdot c_p \cdot (T_i - T_\infty) \quad (23)$$

where V = volume of tuber (m^3), ρ = density ($kg \cdot m^{-3}$), c_p = specific heat capacity ($kJ \cdot kg^{-1} \cdot K^{-1}$). The amount of heat transferred across the domain after a time, t is then calculated by substituting Equation (21), (22) and (23) into Equation (19) to yield Equation (24);

$$Q_{s.c} = \rho \cdot V \cdot c_p \cdot \Omega_i \cdot \left\{ \left(\frac{Q}{Q_T}\right)_c + \left(\frac{Q}{Q_T}\right)_s \cdot \left[1 - \left(\frac{Q}{Q_T}\right)_c \right] \right\} \quad (24)$$

3.2.6 Simulation procedure

The simulation of the amount of time required for cocoyam tubers to cool to the target temperature was conducted in a series of sequential steps as shown in Figure 3.4. It should be observed that the calculation of the lag factors, eigenvalues and dimensionless temperature differences was a repetitive process that required iteration to obtain an accurate answer. A code was therefore written in the Python software (Python Software Foundation, Delaware, USA) to automate the process. From an initial guess of $\lambda_i = 0$ and $t = 0$, the script made increments of 0.0001 to λ_i and 10 to t until the difference between the Biot number and the second term of Equation (11) and (12) converged to 0 and the tuber temperature converged to 12 °C which is in the recommended storage temperature range of 11 – 13 °C (Opara, 1999).

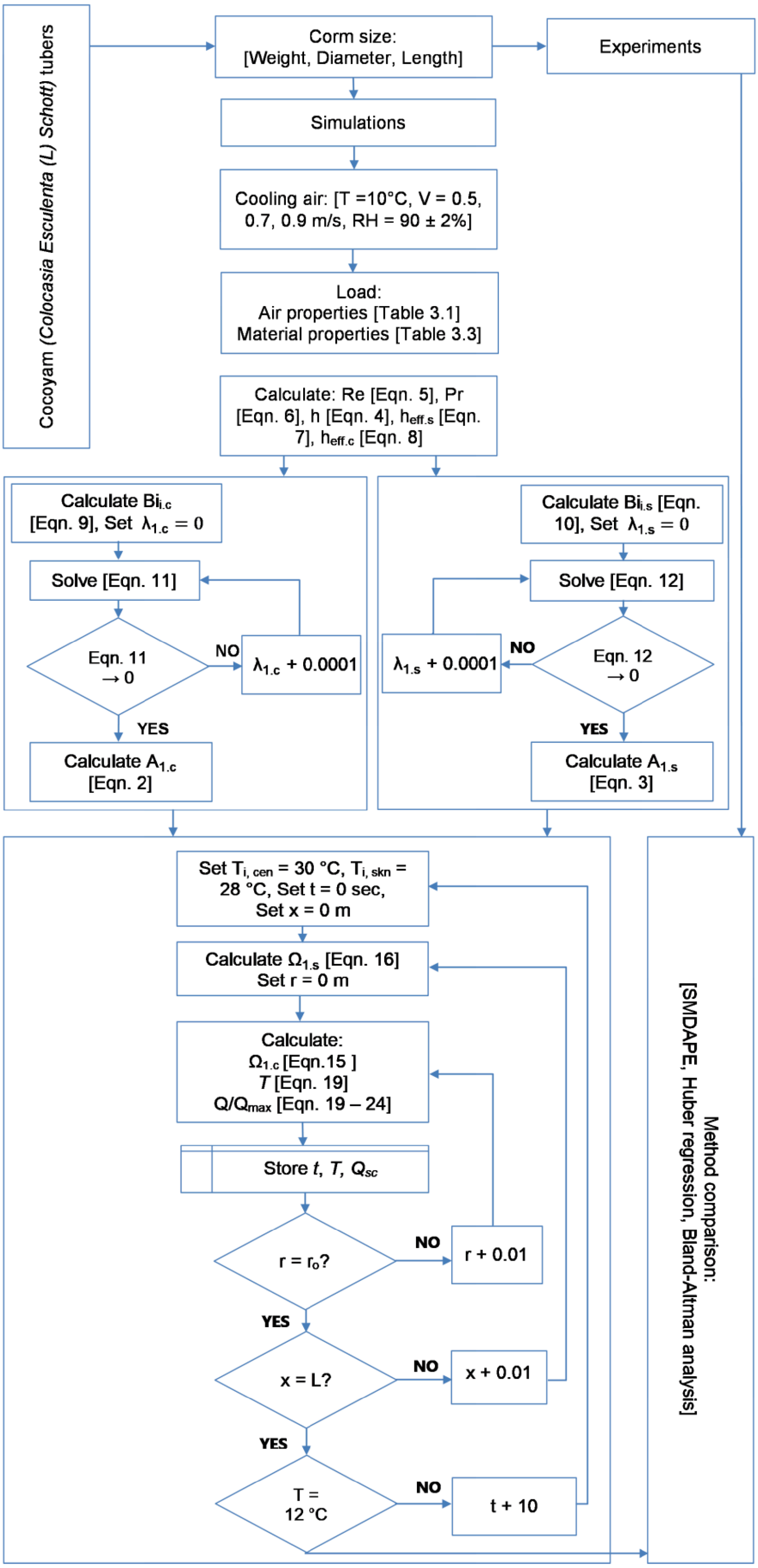


Figure 3.4: Forced convection cooling simulation procedure

3.3 Hot-air drying experiments, modelling and optimisation

3.3.1 Materials

Convective drying experiments utilised two batches of fully-grown cocoyam tubers (var. *Colocasia esculenta (L.) Schott*) harvested in March 2019 and March 2020 respectively. The tubers were examined to select pieces without blemishes and insect infestation and then gently cleaned with a brush before curing in open sunlight. The selected tubers were then kept in cold storage (4 ± 1 °C) until the completion of experiments.

3.3.2 Sample preparation

Ahead of experiments, cocoyam tubers peeled, washed in distilled water and gently dried with a soft towel. To prevent variation as a result of dissimilar properties at end sections of tubers as compared to the mid-section, 25 mm of flesh was sliced-off from both ends. In the first phase of drying experiments, slices of 4 mm, 7 mm and 10 mm thickness were produced by cutting the tubers with a Graef Vivo V20EU bench slicer (GRAEF GmbH, Germany). The slices were further trimmed to a common diameter of 25 mm using a stainless-steel core extractor. Two pretreatments were applied to the slices using the approach proposed by Afolabi et al. (2015) with some modifications. The pretreatment process involved placing a batch of slices in distilled water at 100°C for three minutes and thereafter immediately cooling them in distilled water at 10°C for one minute or in a 0.1% Sodium Metabisulfite ($Na_2S_2O_5$) solution at room temperature for five minutes. Excess liquid on the slice surfaces was wiped-off using an absorbent towel. Non-pretreated control samples were also prepared to provide a baseline for comparison purposes. The second phase of drying experiments utilised non-pretreated slices of 4 mm thickness and 25 mm diameter prepared using the bench slicer and the core extractor.

3.3.3 Experimental design and Drying experiments

In the first phase of investigations, the influence of pretreatments, air temperature and slice thickness on total drying time, colour change, rehydration ratio and drying energy demand was studied. The drying settings utilised are provided in Table 3.4. The experimental design utilised was an I-optimal experimental design with 25 experiments (i.e., 15 main treatments, 1 central treatment with 5 replications and 5 lack-of-fit treatments) with an experimental plan produced from the Design-Expert software version 11 (Stat-Ease Inc., Minneapolis, United States). I-optimal designs belong to class of reduced experimental designs utilised with multiple experimental factors to produce response surfaces in a technique called the Response Surface Methodology (RSM) (Myers et al., 2016). RSM reduces the number of experiments required while maintaining statistical integrity so as to save on experimental resources (Diamante & Yamaguchi, 2013). RSM also provide the possibility to intuitively visualize quadratic behaviour and interactions between experimental factors (Ndisya et al., 2020). With RSM, experimental data is fitted to the generalised polynomial model given in Equation (25).

Table 3.4: Drying settings (Ndisya et al., 2020)

Factor	**Coded units**	**Coded levels**		
		-1	**0**	**1**
Drying temperature (°C)	X_1	40	60	75
Slice thickness (mm)	X_2	4	7	10
Pretreatment (-)	X_3	N	B	B + SM

Where N = control sample/ non-pretreated, B = blanching and B+SM = blanching+ $Na_2S_2O_5$.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i<j} \beta_{ij} X_i X_j + \sum_{i=1}^{k} \beta_{ii} X_i^2 \tag{25}$$

Where Y = predictor variable, X_i, X_j = explanatory variables, k = total number of explanatory variables, β_0, β_i, β_{ii}, β_{ij} = main effects of the intercept, linear, quadratic and factor-factor interactions terms respectively (Box & Wilson, 1951; Montgomery, 2017).

Suitability of the developed models was statistically using analysis of variance (ANOVA), adjusted coefficient of determination (r^2_{adj}) and lack-of-fit tests. Model complexity was reduced by removing the statistically non-significant terms by iteratively applying a leave-one-out operation until a difference of 0.2 between r^2_{adj} and r^2_{pred} was realised. Homoscedasticity was confirmed by utilising a normal probability plot and a residuals plot; any departure from normality was corrected by applying data transformation using the box-cox method.

Drying experiments were undertaken at air temperatures of 40, 60 and 75 °C. For each experiment, nine cocoyam slices were utilised (i.e., three for moisture content and colour determination; six for rehydration ratio determination9). The weight of slices utilised for each experiment was 14.50 g for 4 mm, 26.28 g for 7 mm and 38.38 g for 10 mm slices. Drying experiments were undertaken in a HT-Mini cabinet dryer (Innotech-Ingenieursgesellschaft GmbH, Germany ± 2 °C) with a tray area of 0.18 m^2 at an air velocity of 0.6 m/s. The operating principle of the cabinet dryer is convection with hot-air flowing between trays to ensure uniform distribution of air. At the onset of each experiment, the dryer was run without products at the drying settings of interest for at-least thirty (30) minutes to ensure steady state conditions. All experiments were undertaken in a randomised order as per the prepared experimental plan. As each experiment progressed, slice weight measurements were successively taken, once after each 20 minutes in the first hour and thereafter on an hourly basis using a Sartorius Excellence E2000D digital weighing balance, ±0.001 g (Sartorius AG, Germany) until the estimated final moisture content of ~ 0.1 kg_W/kg_{DM} in accordance with (Ndisya et al., 2020). Triaxial colour readings (CIELAB L*a*b*) were also taken with each weight measurement with a Konica Minolta CR400 Chromameter (Minolta, Osaka, Japan). The dry matter content (DM) of the slices was established by drying in a Memmert Oven Drier (Memmert GmbH, Germany) at the end of each experiment for 24 hours at 105 °C in accordance with AOAC (2000). Moisture reuptake experiments were also conducted at the end of each experiment to establish the Rehydration Ratio (RR).

The second phase of investigations utilised a randomised full factorial experimental design. The explanatory variables included air temperature (40, 60 and 80 °C) and air velocity (2.0 ± 0.2, 3.0 ± 0.4 and 4.6 ± 0.7 $m.s^{-1}$). Drying experiments were undertaken in a HT-Mini cabinet dryer in accordance with the procedure described previously. Air velocity control was achieved indirectly by changing the voltage of the dryer fan. In this phase of investigations, slices were sampled from the dryer every thirty (30) minutes for measurement of moisture, colour, chemical and structural properties. The samples intended for the determination of chemical and structural properties were packed in High Density Polyethylene (HDPE) vacuum bags with a and structural attributes were packed in vacuum-grade transparent plastic bags using a LAVA V300 vacuum sealer (LANDIG Sondergerätebau, Bad Saulgau, Germany) and kept in frozen storage (-28 °C) until further analysis.

3.3.4 Drying quality attributes

3.3.4.1 Moisture attributes

Moisture content was evaluated using Equation (26) – (28). Cocoyam slices were sampled from the drying cabinet during drying and weighed using a Sartorius Excellence E2000D digital weighing balance, ±0.001 g (Sartorius AG, Germany). At the end of during experiments, the slices were dried for 24 hours at 105°C in a Memmert oven (Memmert GmbH, Büchenbach, Germany) to establish the dry matter content (DM) in accordance with AOAC (2000)

$$mc_{wb} = \frac{M_t - M_{DM}}{M_t} \tag{26}$$

Where: mc_{wb} = moisture content (wet basis), M_t = sample weight at time t and M_{DM} = dry matter content.

$$MR = \frac{M_t - M_e}{M_i - M_e} \tag{27}$$

Where MR = moisture ratio (dimensionless), M_i = fresh sample weight (g) and M_e = equilibrium weight (g). Equation (27) can be expressed in the simplified form shown in Equation (28) if the sample weight at equilibrium is considered to be negligible in comparison to M_t and M_i (Menges & Ertekin, 2006).

$$MR = \frac{M_t}{M_i} \tag{28}$$

Slices for the determination of water activity (a_w) were sampled from dryer every thirty (30) minutes with the measurement of slice weights for moisture content determination. Novasina LabSwift a_w meter (Novasina AG, Lachen, Switzerland) was utilised to measure a_w. During measurements, the meter was kept in a climate chamber with the temperature setting at 25 °C.

3.3.4.2 Colour attributes

Triaxial colour measurements (CIELAB L*a*b*) were measured progressively during drying every thirty (30) minutes with a Konica Minolta CR400 chromameter (Minolta, Osaka, Japan) with the observer set at 2° and Illuminant to Type C. The chromameter was also calibrated against a white standard tile. Colour measurements were taken as averages of three slices with three measurements for each slice. The CIELAB colour space was utilised to express the results in a three-dimensional space (Luo, 2015). The derivative colour indices were calculated from Equation (29) – (34) (Ndisya et al., 2020);

$$\Delta E = \sqrt{(L_i - L_t)^2 + \left(a_i^* - a_t^*\right)^2 + \left(b_i^* - b_t^*\right)^2} \tag{29}$$

$$BI = \frac{100 \cdot (x - 0.31)}{0.172} \tag{30}$$

$$x = \frac{a^* + 1.75 \cdot L^*}{5.645 \cdot L^* + a^* - 3.012 \cdot b^*} \tag{31}$$

$$WI = 100 - \left((100 - L_t) + a^* + b^*\right)^{\frac{1}{2}} \tag{32}$$

$$C^* = \left[(a^*)^2 + (b^*)^2\right]^{\frac{1}{2}} \quad (33)$$

$$h^o = \arctan\left(\frac{b^*}{a^*}\right) \quad (34)$$

Where L* = lightness index (0 = dark, 100 = light), a* = greenness/ redness index (- 80 = green, 100 = red) and b* = blueness/ yellowness index (- 80 = blue, 100 = yellow), ΔE = total colour difference, BI = browning index, WI = whiteness index, C* = chroma, h^o = hue angle.

3.3.4.3 Chemical attributes

Before chemical analysis, the preserved cocoyam slices were dried with a Christ Epsilon 2-40 freeze-dryer (Martin Christ Gefriertrocknungsanlagen GmbH, Osterode am Harz, Germany) at a temperature of -85 °C for 96 hours (Ndisya, Gitau, Mbuge, et al., 2021). The slices were then ground to a fine power with a Jankel & Kunkel A10 grinder (Jankel & Kunkel K.G., Staufen im Breisgau, Germany). The ground samples were then kept in airtight PVC container awaiting chemical extraction. During chemical extraction, 0.3 g of the samples was mixed with 10 ml of 80% v/v ethanol (C_2H_6O) then homogenized with a an Assistent Reamix 2789 vortex mixer (Karl Hecht Glaswarenfabrik GmbH & Co KG, Sondheim, Germany). Centrifugal separation of the sample solids from liquid phase of the mixture was then undertaken in a Megafuge 16 centrifuge (Thermo Fisher Scientific, Waltham, United States) at 5000 RPM for ten (10) minutes. Micropipettes were then utilised to carefully collect the of the supernatant into round bottom flask where the difference was made up to ml with 80% v/v ethanol (C_2H_6O). The supernatant was therefore kept in airtight containers at -20 °C until further analysis.

The Folin-Ciocalteu assay discussed in Singleton & Rossi (1965) and Ndisya et al. (2021) with slight modifications was utilised to analyse the total phenolic content (TPC). The chemical reagents for the used in the analysis included 0.5 mol/l of sodium hydroxide (NaOH), 2.643 g/l of gallic acid monohydrate ($C_7H_8O_6$), and the Folin-Ciocalteu reagent (C_6H_6O). Before chemical analysis experiments, a standard solution of $C_7H_8O_6$ in the concentration range 0 – 59.7 µg/ml was prepared (Ndisya, Gitau, Mbuge, et al., 2021). The procedure involved mixing 300 µl of ethanolic extract, 1 ml of NaOH, 100 µl of the Folin-Ciocalteu reagent and 2.6 ml of deionised water in capped centrifuge tubes and homogenizing the mixture with a vortex mixer. The mixture was then incubated in a GFL 1083 water bath (Lauda Wobser GmbH, Lauda-Königshofen, Germany) at 37 °C for fifteen (15) minutes (Ndisya, Gitau, Mbuge, et al., 2021). The tubers were cooled under a stream of water and the mixture transferred into cuvettes. A control sample of 2.9 ml of deionised water and 1.1 ml of 80% v/v was utilised to take a zero-concentration absorbance reading with the spectrophotometer. The concentration of TPC ($\mu g_{GA}/g_{DM}$) was then determined with an Agilent 8453 UV-Vis spectrophotometer (Agilent Technologies, Waldbronn, Germany) at 735.8 nm.

The aluminium chloride assay as discussed in Pękal & Pyrzynska (2014) and Ndisya et al. (2021) with slight modifications was utilised to analyse the total flavonoid content (TFC). The chemical reagents for the used in the analysis included 2% w/v aluminium chloride ($AlCl_3$), 1M of sodium acetate (CH_3COONa) and 125 mg/l quercetin-3-glucoside ($C_{21}H_{20}O_{12}$) in methanol. Before chemical analysis experiments, a standard solution of $C_{21}H_{20}O_{12}$ in the concentration range 0 – 60 mg/l was prepared (Ndisya, Gitau, Mbuge, et al., 2021). The procedure involved mixing 750 µl of the ethanolic extract, 375 µl of $AlCl_3$ and 375 µl of CH_3COONa in capped centrifuge tubes and homogenizing the mixture with a vortex mixer before incubation at room temperature for thirty (30) minutes. A control sample of 750 µl of 80% v/v ethanol, 375 µl of deionised water and 375 µl of CH_3COONa was utilised to take a zero-concentration absorbance reading with the spectrophotometer. The concentration of TPC (mg/g_{DM}) was then determined with the spectrophotometer at 425.0 nm.

The 2,2-Diphenyl-1-picrylhydrazyl (DPPH) assay as discussed by Brand-Williams, Cuvelier, & Berset (1995) and Ndisya et al. (2021) with slight modifications was utilised to analyse the total antioxidant activity (TAA). The chemical reagents for the used in the analysis included 7.88 mg of DPPH reagent ($C_{18}H_{12}N_5O_6$) dissolved in 100 µl of methanol (CH_3OH) incubated for 2 hours in a dark enclosure at room temperature beforehand (Ndisya, Gitau, Mbuge, et al., 2021). The procedure involved mixing 0.3 ml of the ethanolic extract and 1.2 ml of $C_{18}H_{12}N_5O_6$ in capped centrifuge tubes and homogenizing the mixture with a vortex mixer before incubation at room temperature for thirty (30) minutes. A control sample of 1.5 ml of 80% v/v ethanol was utilised to take a zero-concentration absorbance reading with the spectrophotometer. The concentration of TAA (%RSA) was then determined with the spectrophotometer at 515.0 nm using Equation (35).

$$\text{TAA} = \frac{(A_C - A_o)}{A_C} \times 100 \tag{35}$$

Where: A_C = absorbance of control sample at 515 nm, A_o = absorbance of ethanolic extract at 515 nm.

3.3.4.4 Structural attributes

a) Rehydration ratio

Rehydration experiments were undertaken to determine the degree of moisture re-uptake at the start and the end of each drying run following the method discussed by Ndisya et al. (2020) with slight modifications. The experiments involved dipping 3 slices into a GFL 1083 water bath (Lauda Wobser GmBH, Lauda-Königshofen, Germany) with water temperature at 95 °C for 10 min. The weight of fresh slices and the slices after rehydration was determined with a Sartorius Excellence E2000D digital weighing balance, ±0.001 g (Sartorius AG, Göttingen, Germany). The rehydration ratio was then computed using Equation (36);

$$RR = \frac{W_i}{W_r} \tag{36}$$

Where: RR = rehydration ratio (dimensionless), W_i = fresh weight of slice/slice weight after drying (g), W_r = weight of slice after rehydration (g).

b) Volumetric shrinkage

Volumetric shrinkage was determined using a combination of the pixel counting method discussed in Sturm et al. (2012) and physical measurements. The thickness of the slices was measured using a Silver-line micrometre screw gauge (Vogel GmbH, Kevelaer, Germany) at four different points on the slices and the average was computed. Volumetric shrinkage was then computed using Equation (37);

$$V_s = \frac{V_t}{V_o} = \frac{A_t \cdot h_t}{A_o \cdot h_o} \tag{37}$$

Where: V_s = volumetric shrinkage, V_o = initial volume of slice, V_t = slice volume at time t, A_o = initial slice top surface area (pix), A_t = slice top surface area at time t (pix), h_o = initial thickness of slice (mm), h_t = thickness of slice at time t.

c) Structural morphology

Samples drawn during drying for the analysis of structural morphology were studied using Scanning Electron Microscopy (SEM) to extract morphological information including the total area occupied by pores and the circularity of the pores. The samples were freeze dried using a Christ Epsilon 2-40 freeze dryer (Martin Christ Gefriertrocknungsanlagen GmbH, An der Unteren Söse 50, Osterode am Harz, Germany) at -85 °C for 96 hours. SEM was undertaken following the procedure discussed by Ogolla et al. (2019) with slight modifications. The samples were dipped into liquid nitrogen for 5 seconds to prevent structural changes during specimen preparation then attached to a double-sided adhesive carbon tab mounted on the SEM stubs. The samples were then coated with gold-palladium and studied under a Phillips xT Scanning Electron Microscope (Philips Export BV, Netherlands) operating at a low vacuum, a voltage of 5 kV, a pressure of 100 Pa and 200 times magnification.

The Fiji software was utilised to pre-process the SEM images and to extract morphological information (Schindelin et al., 2012). Pre-processing operations applied to improve the quality of the images included scaling, thresholding, filtering, de-speckling and water-shedding. The raw images were converted into 8-bit images where each pixel was assigned a grey-scale value in the range 0 – 255. The Li Minimum Cross-Entropy threshold-based segmentation method was found suitable to categorize pixels as foreground or background pixels depending on their grey-scale values (Li & Lee, 1993). Pores in the material were presented in white colour and the solid cocoyam material in black colour in the binary images. Complete pores with an area equal to or greater than 400 μm^2 were counted while those crossing the edges of the region of interest were ignored. The circularity of the pores was calculated using Equation (38). Circularity values approaching 0 indicated elongated polygons while those approaching 1.0 indicated a perfect circle (Rasband, 2000).

$$PPC = 4 \cdot \pi \cdot \left(\frac{\text{area}}{\text{perimeter}^2} \right) \tag{38}$$

3.3.4.5 Energy demand for drying

The energy consumed during drying was calculated using Equation (39) (Aghbashlo et al., 2008; Koyuncu et al., 2007; Motevali, Minaei, & Khoshtagaza, 2011; Mutuli & Mbuge, 2015).

$$E_t = A \cdot \vartheta \cdot \rho_a \cdot c_a \cdot \Delta T \cdot t \tag{39}$$

Where E_t = total energy consumed during the drying run (kJ), A = cross-sectional area of the drying tray holding the slices (m^2), ϑ = air velocity (m/s), ρ_a = density of air (kg/m^3), c_a = specific heat of air (kJ/kg. K), ΔT = temperature difference (K) and t = total time of the drying run.

The specific energy requirement, E_s (kJ/kg) was calculated using Equation (40);

$$E_s = \frac{E_t}{M_i} \tag{40}$$

Where M_i is the starting weight of the slices (kg).

3.3.5 Optimisation using the desirability function approach

Parameter optimisation was conducted in the Design-Expert version 11 (Stat-Ease Inc., Minneapolis, United States) utilising the desirability function approach. The approach involves the application of mathematical methods to convert a multivariable problem into a single response problem (Del Castillo et al., 1996; Derringer & Suich, 1980). This study applied the desirability function method developed by Harrington (1965) and modified by Derringer & Suich (1980). The objective criteria applied were geared towards the minimisation, maximisation or achievement of a set target of the optimisation function. The desirability function approach converts the estimated response variable Y_n to a desirability index d_n taking values between 0 and 1. Desirability increases as d_n increases from 0 to1. The desirability indices for each response variable are then combined into the composite desirability index by calculating the geometric mean as shown in Equation (41).

$$D=[d_1(Y_1)\times d_2(Y_2)\times\cdots d_n(Y_n)]^{\frac{1}{n}} \tag{41}$$

Where D = composite desirability index, n = number of response variables.

Table 3.5: Numerical optimisation criteria and constraints

Factors & Parameters	Optimisation goal	Lower limit	Upper limit	Importance
Factors				
Drying temperature (°C)	keep in range	40	75	-
Slice thickness (mm)	keep in range	4	10	-
Pretreatment	keep in range	N	B+SM	-
Responses				
Total drying time, *T* (min)	minimise	-	-	5
Colour difference, ΔE (-)	minimise	-	-	5
Browning Index, *BI (-)*	minimise	-	-	5
Rehydration ratio, *RR* (-)	maximise	-	-	5
Specific energy consumption, E_s (kJ/kg)	minimise	-	-	5

Table 3.5 presents the optimisation goals set for the individual responses, the lower and upper parameter constraints and the allocated level of importance. The drying process settings were kept in their range and their importance was left at the default settings. All responses were allocated the maximum level of importance as they are of particular interest to both the food processor and the consumer. Optimisation goals included the maximisation of the RR and the

minimisation of the total drying time, the total colour difference, the browning index and the specific energy consumption.

3.3.6 Empirical and Semi-Empirical model fitting

The results of the drying experiments were fitted to 19 empirical and semi-empirical models commonly applied in modelling drying processes for food materials. The models evaluated included: Newton model, Page model, Modified page (II), Modified page (III), Henderson and Pabis model, Modified Henderson and Pabis model, Midili et al. model, Logarithmic model, Two-term model, Two-term exponential model, Hii et al. model, Demir et al. model, Verma et al. model, Approximation of diffusion, Modified Midili et al., Aghbashlo et al. model, Wang and Singh, Silva et al. model and the Peleg model (Onwude, Hashim, Janius, et al., 2016). Non-linear regression analysis was conducted in MATLAB software version R2019a (MathWorks Inc., USA) to determine the model coefficients. Models were selected based on returning the highest value of the coefficient of determination (r^2), adjusted coefficient of determination (r^2_{adj}) and the lowest Root Mean Square of Error (RMSE) and Sum of the Squared Errors (SSE) at the 0.05 level of significance. A plot of the residuals relative to the curve fits was made where the residuals were checked to be randomly scattered on both sides of the zero line for a good fit.

3.3.7 Hyperspectral image acquisition and processing

3.3.7.1 HSI acquisition

This study utilised a combination of two HSI systems operating in the visible to the near-infrared region (Vis-NIR) with a combined spectral range of 400 – 1720 nm. The first imaging system operated in the spectral range 400 – 1010 nm with a sampling rate of 1.5 nm. The system consisted of a V10E PFD camera (Specim Spectral Imaging Ltd, Oulu, Finland) stocked with a 35 mm Xenoplan 1.9/35 lens (Jos. Schneider Optische Werke GmbH, Bad Kreuznach, Germany) operating on a linear translation stage (Specim Spectral Imaging Ltd, Oulu, Finland). The translation platform was illuminated with a combination of 105 W halogen lamps and 56 W LED lamps fixed at an angle of 45°. A standard white tile with a length and width of 200 mm and 24 mm and a spatial resolution of 1775 pixels was placed alongside the samples on the platform as a reference. A dark reference was acquired before scanning by taking an image with the camera shutter closed. The second system operated in the spectral range of 937 – 1700 nm with a sampling rate of 3.5 nm. It consisted of an FX17 camera (Specim Spectral Imaging Ltd, Oulu, Finland) stocked with a 17.5 mm OLET 17.5 N f/2.1 lens (Specim Spectral Imaging Ltd, Oulu, Finland) with a linear translation stage (Specim Spectral Imaging Ltd, Oulu, Finland).

The translation platform was illuminated with a combination of 120 W halogen lamps fixed at an angle of 45°. A standard white tile with a length and width of 200 mm and 25 mm was placed alongside the samples on the platform as a reference. A dark reference was also taken with the camera shutter closed to assist in the correction of camera sensor noise.

3.3.7.2 HSI processing

The hyperspectral images were processed using an in-house code written in the MATLAB® software version R2020a (MathWorks, Massachusetts, USA). The processing computer was stocked with a 32G Random Access Memory and an octa-core processor (Intel Core i9 9900K 8 × 3.6GHz). The image channels were automatically searched to select the ones providing the best contrast between foreground objects and the backgrounds. The selected channels were then binarized where values of 0 and 1 were assigned to the backgrounds and foreground objects respectively. The binary images were then used as masks to segment the objects from the backgrounds. The white and dark references captured during image acquisition were used to correct the segmented images for non-uniformity of light and sensor noise. Equation (42) was applied in the correction process,

$$R_R = \frac{R_S - R_D}{R_w - R_D} \times 100 \quad (42)$$

Where: R_R = adjusted relative reflectance of the image, R_S = relative reflectance of the original images, R_W = relative reflectance of the white reference, and R_D = relative reflectance of the dark reference.

The average relative reflectance spectra for all samples were then calculated and fused with quality attributes data from laboratory measurements. The spectral data below 425 nm and above 1700 nm were ignored due to the low noise to signal ratio attributable to the low sensitivity of the cameras in that range. The spectra were then improved by applying the Moving Average (MA) filter, Multiplicative Scatter Correction (MSC), the first derivative of reflectance (d.(R)) and the second derivative of reflectance (d^2.(R)). The MA filter was utilised to smooth the spectra and MSC to eliminate multiplicative and additive scattering. The Savitzky-Golay smoothing and differentiation filter with a second-order polynomial was applied to calculate smoothed d.(R) and d^2.(R). The improved spectra were then subjected to multivariate modelling.

3.3.8 Multivariate modelling

Partial Least Squares Regression (PLSR) was implemented in the scikit-learn library of the Python Software to correlate the spectral data to the quality attributes under consideration (Pedregosa et al., 2011). First, the data were transformed to follow a Gaussian distribution by fitting a standard scaler feature-wise. This involved subtracting the mean value of spectra from each value then dividing it by the standard deviation of the whole dataset. The data was then randomly split into a 60 per cent training set and a 40 per cent hold-out testing set. The training set was used for calibration and cross-validation while the independent testing set was utilised to assess the prediction power of the developed PLSR models. 10-fold cross-validation was used on the training data where 9 folds were used for calibration and one-fold for testing in each iteration. The optimal number of components for the PLS models were found using the non-linear iterative partial least squares (NIPALS) algorithm in scikit-learn by setting the maximum number of Latent Variables (LVs) to be 15. The optimal number of PLS components were selected based on returning the lowest Root Mean Squared Error ($RMSE_C$) and the highest coefficient of determination (r^2_C) and Residual Prediction Deviation (RPD_C) using Equation (43) – (45). RPD provides an assessment of the relative predictive performance of the model. Values of RPD less than 1.5 indicates the model is unacceptable, RPD between 1.5 – 2.0 indicates the model can differentiate low from high values of the response, 2.0 – 2.5 indicates rough estimations are possible, 2.5 – 3.0 corresponds to good prediction accuracy while values above 3.0 indicate excellent prediction accuracy (Mariani et al., 2014; Nicolaï et al., 2007). According to (Williams & Sobering, 1993), an RPD value above 10 indicates the model is equivalent to the standard method.

$$RMSE_C/RMSE_P = \sqrt{\frac{\sum_{i=1}^{N}\left(y_i - \hat{y}_i\right)^2}{N}} \tag{43}$$

Where: $RMSE_C$ = Root Mean Squared Error for calibration, $RMSE_P$ = Root Mean Squared Error for prediction , y_i = observations, $\hat{y}_i$ = predictions, N = number of data points.

$$r_C^2/r_P^2 = 1 - \frac{\sum\left(y_i - \hat{y}_i\right)^2}{\sum\left(y_i - \bar{y}\right)^2} \tag{44}$$

Where: r_C^2 = coefficient of determination for calibration, r_P^2 = coefficient of determination for prediction.

$$RPD_C/RPD_P = \sqrt{\frac{\sum\left(y_i - \hat{y}_i\right)^2}{N - 2}} \tag{45}$$

Where: RPD_C = Residual Prediction Deviation for calibration, RPD_P = Residual Prediction Deviation for prediction.

3.3.9 Spectral Feature selection

3.3.9.1 PLS-BETA

The maximum number of wavelengths for the prediction of the quality parameters were identified by filtering and sequential elimination of wavelengths based on the PLS ß-coefficients using Python code. The process involved building the prediction model with the complete spectrum using the optimal PLS components. The PLS ß-coefficients were ranked in ascending order of magnitude and the features with the lowest absolute value of ß-coefficients were then removed one at a time while evaluating the $RMSE_C$, r^2_C and RPD_C values returned by the PLS model without the single wavelengths. The process was iterated until the removal of a single wavelength either degraded or no longer improved the statistical quality measures. New PLS models were then developed with the reduced set of wavelengths and the model predictions were compared to the held-out testing data. $RMSE_P$, r^2_P and RPD_P were computed to evaluate the performance of the new models.

3.3.9.2 PLS-VIP

Partial Least Square Variable Importance in Projection (PLS-VIP) was utilised to select a subset of influential wavelengths from the developed PLS models (Afanador et al., 2014). PLS-VIP plots were used to visualize the relationship between features and PLS-VIP scores for each quality attribute under consideration. The PLS-VIP scores were calculated using Equation (46) in Python using the *find_peaks* and *peak_prominences* functions in the SciPy library (Virtanen et al., 2020). Wavelengths with PLS-VIP scores greater than 1.0 were considered to be the most influential on the particular quality attributes.

$$VIP_j = \sqrt{\frac{\sum_{a=1}^{A} SS_a^2 \cdot \left(W_{aj}/W_a\right)^2}{\left(\frac{1}{N}\right) \cdot \sum_{a=1}^{A} SS_T}} \quad (46)$$

Where VIP_j = PLS-VIP score of the j^{th} wavelength, A = number of PLS components, SS_a = variation explained by the a^{th} component, SS_T = total variance explained by all components, N = total number of features.

Figure 3.5 summarises the process followed in data acquisition, processing and prediction model development.

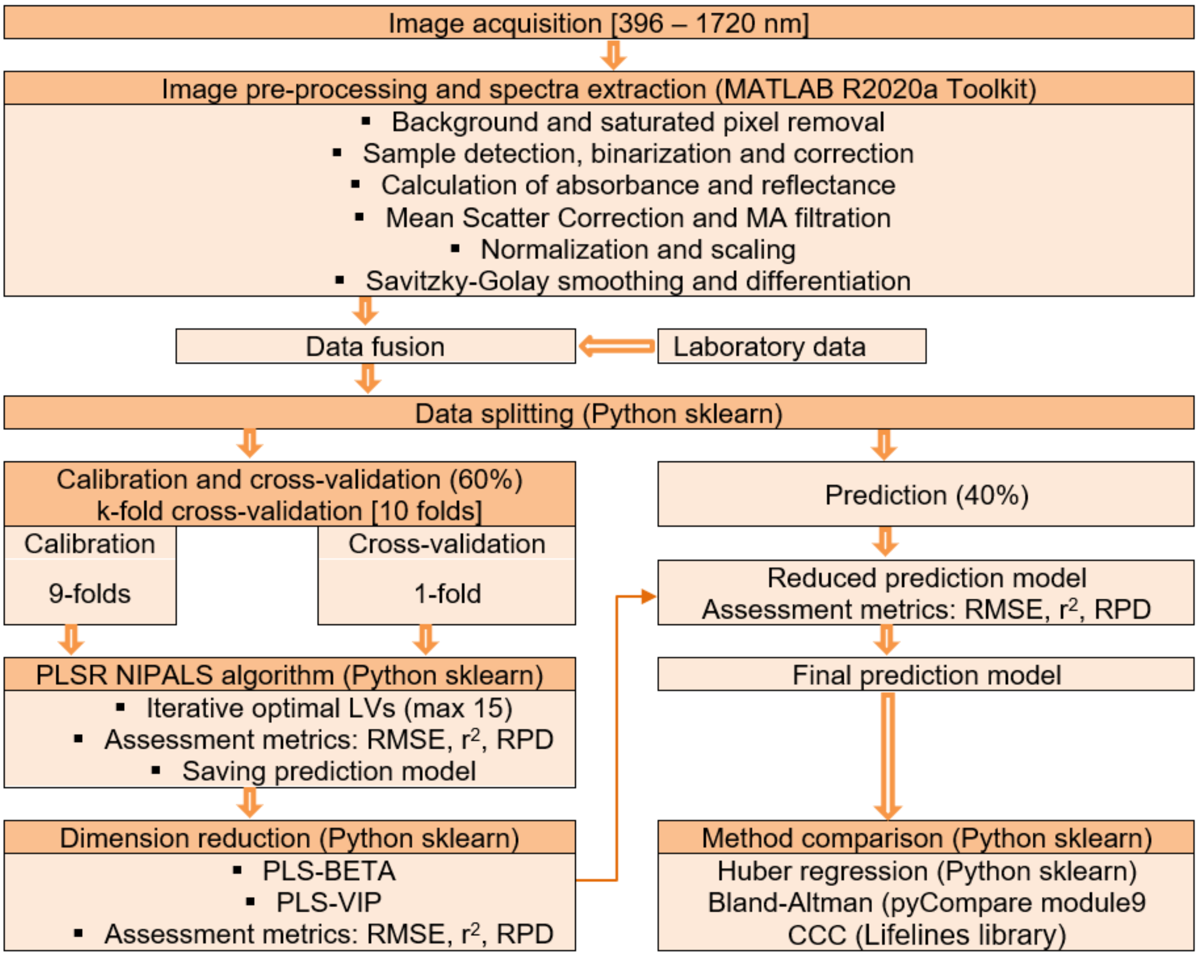


Figure 3.5: Summary of image acquisition, analysis and model development

3.4 Validation and method comparison

Comparison of new methods of measuring particular phenomenon to standard methods to assess their comparability and compatibility is common in the applied sciences. This is because pertinent system variables are often measured with error (Altman & Bland, 1983). Therefore, the comparison process applies statistical methods to quantify the error in the new method and to explain its influence on predictions (Ungerer & Pretorius, 2017). Classical comparison methods utilise indices such as the coefficient of determination (r^2) and the correlation coefficient (r). However, utilisation of these indices has been criticized because they measure the degree of linear association but not the actual agreement between two datasets (Giavarina, 2015; L. Lin, 1989). Nonetheless, techniques utilising robust estimates of regression coefficients, robust metrics of prediction accuracy, concordance indices and analysis of differences are more appropriate in method comparison studies to assess the degree of agreement (L. Lin et al., 2002; Morley et al., 2018; Shrestha, Crichton, et al., 2020; Ungerer & Pretorius, 2017). In this study, the following methods were applied to assess the agreement between predictions and observations;

a) Symmetric Median Absolute Percentage Error (SMDAPE)

When comparing independent datasets from unrelated sources, utilisation of measures of accuracy that are independent of the scale of the data such as percentage errors is recommended (Morley et al., 2018). The Mean Absolute Percentage Error (MAPE) is a frequently utilised metric when the quantity to be predicted is known to be always positive (de Myttenaere et al., 2016). MAPE is popular because it is intuitively interpreted in terms of a relative error (de Myttenaere et al., 2016; Morley et al., 2018). However, Morley et al. (2018) propose the Symmetric Median Absolute Percentage Error (SMDAPE). SMDAPE is equally intuitive to interpret, penalizes over-prediction and under-prediction equally and is robust in the presence of outliers (Morley et al., 2018). The lower the value of SMDAPE, the closer the predictions to the observations (Morley et al., 2018; Swamidass, 2000). The FindErrors module in TSErrors 1.0 library of the Python software was applied to compute the MAPE and SMDAPE (Abbas, 2020).

$$SMDAPE=100\cdot(\exp(M(|\log_e(Q)|))-1) \qquad (47)$$

where M = median, Q = ratio of prediction to observation

b) Huber regression

Huber regression is a commonly used method for robust regression to provide reliable regression results in the presence of outliers and high leverage points (Fox & Weisberg, 2012). This was achieved by minimizing the Mean Squared Error (MSE) in the Huber loss function (de Myttenaere et al., 2016; Huber, 1992). Assessment of agreement using regression coefficients involves testing the slope coefficient and the intercept coefficient against the ideal values of 1 and 0 respectively (Golbraikh & Tropsha, 2002). Deviation of the slope from 1 or the intercept from 0 indicates the presence of a systematic error (Altman & Bland, 1983). In this study, the Huber regression was applied to calculate the slope and intercept of the regression line between the predictions and observations. The Huber Regressor class in the Scikit-learn library of the Python software was applied to compute the robust slope and intercept of the linear regression line and to flag outliers (Pedregosa et al., 2011). The Huber loss function was fit with a value of epsilon of 1.0, which attempts to leave the fewest data points out of the fit for maximum robustness to outliers.

c) Bland-Altman plots and analysis

Bland-Altman analysis quantifies the agreement between predictions and observations using their differences (Bland & Altman, 1999). The method evaluates the bias between the mean differences between predictions and observations and constructs limits of agreement within which 95 per cent of the differences should lie if a good agreement is present (Giavarina, 2015). For two datasets to be deemed to agree, the scattered differences in the Bland-Altman plot should lie within the upper and lower limits of agreement, the differences should also be uniformly distributed on both sides of the mean difference and zero bias lines and heteroscedasticity should be absent (Bland & Altman, 1999). The Bland-Altman method only establishes the limits of agreement but does not define whether those limits are acceptable or not (Giavarina, 2015). Therefore, acceptable limits of agreement should be defined from experience or established industry standards (Giavarina, 2015). In this study, Bland-Atman plots were constructed in Python software using the pyCompare module (Jake & Tirrell, 2020). The plots were then visually inspected for patterns and the absence of bias. An ideal agreement between predictions and observations is achieved when the Bland-Altman plots display accuracy (i.e. when the bias is zero or close to zero) and precision (i.e. when the LOA are close to the bias line) (Bland & Altman, 1999).

d) Concordance Correlation Coefficient

The concordance correlation coefficient (CCC) is a popular index which measures the agreement between two datasets by testing the differences in the scale and location of the regression with the line of equality (L. Lin, 1989). CCC standardizes the Mean Squared Error (MSE) as a correlation coefficient where a value of 1 $\left(y_{pred} = y_{obs}\right)$ represents a perfect agreement, a value of -1 represents perfect disagreement $\left(y_{pred} = -y_{obs}\right)$ and a value of 0 represents no agreement (L. Lin et al., 2002). Various interpretations of the values of CCC are available in literature. However, the interpretation presented by McBride (2005) is probably the most recognized. In this study, the value of CCC was calculated using the Lifelines library in the Python software (Davidson-Pilon et al., 2020), the strength of agreement between predictions and observations was then calculated using Equation (47) and assessed in-accordance with Table 3.6;

$$\mathrm{CCC} = \frac{2\mathrm{S_{xy}}}{\mathrm{S_x^2} + \mathrm{S_y^2} + (\bar{\mathrm{x}} - \bar{\mathrm{y}})^2} \qquad (47)$$

Where: S_x = variance in observations, S_y = variance in predictions, S_{xy} = covariance between observations and predictions, $\bar{x}$ = mean of observations, $\bar{y}$ = mean of predictions.

Table 3.6: Interpretation of CCC (McBride, 2005)

Concordance Correlation Coefficient	strength-of-agreement
> 0.99	almost perfect
0.95 – 0.99	substantial
0.90 – 0.95	moderate
< 0.90	poor

3.5 Statistical analysis

The computations, multivariate analyses and statistical analysis performed in this study rely on the assumption that the datasets depict a Gaussian distribution, and that the variance is uniform. Therefore, various statistical checks were performed to ensure that these basic assumptions were obeyed. The D'Agostino-Pearson test was performed to test for Gaussian distributions and histograms were also constructed to visually confirm the same (D'Agostino & Pearson, 1973). Homogeneity of variance was confirmed by performing Levene's test (Levene, 1960). Finally, the student's *t*-test was also performed as an initial gauge for the existence of bias between observations and predictions. The SciPy library in the Python software was utilised to perform all statistical analyses (Virtanen et al., 2020).

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Baseline survey

4.1.1 Characteristics of the sampled respondents

In this section, the results from the baseline survey are synthesized. Table 4.1 provides the demographic profile of the sampled respondents in the representative rural and urban areas respectively.

Table 4.1: Demographic profile of sampled respondents

Demographic characteristic	Survey respondents (per cent)	
	Farmers (%), n = 120	**Consumers (%), n = 112**
Gender		
• Male	50.8	58.0
• Female	49.2	42.0
Age (years)		
• 18 – 25	5.0	32.7
• 26 – 35	17.5	35.5
• 36 – 45	21.7	17.3
• Over 45	55.8	14.5
Highest education level		
• Prefer not to say	2.5	2.7
• Primary	2.5	8.0
• Secondary	54.2	29.5
• Post-secondary	40.8	59.9
Income level (per month)*		
• Below KSh.6,179.00[a]	40.8	20.5
• KSh. 6,180 – 12,215.00[b]	28.3	30.4
• KSh. 12,216.00 – 61,079.00[c]	27.5	42.9
• Above Ksh. 61,080.00[d]	0	6.3

**Class definitions (AfDB, 2011): [a] below poverty line, [b] floating class, [c] middle class, [d] upper class*

In this study, 120 farmers and 112 consumers in the representative urban area were selected. The sampled respondents were fairly balanced in regards to gender with 50.8% and 49.2% male and female respondents as farmers and 58.0% and 42.0% male and female as urban consumers. A large percentage of the farmer respondents (55.8%) were above the age of 45 years in comparison with the highest percentage of the consumers (35.5%) being 26 – 35 years of age. This finding confirms recent scientific and media reports that the rural farming workforce is ageing while the young people are neglecting agriculture due to low productivity and low profitability and instead preferring to migrate to urban areas for work (Mis & Esipisu, 2016; Njeru, 2017; Thurlow et al., 2019; White, 2015; Yeboah & Jayne, 2018). Rural-urban migration decreases the ratio of food producers to food consumers and may increase the incidence of urban poverty and undernutrition (Ruel et al., 2017; Satterthwaite et al., 2010). However, urbanisation opens up job opportunities in fresh food trade, food processing, packaging and transportation (Seto & Ramankutty, 2016).

The information in Table 4.1 reveals that a majority of the sampled urban dwellers (59.9%) were highly educated people making decent earnings to place them in the middle social class (42.9%) as compared to the rural area respondents where the majority (54.2%) were educated up to the secondary level but with comparatively smaller percentage (27.5%) in the middle social class. Previous studies have shown that urban consumers with disposable incomes can prioritize freshness, quality, and convenience over price when making decisions to purchase food (Ali et al., 2010; Bell et al., 2021). This presents an opportunity for food producers to utilise innovative food preservation and value addition methods to satisfy the needs of the modern urban consumer.

4.1.2 Description of the cocoyam value chain

A value chain is defined as an ordered sequence of value-creation and addition activities aimed at converting raw materials to finished products (Vroegindewey & Hodbod, 2018). As the product moves through different phases of production and handling, various actors including suppliers of agricultural inputs, farmers, traders, processors, transporters, wholesalers and retailers add some value before it reaches the final consumer (Hellin & Meijer, 2006). Resilient agricultural value chains are important employment and income growth and are critical in availing a variety of nutritious foods to consumers even in the face of shocks (Tendall et al., 2015; Vroegindewey & Hodbod, 2018). General information on agronomy, production and post-harvest handling of cocoyam are available in the literature (Agbor-Egbe & Rickard, 1991; Bamidele et al., 2015; Deo et al., 2009; Kaushal et al., 2015; Ndisya, Gitau, Roman, et al., 2021a; Pérez et al., 2007). However, information on the current structure and functioning of the Kenyan cocoyam value chain is unavailable.

4.1.2.1 Value chain map

Value chain mapping is an exercise that involves creating a visual representation of actors along a value chain and their relationships thereby exemplifying the entire value creation and addition process from raw materials to the final consumer (Herr, 2007). Figure 4.1 provides a map of the cocoyam value chain as derived from the information obtained through the baseline survey.

The map provides a structure in the forms of production, harvesting and yields, and post-harvest handling operations (transportation, marketing, processing/ value addition and consumption).

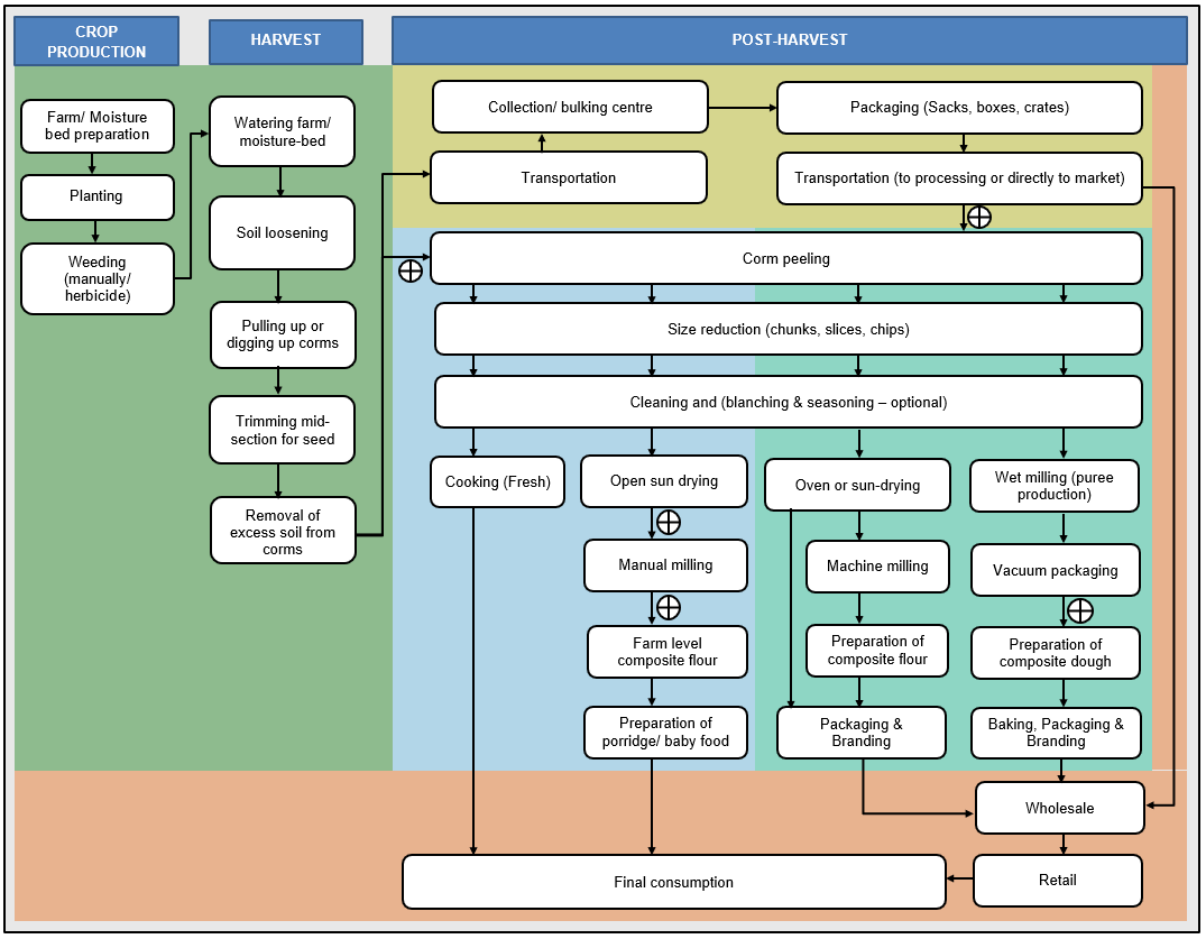


Figure 4.1: Map of the Kenyan cocoyam value chain

The most important activities observed within the cocoyam value chain in Kenya included crop production using the traditional methods or moisture beds, harvesting, storage, transportation, value addition, marketing and consumption. These activities are executed by a myriad of players in the value chain that include individual farmers, farmer groups, community-based organisations, transporters, agro-processors, retailers or supermarket outlets and the final consumers. Table 4.2 provides details on raw materials, products, actors, enablers tools, equipment and facilities observed within the value chain.

Table 4.2: Details on the cocoyam value chain in Kenya

Processes	Crop production	Harvest	Post-harvest
Products	• Mature cocoyam crops	• Tubers, leaves • New seed • Organic waste • Waste water	• Fresh tubers • Porridge flour, composite baking flour • Cocoyam puree

Processes	Crop production	Harvest	Post-harvest
			• Baked goods: bread, buns, muffins, cakes, cookies
Actors	• Farmers • Farmer groups • Community-based organisations	• Farmers, • Farmer groups	• Farmers, Farmer groups • Community-based organisations • Aggregators, Middlemen, Transporters • Agroprocessors • Wholesalers, Retailers, Hoteliers • Consumers
Enablers	• Family labour • Seasonal labour	• Family labour • Casual labour	• Family labour • Permanent and casual labour
Tools, equipment and facilities	• Picks • Spades • Hand hoes • Machetes • Knapsack sprayers • Irrigation equipment • Water	• Water • Picks • Hand hoes • Machetes • Knives	• Kitchen knives • Vehicles and ox-carts • Cold rooms and refrigerators • Slicing machines, graters, chopping boards, cooking pots, ovens, sun dryers, wet milling machines, hammer mills, mixers, blenders, sieves and screens. • Packaging materials and equipment • Warehouses

4.1.2.2 Production, harvesting and yields

Cocoyam thrives in wet tropical lowlands with temperatures of 20 – 30 °C, rainfall of up to 2500 mm p.a and soil pH of 5.5 – 6.5. (Anikwe et al., 2007; Onyeka, 2014). There are two cocoyam production methods utilised in Kenya, the traditional method and the upland method. The traditional method involves making farm plots near streams, riverbeds or any other wet area with soil in a state of near saturation. Land is prepared by clearing vegetation with hoes and machetes and the soil is loosened with draft animal implements, hand hoes, picks or mattocks. The soil is then enriched with farmyard manure or fertiliser rich in Nitrogen, Phosphorous and Potassium. Holes 30cm deep and spaced by 30cm are made and the prepared seed is placed and covered with the layer of soil. The crops are then sustained by the natural moisture of the wetland until maturity. Weed removal is conducted on a needs-basis using hand hoes. The farmers interviewed grew cocoyam in privately owned farmers of acreages ≤ 0.125 acres (23.7%), 0.125 – 0.25 acres (39.0%), 0.25 – 0.50 acres (25.4%), 0.50 – 0.75 acres (5.9%), 0.75 – 1.0 acres (5.1%) and > 1.0 acres (0.8%). Figure 4.2 shows cocoyam crops grown in a wetland farm.

Figure 4.2: Cocoyam production in a wetland

Cocoyam also grows in artificial unflooded upland conditions away from the traditional wetlands (Adekiya et al., 2016; Anikwe et al., 2007; Tumuhimbise et al., 2020). This method enables farmers to grow cocoyam in moisture beds far away from wetlands with fewer water requirements thereby enabling them to expand their production boundaries (Otieno, 2017; Tumuhimbise et al., 2020). The moisture beds are watered using harvested rainwater, surface runoff, grey water from kitchens and water from piped water mains. This enables the farmers to have greater control over their production. The method also contributes to the protection of wetlands from the destruction associated with agricultural activities such as soil erosion, siltation and chemical pollution. A moisture bed is made by marking out a convenient area with dimensions 10 metres length by 2 metres wide. Such an area can accommodate a total of 200 plants. A hole of 35cm depth is dug out using picks and shovels and the excavated soil is kept aside for later treatment. A dam lining plastic material Gage 1000 (i.e., 200 microns thickness) is placed to cover the bottom and the sides of the hole. The plastic liner assists in holding moisture and nutrients above it by preventing seepage of irrigation water and leaching of soil nutrients. The plastic liner has an estimated service life of five years. The excavated soil is mixed with five 90kg bags of organic manure and then returned to cover the plastic liner. The moisture bed is then watered to wet consistency and the planting materials is placed in holes of 30 cm depth and spaced at 30 cm between each plant. Subsequent watering is done after every one week. A top soil cover of plastic mulch of biomass is placed to prevent loss of water by evaporation and the growth of weeds. Three months after planting, the mulch is removed and an additional 4 in layer of soil is placed on the moisture bed to cover the now visible root since the plant grows upwards and not downwards like other plants. The mulch is then returned to cover the soil. Figure 4.3 shows cocoyam production in a moisture bed.

Figure 4.3: Cocoyam production in a moisture bed (upland methodology)

Figure 4.4: Manual cocoyam harvesting

Cocoyam tubers are mature for harvesting when the leaves wither and turn yellow which is 4 – 6 months after planting (Opara, 1999). The timing of harvesting operations is of paramount importance in avoiding pre-harvest losses. Traditional and small-scale harvesting of cocoyam tubers in Kenya involves uprooting by hand (Naika, 2017), digging up with a hoe or machete (Oshunsanya, 2016; Wamucii, 2017) or by passing a plough close to the furrows and exposing the tubers. Mechanized harvesting methods have also been reported (Oshunsanya et al., 2018). During harvesting activities, there is a need for farmers to adopt the correct techniques and a heightened degree of caution to avoid injuring the tubers thereby increasing the likelihood of rotting (Wamucii, 2017). During the harvesting of cocoyam tubers, two wounds are inflicted on the tuber, one to trim the dry bottommost end and one at the petiole base to remove the foliage. Figure 4.4 shows cocoyam harvesting operations with machetes.

Like other crops, the yield of cocoyam varies with variety, location, soil type, and agronomic practices. Crop production statistics for the duration 2015 – 2018 from the Ministry of Agriculture, Livestock, Fisheries and Cooperatives (MoALFC) show an average yield of 7.5 ton/ha from 705.6 ha of farm area in Meru county. As shown in Figure 4.5, in this study, a majority of the farmers (38.5%) reported yields of 1.0 – 2.5 tonnes per harvest, with 11% reporting yields greater than 2.5 tonnes per harvest and 8.8% reporting yields less than 0.1 tonnes per harvest.

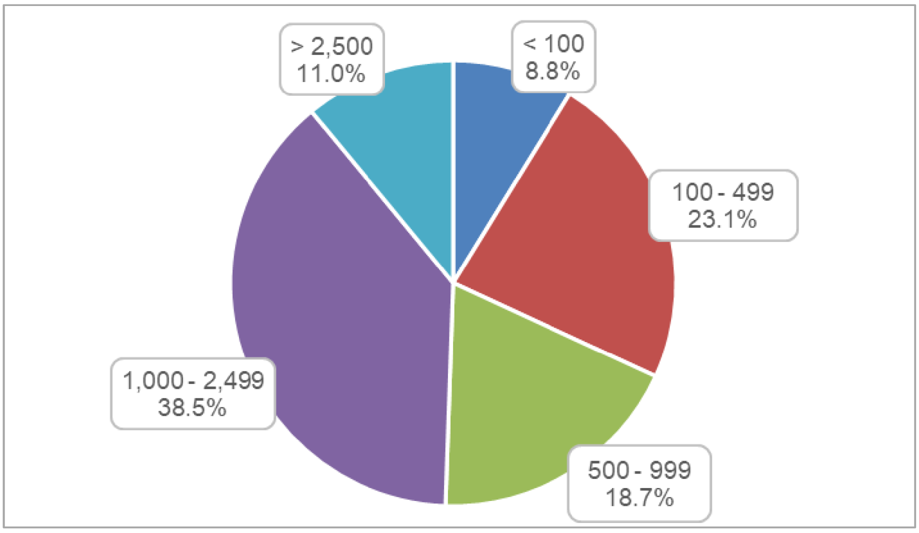


Figure 4.5: Reported yields, tonnes per harvest (percentage of respondents, n = 92)

4.1.2.3 Post-harvest operations

i). Transportation and marketing

Immediately after harvesting, cocoyam tubers destined for storage or local market are cleaned with a soft brush to remove soil and dry matter from the surfaces and cured in open sunlight to heal harvesting wounds before storage. The tubers destined for supermarket chains, restaurants and processing plants are washed with water and transported to the collection centre where they are packed in sacks, boxes and crates. Means of transportation include mostly by motorcycle, but also by vehicles (Toyota Probox, pickups), by ox and donkey carts and on human backs. After the collection centre, bulked tubers are then transported by vehicles (Toyota Probox, pickups and lorries) to processing centres or wholesale markets, restaurants, supermarket outlets and open-air markets. Sometimes, traders visit the farms to purchase the tubers directly from the farmers.

Figure 4.6 shows the market outlets utilised by farmers while Figure 4.7 shows cocoyam tubers displayed on a supermarket shelf and in an open-air market. As shown in Figure 4.6, it is apparent that none of the farmers interviewed grows cocoyam solely for subsistence. The findings revealed that a majority of the farmers (58.3%) sold their produce in markets and local shops. However, 40% of them sold to intermediaries who then further resold the tubers to open-air market traders, hotels and restaurants and supermarket chains. Figure 4.7 shows cocoyam tubers displayed and sold alongside other fresh produce in open-air markets and supermarket outlets. Notably, 26.7% of the farmers sold their tubers to a local agro-processing plant under contract farming.

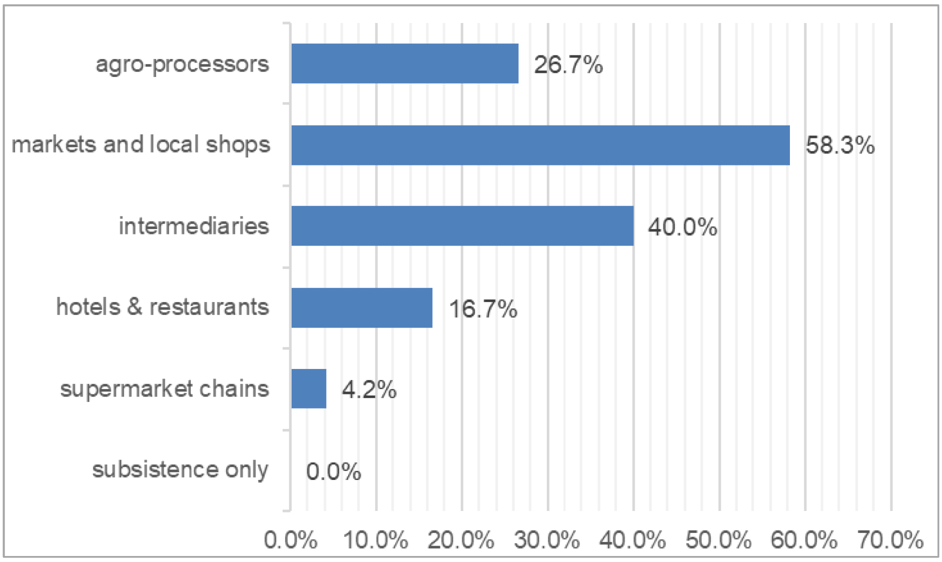


Figure 4.6: Market outlets utilised by farmers (percentage of respondents, n = 120)

Figure 4.7: Tubers displayed to customers. a). Supermarket shelf, b). Open-air market

ii). On-farm preservation and storage

Despite the county being a leading producer of a variety of food products in the country, Meru county experiences high post-harvest losses due to inadequate and inefficient storage facilities (CoGM, 2018). This forces farmers to either keep the tubers unharvested in the farm or immediately sell harvested tubers often at sub-optimal prices during seasons of over-supply (CoGM, 2018). This study observed that a few of the farmers interviewed (34%) engaged in tuber preservation by drying in open sunlight on tarpaulins for later household consumption. However, drying in open sunlight is a weather-depended process and exposes tubers to contamination with microbial elements and other foreign materials thereby causing loss of product quality (El Hage et al., 2018; P. Singh et al., 2018; Udomkun et al., 2020).

Figure 4.8: Cocoyam tubers: a). Stored on a tarpaulin inhouse, b). Sample from storage

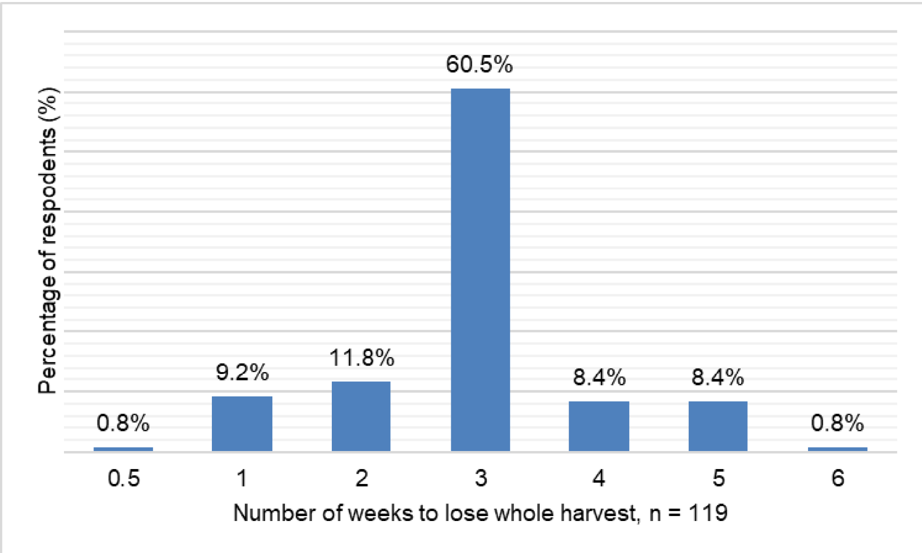


Figure 4.9: Number of weeks to lose the whole tuber harvest (percentage of respondents, n = 119)

When the tubers were not required for immediate consumption or marketing, the farmers stored them on-farm using various methods including in farm/unharvested (61.7%), in ventilated stores (34.2%), in gunny bags inside residential houses (3.3%) or crates and boxes inside residential houses (0.8%). Figure 4.8 shows the state of tubers sampled from a farmer's store. The storage methods were observed to cause a high incidence of tuber rot as a result of poorly designed stores without proper consideration of environmental factors including temperature, relative humidity and air circulation. As a consequence, Figure 4.9 shows that a majority of the farmers (82.3%) lost the whole harvest within the first three weeks of storage. Considering the case of the 38.5% of the farmers who reported yields of 1.0 – 2.5 tonnes per harvest and the agriculture and trade statistics from MoALFC for 2018 (KSh. 2,512.00 per 50 kg bag), the equivalent financial loss per farmer would be KSh. 50,240.00 – KSh. 125,600.00 (USD 454.66 – 1136.65[2]) per harvest. This translates to KSh. 8,373.33 – KSh. 20,933.33 (USD 75.78 – 189.44[2]) per month which is quite significant considering that 69.1% of the farmers interviewed earned less than KSh. 12,215.00 per month. The financial loss resulting from the loss of tubers due to poor storage could be prevented by utilisation of proper preservation, value addition and storage methods.

iii). Processing

The tubers bought by the local agro-processing plant are subjected to various processing operations to convert them into end products which included flour for baking, making porridge and baby food. The processing operations include peeling, size reduction, cleaning and optional blanching/seasoning, drying in an oven or solar greenhouse dryers, machine milling, blending with other flours (dried cocoyam leaves, banana, sweet potato, pumpkin, cassava and wheat flour) in various proportions, branding and packaging. The packaged products were then sold to wholesalers or other plants for further processing. Figure 4.10 shows the tubers in various stages of processing.

[2] Official Central Bank of Kenya exchange rate on 01.10.2021: $1 = KSh. 110.50

Figure 4.10: Cocoyam tubers and admixtures and different stages of processing

A second processing route involves wet milling to produce puree, packing the puree in airtight drums or vacuum packaging and transportation to a baking plant belong to a leading supermarket chain in Nairobi. At the baking plant, the puree was kept in a cold room and later utilised to prepare composite dough with wheat and production of bread, branding, packaging and retailing at the supermarket chain outlets. Figure 4.11 shows pictures taken from inside the baking plant showing various doughs in storage and the final baked products before packaging.

Figure 4.11: Baking raw materials and finished products. a). Dough in cold storage, b). Baked products before packaging

iv). Consumption

In many parts of the world where it is grown, cocoyam tubers are consumed boiled, fried, baked, roasted or mashed with stew (Adekiya et al., 2016; Lewu et al., 2010). The tubers can also be deep-fried or dried and milled into flour which is then blended with flour from other crops for baking or to make porridge (Falade & Okafor, 2014; Macmanus C. Ndukwu et al., 2017). The situation is similar in Kenya. In this study, all respondents both farmers and urban consumers interviewed reported that cocoyam is an integral part of their diet with every one of them consuming it at least once per week as breakfast or a main meal. Both the tubers and the leaves are consumed with higher preference being placed on the tuber (i.e., 100% of respondents) but with the leaves also consumed (57.1% of respondents) as a vegetable or dried leaves being blended with other flours such as maize, millet and sorghum to make porridge. Figure 4.12 shows the reported methods of cooking the tubers for consumption. Boiling is by far is the most popular method of tuber preparation with 99.2% and 72.7% of rural and urban consumers respectively reporting to utilise the method. Methods such as boiling, mashing, frying and stewing could utilise tubers preserved by drying and the rehydrated to reintegrate moisture before cooking. On the other hand, all the methods of preparation could be utilised to cook freshly harvested or fresh tubers preserved in a suitable cold storage. Figure 4.13 shows chunks of cocoyam tubers ready for preparation by boiling and the boiled tubers served and ready for consumption.

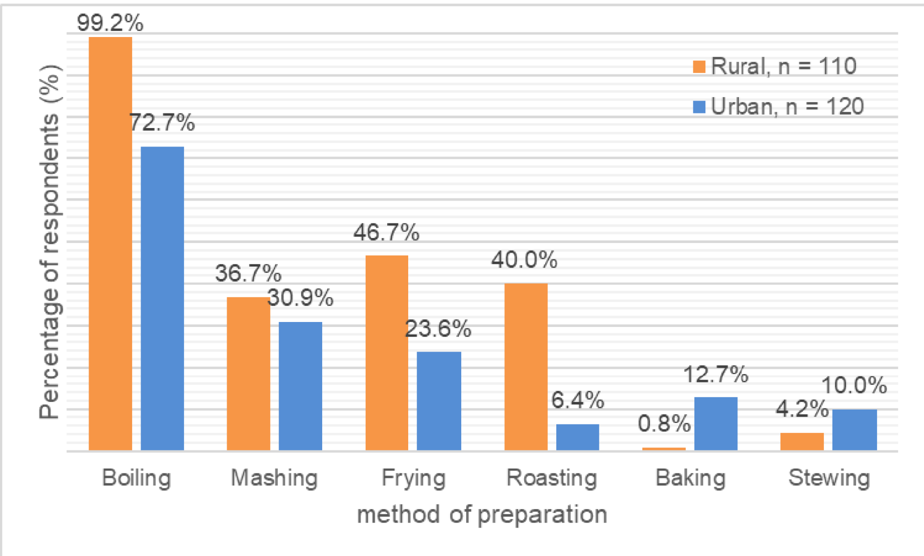


Figure 4.12: Preparation methods for cocoyam tubers

Figure 4.13: Cocoyam preparation by boiling. a). Peeled tubers before boiling, b). Boiled tubers ready for consumption

4.2 Forced convection cooling of cocoyam

4.2.1 Method comparison

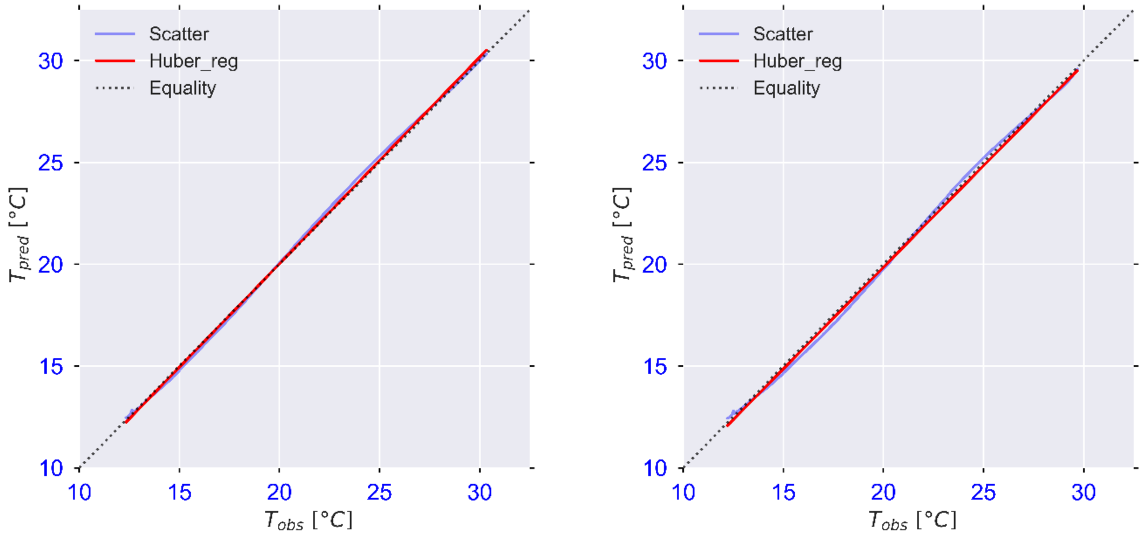


Figure 4.14: Temperature predictions against observations (small size, across orientation, ϑ = 0.9 m.s^{-1}) a). at core b). under the skin

Figure 4.14 presents a plot of the temperature predictions against observations at the core and under the core of the tubers. The plots depict a near perfect linear orientation to the line of equality. The red plot represents the Huber regression fit to the predictions and observations. Table 4.3 provides robust estimates of the regression coefficients at the core of the tubers. While the regression coefficients have individual variations from the expected ideal values, an examination of the mean values using the Student's t-test reveals that the overall slope and intercept are not significantly different from 1 and 0 respectively at the 0.05 level of significance. The *t*-test results are provided in Table 4.4.

Table 4.3: Model performance metrics at the core – across orientation (Mean ± SD)

ϑ_a ($m \cdot s^{-1}$)	Tuber size	Huber regression $\hat{y}_{pred} = \beta_0 + \beta_1 \cdot \hat{y}_{obs}$		MAPE (%)	SMDAPE (%)	CCC
		β_0	β_1			
0.5	small	0.62 ± 0.58	1.69 ± 0.05	0.97 ± 0.04	1.60 ± 0.33	0.999 ± 0.001
	large	-0.50 ±1.52	1.99 ± 0.55	0.95 ± 0.00	1.96 ± 0.69	0.999 ± 0.000
0.7	small	-0.63 ± 1.50	2.29 ± 0.87	1.03 ± 0.09	2.45 ± 1.01	0.999 ± 0.000
	large	0.37 ± 0.05	1.50 ± 0.13	0.96 ± 0.01	1.64 ± 0.23	0.999 ± 0.000
0.9	small	-0.31 ± 0.00	0.82 ± 0.00	1.02 ± 0.00	0.85 ± 0.00	0.999 ± 0.000
	large	0.16 ± 0.34	3.49 ± 0.25	0.96 ± 0.02	3.74 ± 0.21	0.996 ±0.002

Table 4.4: Student's t-test results – across orientation

Sensor location	Huber Regression				Bland-Altman	
	$\bar{\beta}_0$	$\bar{\beta}_0$- 95% C.I [LCL, UCL]	$\bar{\beta}_1$	$\bar{\beta}_1$ - 95% C.I [LCL, UCL]	Mean diff.	95% C.I [LCL, UCL]
At the core	-0.06	[-2.31, 2.19][b]	0.99	[0.82, 1.15][b]	0.09	[-0.46, 0.63][b]
Under the skin	-0.78	[-2.10, 0.55][b]	1.05	[0.96, 1.14][b]	0.15	[-0.42, 0.72][b]

Significance: H_0: $\beta_0.LCL < 0 < \beta_0.UCL$ and $\beta_1.LCL < 1 < \beta_1.UCL$, [a]$p < 0.05$ = significant, [b]p = non-significant

The values of MAPE, SMDAPE and CCC realised at the core of the tubers are provided in Table 4.3. The values of MAPE and SMDAPE are in the range 0.92 – 1.08 per cent and 0.85 – 3.73 per cent respectively at the core of the tubers and 0.87 – 2.75 per cent and 0.94 – 2.91 per cent respectively under the skin of the tubers. Taking into consideration the SMDAPE, the difference between model predictions and observations are in the range 0.26 – 1.12 °C at the start of cooling (i.e., 30 °C) and 0.10 – 0.45 °C at the end of cooling (i.e., 12 °C) at the core of the tubers. Additionally, the differences between model predictions and observations are in the range 0.28 – 0.87 °C at the start of cooling (i.e., 30 °C) and 0.11 – 0.35 °C at the end of cooling (i.e., 12 °C) under the skin of the tubers. If a maximum temperature deviation of 2 °C is acceptable, the model can be used interchangeably or in the place of direct experimental measurements. The values of CCC obtained were notably all greater than 0.99, some are equal to 1.0. This indicates an almost perfect or perfect strength of agreement between the model predictions and the experimental observations.

Figure 4.15 presents an exemplary Bland-Altman plot at the core of the tubers. For this study, the theoretical limits of agreement are set to be equal to ±2 °C, which is a variation that can be reasonably tolerated in a bulk storage of well-cured cocoyam tubers (Opara, 1999). It can be observed that the limits of agreement for each case are narrower than the proposed theoretical limits of agreement. Further, the scattered differences lie inside the limits of agreement and their distribution on both sides of the mean difference line is approximately proportionate. However, Figure 4.15 as read together with Table 4.5 reveals the existence of minor systematic and proportional biases. In the Bland-Altman plots, the systematic bias is quantitatively equal to the mean difference while the proportional bias is depicted by the notably curvy scatter lines of differences. This is probably due to the imprecise placement of the temperature sensors inside the tubers and spatial variation in the thermo-physical properties of the cocoyam material. Differences in tolerances and errors in the instruments utilised to take measurements could also have contributed to biases. Nonetheless, this is a common challenge that has been acknowledged and discussed in other studies (da Silva et al., 2010; Korese et al., 2017). However, Table 4.4 and Table 4.5 show that the biases observed in this study are less than the tolerable maximum variation of ±2 °C and that the overall mean bias is statistically not different from zero within the 0.05 level of significance. This variation could therefore be disregarded in practice.

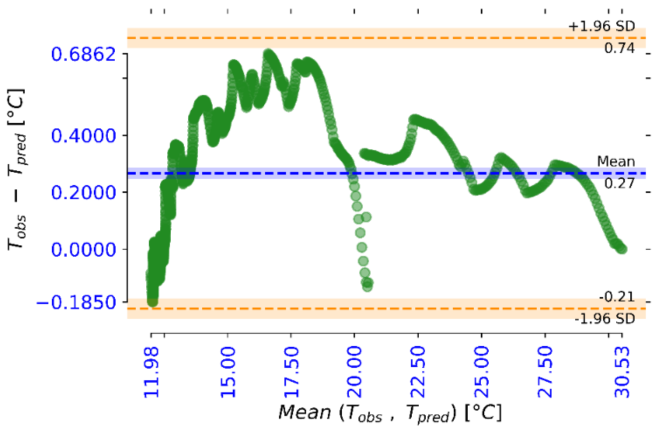


Figure 4.15: Bland-Altman plots (small size, across orientation, ϑ = 0.9 m.s^{-1}) at the core of tubers

Table 4.5: Bland-Altman mean differences and limits of agreement - across orientation (Mean ± SD)

ϑ_a (m·s^{-1})	**Tuber size**	**At the core**			**Under the skin**		
		Mean diff. (°C)	**U.LOA (°C)**	**L.LOA (°C)**	**Mean diff. (°C)**	**U.LOA (°C)**	**L.LOA (°C)**
0.5	small	-0.07 ± 0.01	0.51 ± 0.17	-0.65 ± 0.15	-0.31 ± 0.04	0.07 ± 0.05	-0.69 ± 0.14
	large	-0.01 ± 0.07	0.54 ± 0.15	-0.54 ± 0.02	0.12 ± 0.04	0.68 ± 0.26	-0.46 ± 0.33
0.7	small	0.58 ± 0.46	1.29 ± 0.53	-0.53 ± 0.39	0.12 ± 0.02	1.07 ± 0.41	-0.83 ± 0.38
	large	0.03 ± 0.06	0.44 ± 0.09	-0.39 ± 0.02	0.13 ± 0.09	0.81 ± 0.10	-0.56 ± 0.07
0.9	small	0.14 ± 0.00	0.57 ± 0.00	-0.29 ± 0.00	0.22 ± 0.00	0.34 ± 0.00	-0.29 ± 0.00
	large	0.10 ± 0.03	0.62 ± 0.25	-0.43 ± 0.31	0.45 ± 0.01	1.71 ± 0.12	-0.82 ± 0.11

4.2.2 Cooling kinetics

The efficiency of cooling operations for food products is dependent on the proper design of cooling equipment to suit the particular requirements of the cooling application (Becker & Fricke, 2004). Cooling kinetics provide important design information for the prediction of the amount of time required to cool a product to its target temperature (Carroll et al., 1996). In turn, the cooling time helps in the estimation of the corresponding cooling loads (Becker & Fricke, 2004). Cooling kinetics are therefore an important design and management tool for cooling applications.

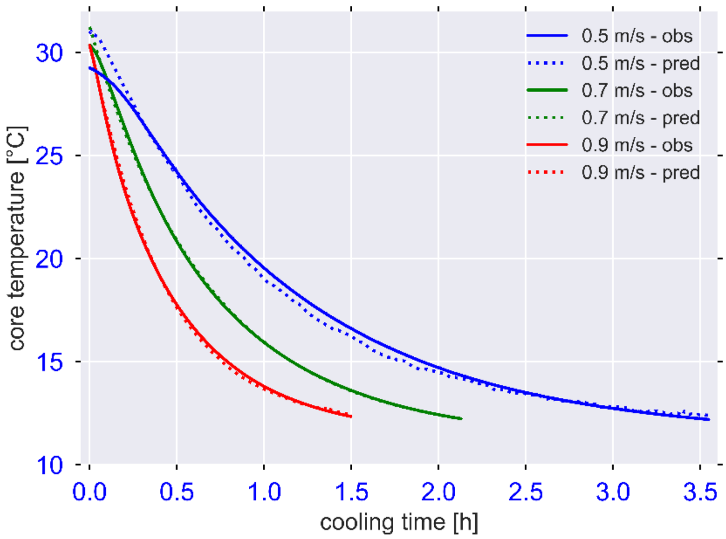


Figure 4.16: Cooling kinetics at the core (small size, across orientation)

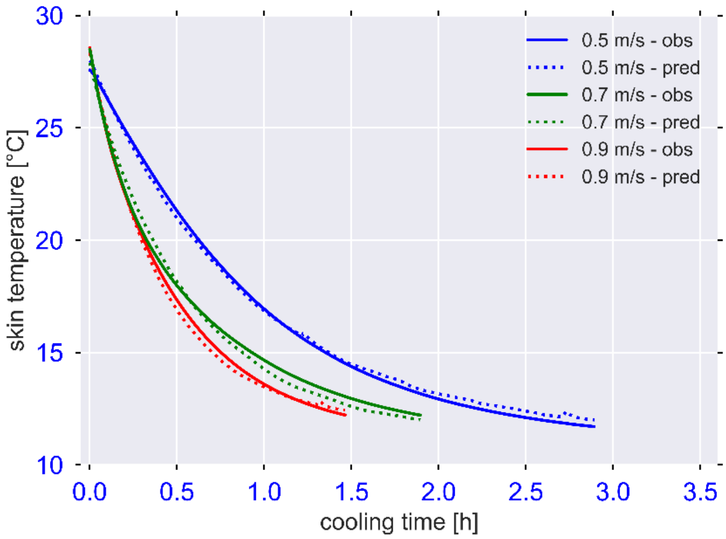


Figure 4.17: Cooling kinetics under the skin (small size, across orientation)

Figure 4.16 and Figure 4.17 illustrate the change in temperature with time at the core and under the skin of tubers respectively. The curves portray an exponential decay behaviour with a rapid cooling rate at the start of the cooling process which levels off towards the end of cooling. Similar behaviour has been observed during the cooling of sweet potatoes (Korese et al., 2017), grapes (Dincer, 1995a), southern bluefin tuna (Davey, 2015), oranges and tomatoes (Kumar et al., 2008). Notably, the curves for predictions closely mimic the observations further confirming the comparability of the datasets.

4.2.3 Biot number

The Biot number is a dimensionless quantity that provides information on the controlling mechanism of heat transfer (Becker & Fricke, 2004; Giner et al., 2010; van der Sman, 2003). When the internal resistance is less than 10 per cent of the external resistance to heat transfer (i.e. $Bi < 0.1$), lumped system analysis could be applied for transient heat transfer analysis (Çengel & Ghajar, 2015; X. D. Chen, 2005). Table 4.6 provides the calculated values of Bi with the tubers idealised as infinite cylinders and infinite slabs. In this study, the values of Bi range from 0.26 – 0.43 for cylindrical geometries and 0.83 – 1.69 for slab geometries respectively. These values are on average 3 – 13 times greater than 0.1. This signifies that temperature distribution in the tubers is non-uniform and therefore the internal resistance to heat conduction is substantial. Therefore, classical lumped system analysis of transient heat transfer is invalid. However, when the effective convective heat transfer coefficients are introduced in the Biot number formulae, an effective Biot number is calculated and the heat transfer problem can be solved using a modified lumped system approach (Xu et al., 2012).

Table 4.6: Biot numbers – across orientation (Mean ± SD)

ϑ_a ($m \cdot s^{-1}$)	Tuber size	infinite cylinder		infinite slab	
		D (mm)	$Bi_{eff,c}$	L (mm)	$Bi_{eff,s}$
0.5	small	49.25 ± 1.00	0.26 ± 0.04	79.75 ± 2.75	0.83 ± 0.13
	large	79.63 ± 3.38	0.38 ± 0.01	116.25 ± 13.75	1.10 ± 0.25
0.7	small	52.75 ± 0.25	0.34 ± 0.02	90.50 ± 0.50	1.32 ± 0.13
	large	72.00 ± 0.50	0.40 ± 0.02	101.00 ± 6.00	1.00 ± 0.04
0.9	small	52.13 ± 5.38	0.37 ± 0.00	72.50 ± 12.50	1.05 ± 0.28
	large	66.88 ± 3.38	0.41 ± 0.01	137.25 ± 15.25	1.69 ± 0.07

In this study, the Biot number was significantly influenced by the air velocity ($p < 0.0001$) and the tuber size ($p < 0.0001$) but not the orientation to airflow ($p > 0.05$). As shown in Figure 4.18, the Biot number was observed to increase with an increase in air velocity from 0.5 to 0.9 $m \cdot s^{-1}$. Moreover, Çengel & Ghajar (2015) report that small-sized bodies in a medium such as air which is a poor conductor of heat exhibit relatively lower values of the Biot number. A similar finding was obtained for sweet potatoes where lower values of the Biot number corresponded with medium-sized sweet potato roots and slower air velocities (Korese et al., 2017).

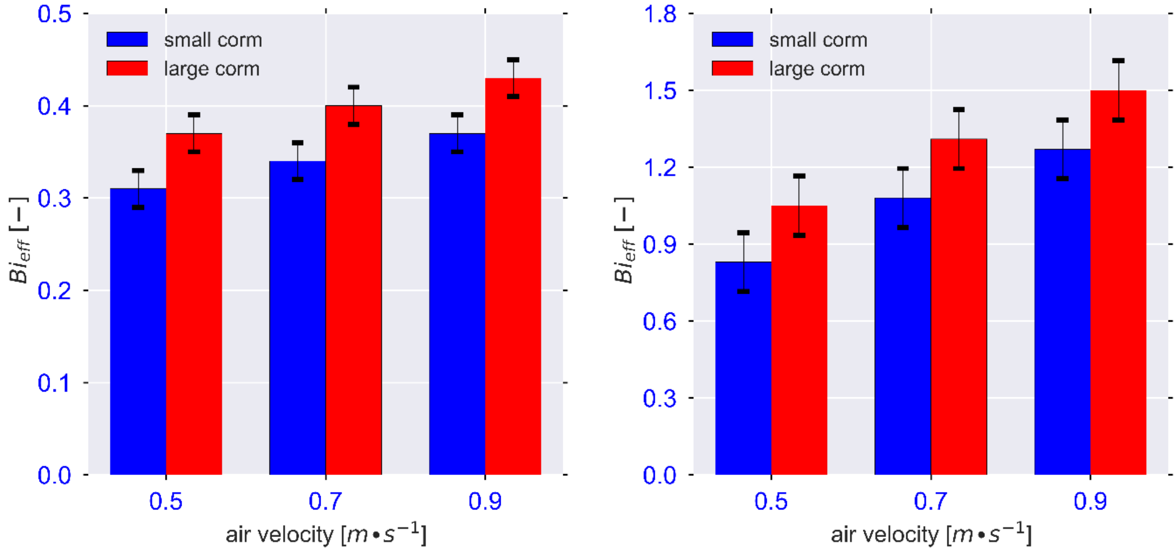


Figure 4.18: Biot number against air velocity a). Cylinder geometry, b). Slab geometry

4.2.4 Surface heat transfer coefficient

Information on product surface heat transfer coefficients is critical in the design of food refrigeration systems (Kumar et al., 2008). Accurate prediction of the total cooling time and the corresponding cooling loads is contingent on the accurate estimation of the surface heat transfer coefficient (Becker & Fricke, 2004). Table 4.7 provides the convective heat transfer coefficients as calculated using Equation (4), (7) and (8).

Table 4.7: Surface heat transfer coefficients – across orientation (Mean ± SD)

ϑ_a ($m \cdot s^{-1}$)	Tuber size	h ($W \cdot m^{-2} \cdot K^{-1}$)		
		$h_{overall}$	$h_{eff,c}$	$h_{eff,s}$
0.5	small	8.63 ± 1.10	7.63 ± 0.85	6.73 ± 0.63
	large	7.96 ± 0.52	6.68 ± 0.41	5.87 ± 0.74
0.7	small	10.78 ± 0.43	9.20 ± 0.31	7.49 ± 0.07
	large	9.13 ± 0.42	7.62 ± 0.30	6.85 ± 0.25
0.9	small	11.84 ± 1.11	10.00 ± 0.95	8.75 ± 0.23
	large	10.26 ± 0.74	8.50 ± 0.58	6.57 ± 0.57

In this study, the surface heat transfer coefficients are calculated from Reynolds number and Prandtl number correlations. These correlations utilise the thermophysical properties of the cooling air and the dimensions of the tubers as inputs. With the density, viscosity, specific heat capacity and thermal conductivity as constant inputs, the surface heat transfer coefficient is therefore influenced by the air velocity, the radius and the length of the tubers. This was confirmed by statistical analysis which found only the air velocity ($p < 0.0001$) and tuber size ($p < 0.0001$) to be influential at the 0.05 level of significance as opposed to the tuber orientation ($p > 0.05$).

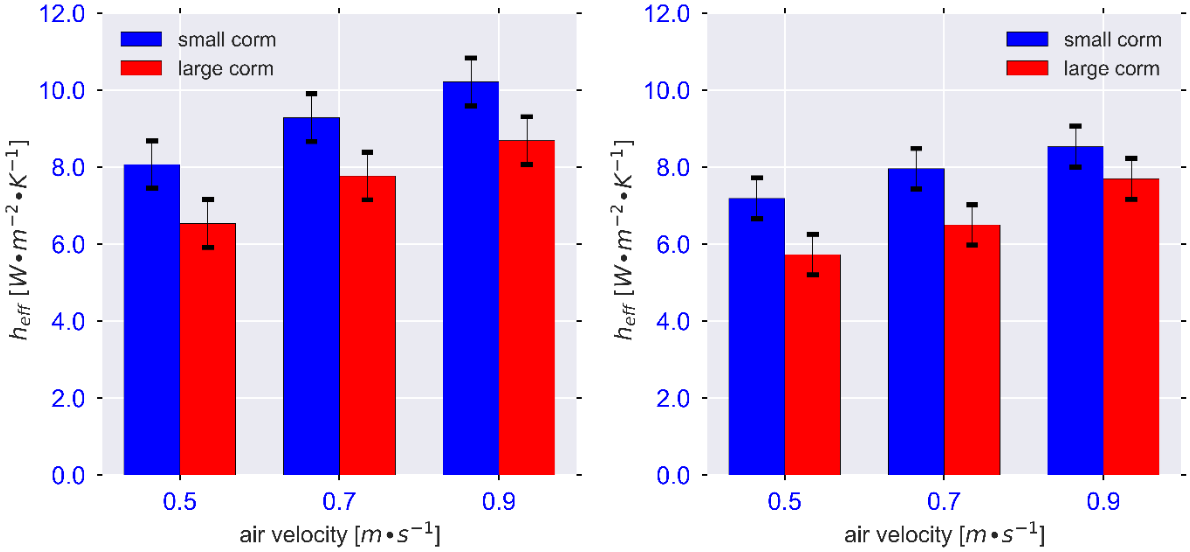


Figure 4.19: Heat transfer coefficients against air velocity (across orientation) a). Cylinder geometry, b). Slab geometry

Figure 4.19 presents the plot of the surface heat transfer coefficients against air velocity segmented by tuber size for cylinder and slab geometries respectively. Small tubers exhibited higher values of the surface heat transfer coefficients than larger tubers. The surface heat transfer coefficient is also found to increase with an increase in air velocity from 0.5 to 0.9 $m \cdot s^{-1}$. This finding is consistent with similar reports on forced air cooling of tomatoes and oranges (Kumar et al., 2008).

4.2.5 Cooling time

For cooling applications, the velocity of the cooling air flowing past the product is the most significant factor influencing the surface heat transfer coefficient which in turn influences the length of the cooling process (Becker & Fricke, 2004). As shown in Figure 4.20, the air velocity significantly influenced the amount of time required to attain 12 °C both at the core ($p < 0.05$) and just under the skin ($p < 0.05$) of the tubers. Increasing the air velocity significantly reduced the total amount of time required to cool the tubers to the final temperature of 12 °C. This agrees well with the findings of Dehghannya et al. (2010), Dincer (1995), Gaffney & Baird (1977) and Kumar et al. (2008).

Knowledge of the influence of product size is critical in deciding the best strategy for the reduction of cooling time. This is because product size has a significant influence on the heat transfer coefficients (Dehghannya et al., 2010; Dincer & Genceli, 1994; Wang et al., 2001). In the case where the internal resistance to heat transfer supersedes the external resistance, a better result can be achieved by reducing product dimensions as compared to reducing the size of packaging or increasing air velocity (Glavina et al., 2007; Pham, 2002). As shown in Figure 4.20, tuber size significantly influenced the amount of time required to attain 12 °C both at the core ($p < 0.0001$) and just under the skin ($p < 0.0001$) of the tubers. The influence of the tuber size on the cooling time was observed to be greater than that of the air velocity. As depicted in Figure 4.20, small-sized tubers required less time to cool to the target temperature as compared to large-sized tubers. Similar behaviour has been observed for potatoes (Glavina et al., 2007) and sweet potatoes (Korese et al., 2017). The orientation of the tubers to the airflow can be intuitively understood to change the shape of the tubers depending on the tuber face perpendicular to the airflow. During forced air cooling of agricultural products, the shape of the product is known to influence the heat transfer coefficients (Becker & Fricke, 2004). However, this study found the tuber orientation to airflow (tuber shape) to neither influence the heat transfer coefficients nor the cooling time at the core and under the skin ($p > 0.05$).

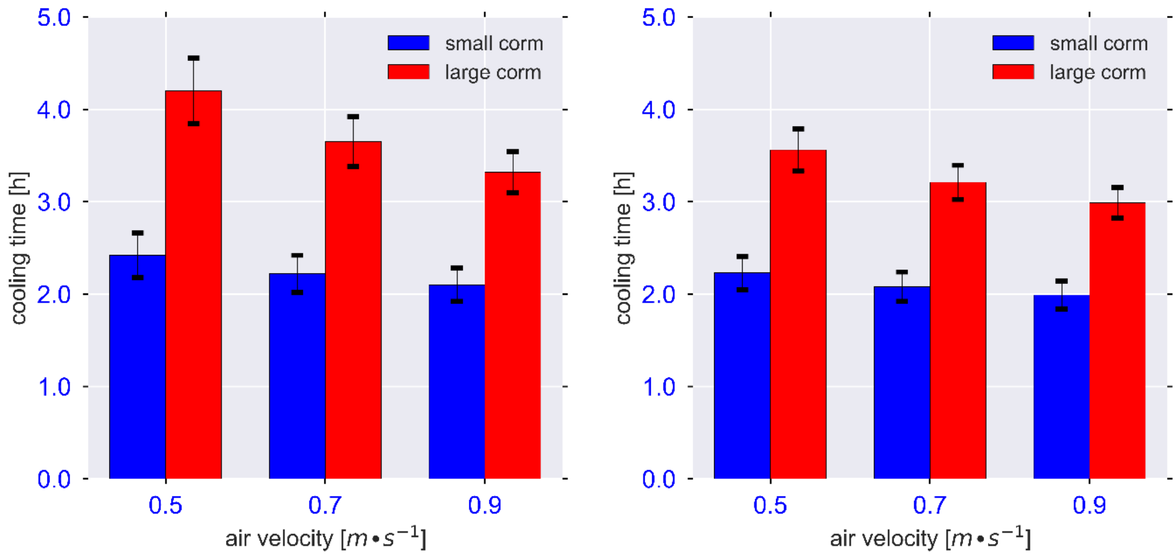


Figure 4.20: Cooling time against air velocity a). at the core, b). under the skin

4.2.6 Energy removed from tubers

Forced convection cooling is a critical undertaking commonly applied to agricultural produce after harvest to remove the field heat and to provide favourable conditions for storage (Defraeye et al., 2014). This is because the quality of the produce after harvest and the storage time is highly influenced by the product temperature and in extension the sensible heat content. The amount of heat removed from a product to its surroundings during cooling is equivalent to the change in the energy content of the product (Çengel & Ghajar, 2015). This quantity contributes to the cooling load but is different from the energy required to precool the air and to run the ventilation system (Ndisya, Gitau, Roman, et al., 2021b). Information on the cooling load is pertinent in the design, operation and control of the cooling system (Dincer, 2003).

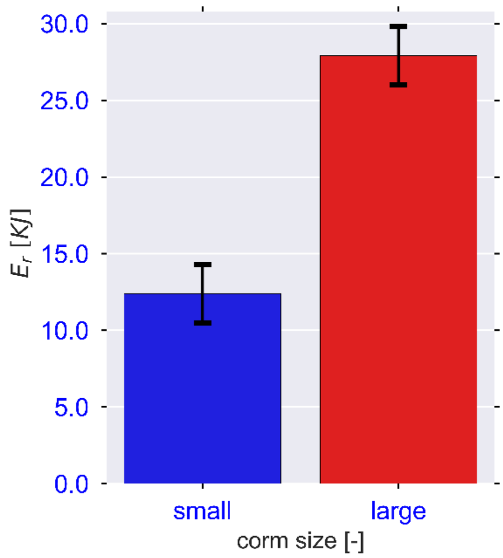


Figure 4.21: Energy removed from tubers

Table 4.8: energy removed from tubers – across orientation (Mean ± SD)

ϑ_a ($m \cdot s^{-1}$)	small tubers		large tubers	
	Weight (g)	**E_r (kJ)**	**Weight (g)**	**E_r (kJ)**
0.5	160.70 ± 5.92	10.17 ± 0.48	526.72 ± 42.05	24.78 ± 0.00
0.7	219.77 ± 24.19	14.59 ± 2.59	381.00 ± 4.02	21.88 ± 0.65
0.9	152.57 ± 7.76	9.61 ± 0.36	510.30 ± 13.17	31.90 ± 4.75

Figure 4.21 and Table 4.8 provide the amount of energy removed from the tubers by cooling as determined using the method proposed by Çengel & Ghajar (2015). The amount of the energy removed was significantly influenced by the tuber size ($p < 0.0001$) but not the air velocity and the tuber orientation to airflow ($p > 0.05$). On average, large-sized tubers contained approximately 55.6 per cent more energy than small-sized tubers. Since the temperature difference and the thermophysical properties of the cocoyam material are assumed to be constant in the modelling process, the energy content is therefore solely influenced by the weight of the tubers. As shown in Equation (23), the weight of the tubers is represented as a product of the tuber density and volume and is directly proportional to the energy content. Therefore, an increase in the tuber size from small to large corresponds to an increase in the energy content and therefore the energy removed.

4.3 Hot-air drying of cocoyam

4.3.1 Drying kinetics and model fitting

Drying kinetics provide the most important data for the design and simulation of drying systems (Ratti, 2001). Figure 4.22 shows the changes in moisture ratio as a function of time at the different settings during hot-air drying. The purple-speckled cocoyam material utilised had an average initial moisture content of 1.74 kg_W/kg_{DM} which increased to an average of 2.65 kg_W/kg_{DM} after pretreatment. The fastest drying time (i.e., 108 min) occurred at 75 °C temperature and 4 mm thickness without pretreatment while the slowest drying time (i.e., 1560 min) occurred at 40 °C temperature and 10 mm thickness with the blanching pretreatment.

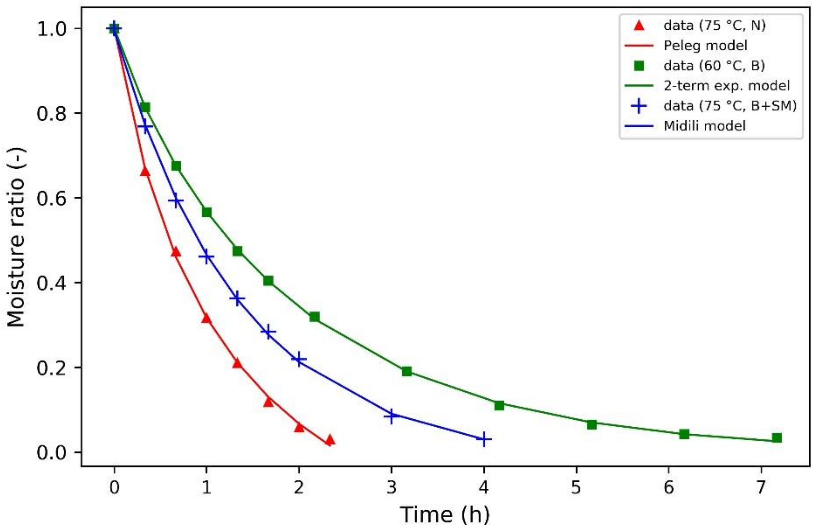


Figure 4.22: Drying kinetics at 4 mm slice thickness showing the fitted models

Model fitting revealed that the Two-term exponential model, the Peleg model and the Midili model consistently returned desirable values for the statistical measures of fit under consideration. The three models therefore adequately modelled the drying kinetics of purple-speckled cocoyam under the selected experimental conditions. The Logarithmic model was also found to slightly over-predict the drying kinetics but with less desirable statistics than the three models above. This compares well with the findings of Afolabi, Tunde-Akintunde, & Adeyanju (2015) who found the Logarithmic and Parabolic models to best describe the oven and sun-drying behaviour of cocoyam. Kumar et al. (2016) found the Page model to be adequate in describing the drying kinetics of cocoyam using the microwave drying method. Table 4.9 presents the models fitted to the data.

Table 4.9: Drying models that best fitted the drying data

Model name	Frequency (n = 25)	Form of model	Model Author
Two-Term Exponential model	14	$MR = a.\exp(-k_o.t) + (1-a).\exp(-k_1.a.t)$	(Sharaf-Eldeen et al., 1979)
Peleg model	9	$MR = 1 - \frac{t}{(a+b.t)}$	(Peleg, 1988)
Midili model	2	$MR = a.\exp(-k.t) + b.t$	(Midilli et al., 2002)

Where M.R = moisture ratio, t = drying time, a and b = model coefficients, k_0 and k_1 = drying rate constants

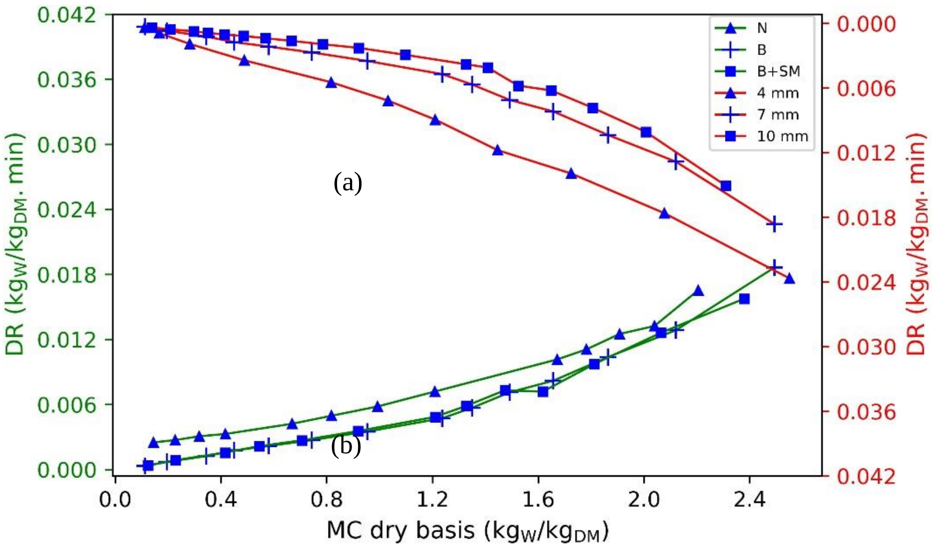


Figure 4.23: Drying rate curves of slices dried at 60 °C temperature (a). blanched slices (b). 7 mm slice thickness

Figure 4.23 shows the plots of the drying rate against the dry-basis moisture content for the drying experiments for the different pretreatments and slice thicknesses. The drying curves exhibit a 2-stage falling rate drying behaviour with a faster first stage and decelerating in the second stage. The non-pretreated slices and the 4 mm slices exhibited a higher drying rate at the same value of moisture content as compared to the other conditions. This is due to the lower value of moisture content of non-pretreated slices and the shorter distance of moisture molecules travel to the surface of the 4 mm slices. It can be observed that the non-pretreated slices retained a drying rate higher than the pretreated slices up to the end of the drying process. The B and B+SM pretreatments demonstrated a comparable drying rate behaviour. This could be due to the similar pretreatment procedure followed that subjected the slices to blanching water containing a similar amount of heat. The 4 mm slices had a higher initial moisture content than both the 7 mm and 10 mm slices. This could be due to the lower surface area to volume ratio and the longer moisture migration path that made them absorb less moisture during pretreatment. Table 4.10 presents the regression equations fitted to the studied responses alongside the adjusted r^2 coefficients and the Fishers F-values. Total drying time was fitted with a 2-factor interaction model, BI with a linear model, RR with a linear model and specific energy consumption with a second-order polynomial model. No model was fitted to ΔE as it was found to be solely significantly influenced by the pretreatment.

Table 4.10: Regression equations fitted to response variables

Response	Model (in actual units)/ parameter setting	Adj. r^2	F-value (model)	F-value (lack of fit)
Total drying time, T	$T^{1/2} = 1.912 - 0.014A + 0.398B - 0.004AB$	0.990	215.18***	0.482[a]
Total colour diff., ΔE	N	0.948	218.93***	0.456[a]
Browning Index, BI	$BI = 7.023 + 0.034A$	0.952	140.86***	0.285[a]
Rehydration ratio, RR	$RR = 0.773 - 0.022B$	0.729	20.74***	0.642[a]
Specific energy consumption, E_s	$\ln E_s = -0.628 + 0.07A + 0.121B - 0.0005A^2$	0.925	43.09***	0.617[a]

*Where A = drying temperature (°C), B = slice thickness (mm), N = non-pretreated. Statistical levels of significance: ***p < 0.0001, **p < 0.001, *p < 0.05, [a]p = non-significant*

4.3.2 Effect of pretreatment and process settings on the total drying time

The drying time was significantly influenced by the drying temperature ($p < 0.0001$), the slice thickness ($p < 0.0001$), the pretreatment ($p < 0.0001$), the interaction between the drying temperature and slice thickness ($p < 0.001$) and the interaction between the slice thickness and pretreatment ($p < 0.001$). The effect of pretreatments and process settings on the total drying time is presented in Figure 4.24. An increase in the drying temperature from 40 °C to 75 °C and a corresponding decrease in the slice thickness was found to decrease the drying time. An increase in the air temperature decreases the vapour pressure, increases the moisture-holding capacity of the drying air (Valsson & Bharat, 2011) and also the vapour pressure within the product (Afolabi et al., 2015). This increases the drying rate and a subsequent decrease in the drying time. This phenomenon was confirmed by monitoring the relative humidity of the air inside the drying cabinet during the drying process. The relative humidity was observed to reduce from the average ambient value of 30 – 40 per cent to an average of 5 – 10 per cent inside the drying cabinet during the experiments. An increase in the slice thickness may help reduce the incidence of surface shrinkage during drying (Raponi et al., 2017). However, a greater slice thickness also increases the length of the path that moisture molecules have to travel from the slice centre to the surface (Amjad et al., 2016). Consequently, the time required for drying increases as shown in Fig. (3b). Similar results on the effect of the thickness have been reported for pumpkin slices (Limpaiboon, 2011), potato slices (Amjad et al., 2016) and papaya (Sairam et al., 2017).

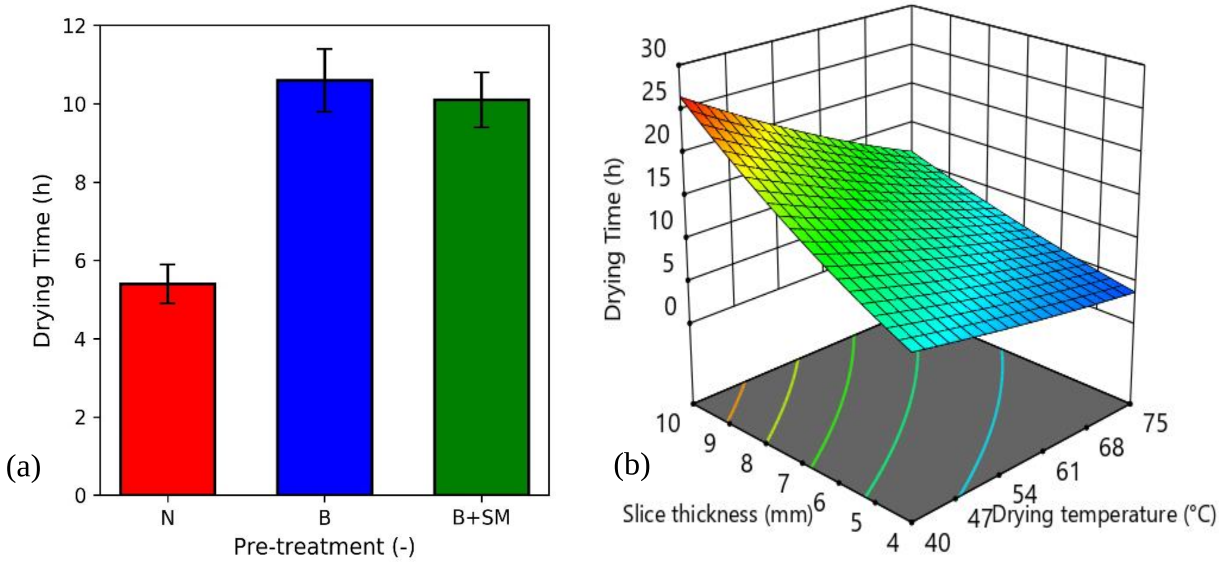


Figure 4.24: Effect of drying settings on the total drying time at 60 °C temperature (a) at 7mm slice thickness (b). blanch pretreatment

As shown in Figure 4.24a, the B and B+SM pretreatments increased the drying time significantly above the non-pretreated status. A similar observation on the drying time was made by Afolabi et al. (2015). The application of water and heat during blanching causes the uptake of water and swelling of starch granules. Amylose molecules then leach into the surrounding water causing a collapse of the starch granule. During the cooling step, gelatinized starch molecules aggregate forming a stiff gel layer on the surface layer on the slices that prevents moisture migration to the slice surface thereby increasing the drying time (Kumar et al., 2017). Additionally, the moisture content added to the slices during pretreatment requires additional time to remove the extra moisture. RSM analysis and ANOVA revealed that drying of purple-speckled cocoyam at a temperature of 75 °C, at 4 mm slice thickness without pretreatment provides the best settings for a decreased total drying time.

4.3.3 Effect of pretreatment and process settings on slice colour change

As shown in Figure 4.25, ΔE was found to be solely influenced by the pretreatments at all factor settings ($p < 0.0001$) while BI was significantly influenced by pretreatment ($p < 0.0001$) and the drying temperature ($p < 0.05$). The B pretreatment caused the most significant increase in ΔE and BI while the non-pretreated status caused the least absolute change of both colour indices. As shown in Figure 4.25b, an increase in the drying temperature from 40 °C to 75 °C caused a linear increase in BI. Moreover, an analysis on the individual colour parameters found ΔL^* and Δa^* to be both significantly influenced by the pretreatment only ($p < 0.0001$) just like

ΔE and the Δb* by the slice thickness and the interaction between the drying temperature and the slice thickness (i.e., $p < 0.01$ and $p < 0.05$ respectively).

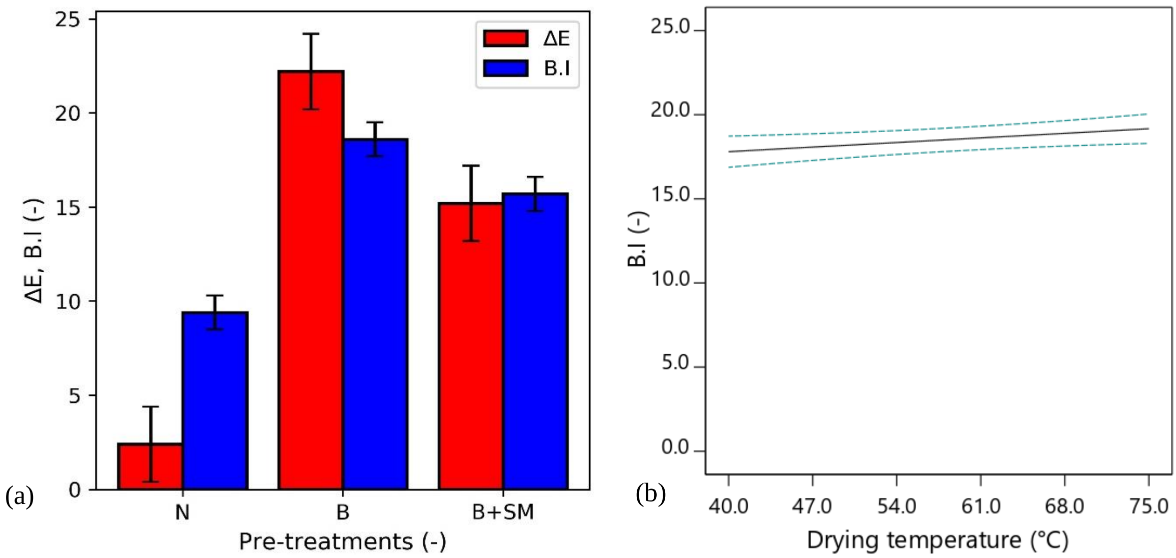


Figure 4.25: Effect of drying settings on ΔE and BI at 7 mm slice thickness

CIELAB a* parameter was observed to depict greater stability as compared to the L* and b* parameters. Similar behaviour has been observed for red pepper (Yang et al., 2018) and paprika (Minguez-Mosquera & Hornero-Mendez, 1994). However, as shown in Figure 4.25a, the B pretreatment was observed to cause a significant increase in a* above the non-pretreated state as compared to B+SM after pretreatment contributing to higher values of both ΔE and BI as compared to the B+SM pretreatment. The reason for this is that the blanching process degraded the purple coloured anthocyanins in the slices to form Chalcone, an unstable form with a tendency to degrade further to brown products such as malvidin 3-O-glucoside (Francis & Markakis, 1989; Ziabakhsh et al., 2016). In contrast, sulphur dioxide from the B+SM pretreatment rapidly bleached the brown products forming colourless compounds leaving the slices with comparatively lower values of ΔE and BI (Berké et al., 1998).

Figure 4.26 and Figure 4.27 present the evolution of ΔE and BI as functions of the moisture ratio. A new colour index (i.e., the whiteness index) is also introduced to help elaborate the evolution of colour. Figure 4.26 shows the evolution of ΔE, BI and WI for non-pretreated slices. It was observed that both ΔE and WI gradually increased to attain a subtle peak at the moisture ratio between 0.5 and 0.6. The BI also decreased to attain the minimum value in the same range of the moisture ratio. This could be due to an increase in the L* parameter and a slight decline of the a* and b* parameters. This phenomenon can be explained as follows; slicing exposed a fresh surface which allowed rapid removal of moisture from the non-pretreated slice surface causing a slow emergence of a reflective white starchy colour hence an increase in L*, ΔE and WI during the first stage of drying up to the level of moisture content where the drying rate switched from the first to the second drying phase. With the slow onset of enzymatic browning due to a gradual formation of brown pigments from an increase in both a* and b* at the slice surfaces and a reduction in the L* parameter, this increased BI, a decline of WI and a smaller absolute ΔE between the start and the end of the drying process.

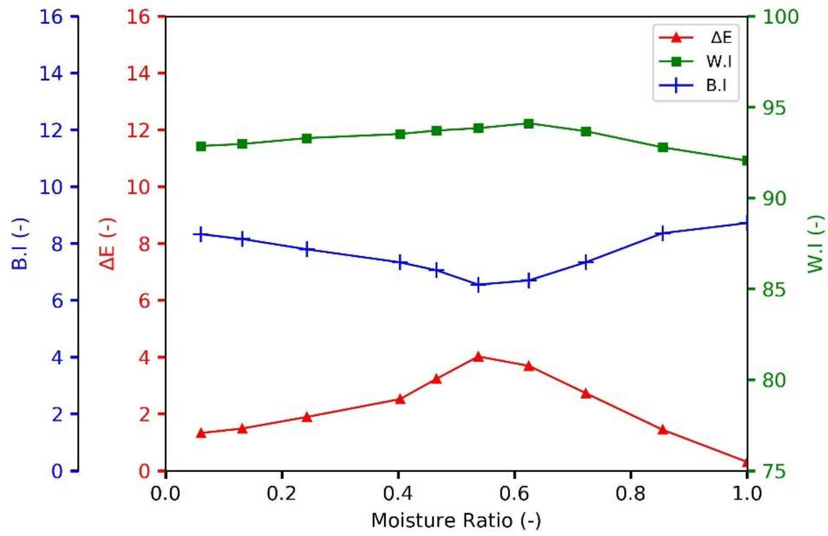


Figure 4.26: Evolution of ΔE, BI and WI at 60 °C temperature and 7 mm slice thickness for non-pretreated slices

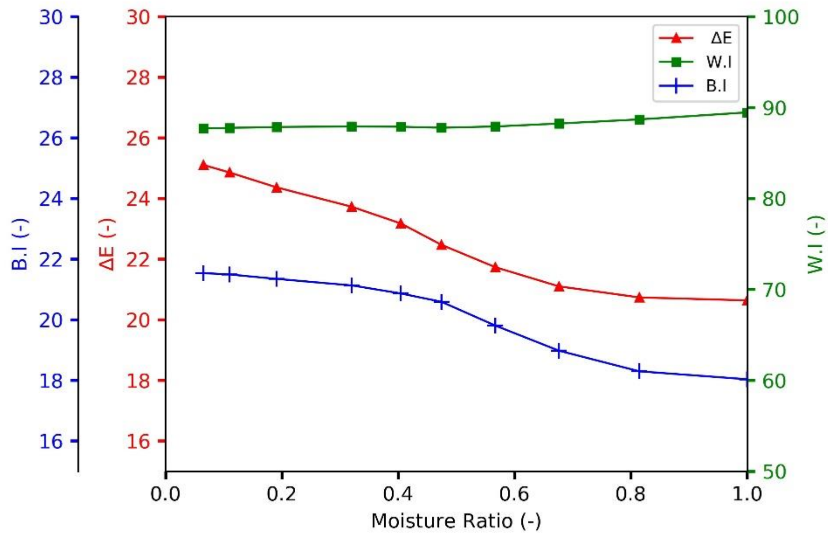


Figure 4.27: Evolution of ΔE, BI and WI at 60 °C and 4 mm thickness for Blanch pretreated slices

Figure 4.27 shows the evolution of the colour indices for blanched slices. Unlike in the non-pretreated case, the heat pretreatment process for both B and B+SM rapidly denatured the heat-labile part of the slice enzymes; the relatively heat stable part then dominated the entire drying process causing a consistent reduction in L* (Maskan, 2001; Yemenicioglu et al., 1999). Similar behaviour was reported for potato chips dried after various pretreatment combinations that included blanching (Pimpaporn et al., 2007). Moreover, starch gelatinisation and hydrolysis during the blanching process could have altered the optical properties of the slices making them exhibit a lower level of lightness (Pimpaporn et al., 2007; Z. Zhang et al., 2017). This effect in combination with a concurrent increase in both a* and b* caused the consistent decrease in WI and an increase in both ΔE and BI.

The stability and acceptability of dried products can be predicted from the extent of colour change after thermal processing (Yang et al., 2018). Overall, the B pretreatment caused the most significant increase in ΔE and browning while the non-pretreated slices experienced the least ΔE and browning as demonstrated in Fig. (4a). Further, both the B and B+SM pretreatments were observed to not offer any colour preservation benefits to the subsequent drying process. This suggests that drying processes for purple-speckled cocoyam should be conducted without the studied pretreatments. A similar recommendation was made for hot-air drying of Boletus edulis mushrooms under similar pretreatments as used in this study (Argyropoulos et al., 2011).

4.3.4 Effect of pretreatment and process settings on the rehydration ratio

As demonstrated in Figure 4.28, RR was significantly influenced by the pretreatment ($p < 0.0001$) and the slice thickness ($p < 0.05$). The drying temperature was found to have an insignificant effect on RR. The general effect of the process settings observed was that both B and B+SM pretreatments resulted in an increase in RR above the non-pretreated status as shown in Figure 4.28a. This result compares to the findings of Maldonado, Arnau, & Bertuzzi (2010) where mangoes osmotically dehydrated with glucose exhibited larger moisture reuptake on rehydration as compared to non-pretreated mango samples. Moreover, RR was highest at the slice thickness of 4 mm and decreased with an increase in slice thickness to attain a minimum value at the 10 mm slice thickness as shown in Figure 4.28b.

According to Krokida & Marinos-Kouris (2003), lower values of RR after drying indicate a high incidence of cellular and structural damage during the drying process. This results in a dense structure with collapsed capillaries and shrunken pores that block the material’s moisture reuptake (Krokida & Marinos-Kouris, 2003). It can be observed from Figure 4.28a and Figure 4.28b that hot-air drying of purple-speckled cocoyam without pretreatment and at the 10 mm slice thickness led to a denser material structure hence a low value of RR. Hot-air drying of purple-speckled cocoyam material at 4 mm slice thickness with the B and B+SM pretreatments provided a higher value of RR. This behaviour is likely due to extensive cellular damage during the blanching pretreatment which opened pathways in the product for the uptake of moisture after drying during the rehydration process. The best drying settings for a desirable outcome of RR were observed to be at the 4 mm slice thickness with the B+SM pretreatment.

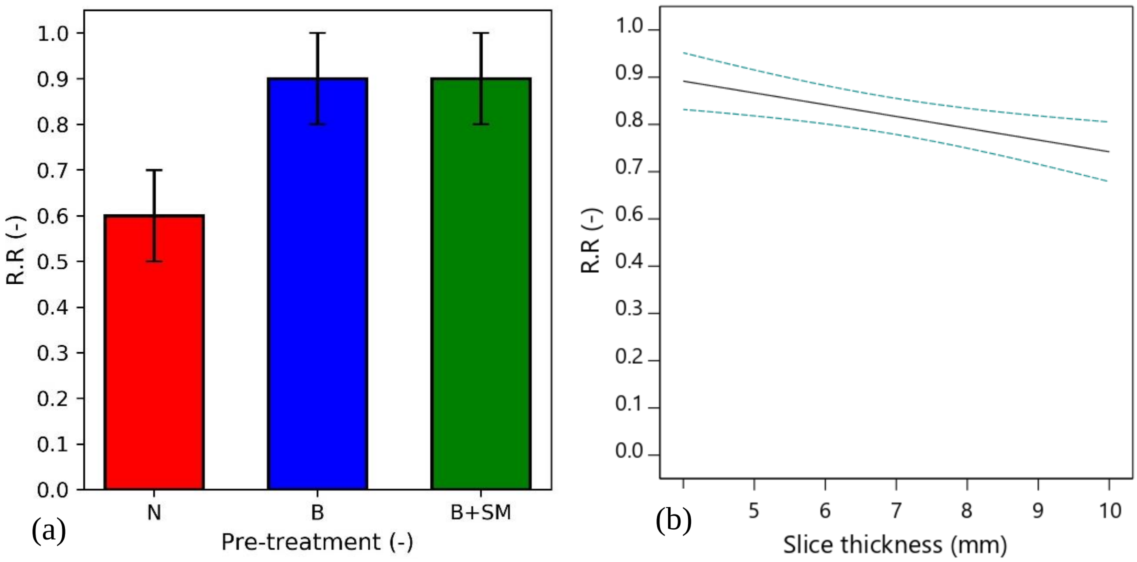


Figure 4.28: Effect of process settings on RR (a) 7mm slice thickness, (b) for Blanch pretreated slices

4.3.5 Effect of pretreatment and process settings on the energy consumption

Figure 4.29 presents the specific energy consumption for the selected drying settings. The specific energy consumption was observed to be significantly influenced by the drying temperature ($p < 0.05$), slice thickness ($p < 0.0001$) and pretreatment ($p < 0.0001$).

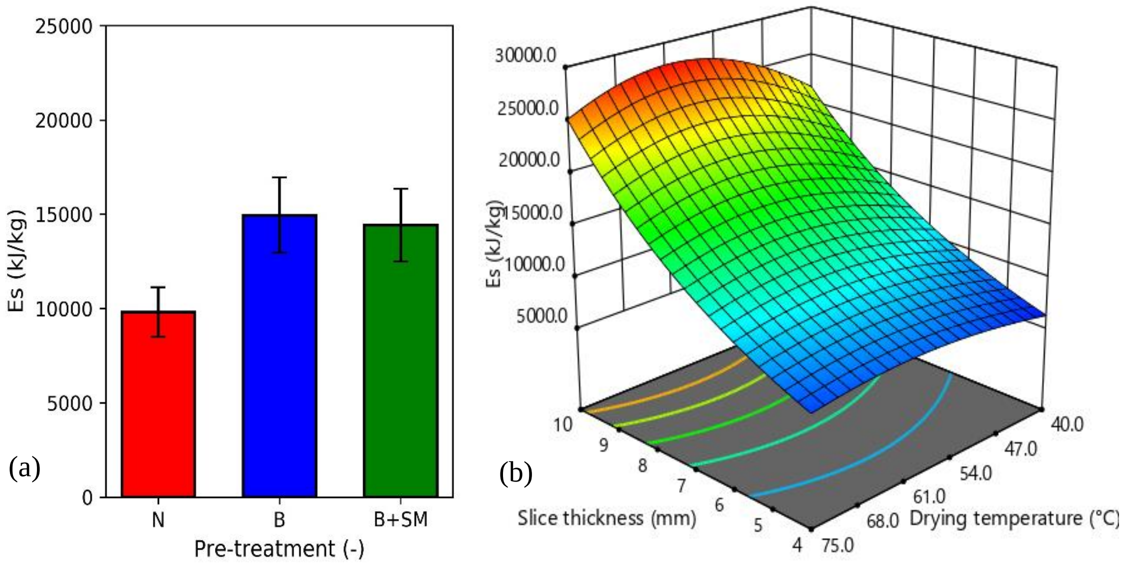


Figure 4.29: Effect of process settings on specific energy consumption (a). 7 mm slice thickness (b). blanch pretreatment

As shown in Figure 4.29b, drying temperature had a quadratic effect on the specific energy consumption, with more energy being consumed at the drying temperature of 60 °C and less at the other temperature settings. This result is in agreement with the findings of Koyuncu et al.

(2007) who found the temperature to have a significant effect on the specific energy consumption during drying of red and yellow azarole fruits. The minimum specific energy consumption was found to occur at 40 °C and the maximum at 60 °C. At 75 °C, the specific energy consumption was observed to decrease. This could be because, with the increase in temperature beyond 60 °C, the accompanying decrease in drying time compensates for the specifically higher energy demand for air heating.

The slice thickness and pretreatment were found to have a greater effect on the specific energy consumption than the drying temperature. As shown in Figure 4.29b, the specific energy consumption was found to increase with an increase in the slice thickness from 4 mm to 10 mm. This occurred because larger material dimensions at 10 mm thickness and a comparatively smaller surface area to volume ratio held a higher amount of moisture content. This increased the residence time in the dryer causing an increase in energy consumption. Figure 4.29 presents the effect of the pretreatments on the specific energy consumption. Both the B and B+SM pretreatments resulted in a similar amount of specific energy consumption. The pretreated slices required more energy to remove the extra moisture added during pretreatment. Further, the formation of a hard surface layer due to starch gelatinisation during pretreatment prevented the migration of moisture to the slice surfaces for removal (Kumar et al., 2017). Both factors increased the residence time of the slices in the dryer and thus the higher specific energy consumption. The results reveal that hot-air drying at the 4 mm slice thickness without pretreatment and with drying temperature of 75 °C provide the best settings for the specific energy consumption.

4.3.6 Parameter optimisation using the desirability function approach

Table 4.11 presents the most desirable solution which provides the parameter settings for the most optimal drying conditions. Optimisation results revealed that the most suitable drying conditions are at a drying temperature of 75 °C, slice thickness of 4 mm without pretreatment. At these settings, the composite desirability index was 0.78. These settings yield a total drying time of 109 min, a total colour difference of 2.4, a browning index of 9.96, a rehydration ratio of 0.7 and specific energy consumption of 6,119.3 kJ/kg. However, a storage study is needed to confirm the suitability of these settings on quality retention during storage.

Table 4.11: Selected optimal solution for hot-air drying

Parameter	Optimisation goal	Setting/value	Desirability indices
Factors			
Drying temperature (°C)	keep in range	75.0	1.0
Slice thickness (mm)	keep in range	4.0	1.0
Pretreatment	keep in range	N	1.0
Parameters			
Total drying time, *T* (min)	minimise	110.0	1.0
Colour difference, Δ*E* (-)	minimise	2.4	0.94
Browning Index, *BI* (-)	minimise	9.96	0.83
Rehydration ratio, *RR* (-)	maximise	0.7	0.39
Specific energy consumption, E_s (kJ/kg)	minimise	6,175.0	0.96
Overall desirability index	***maximise***	-	***0.78***

4.3.7 Hyperspectral image analysis and multivariate modelling

4.3.7.1 Spectral analysis

The spectral signatures of cocoyam slices over the ranges 400 – 1700 nm during hot-air drying are shown in Figure 4.30.

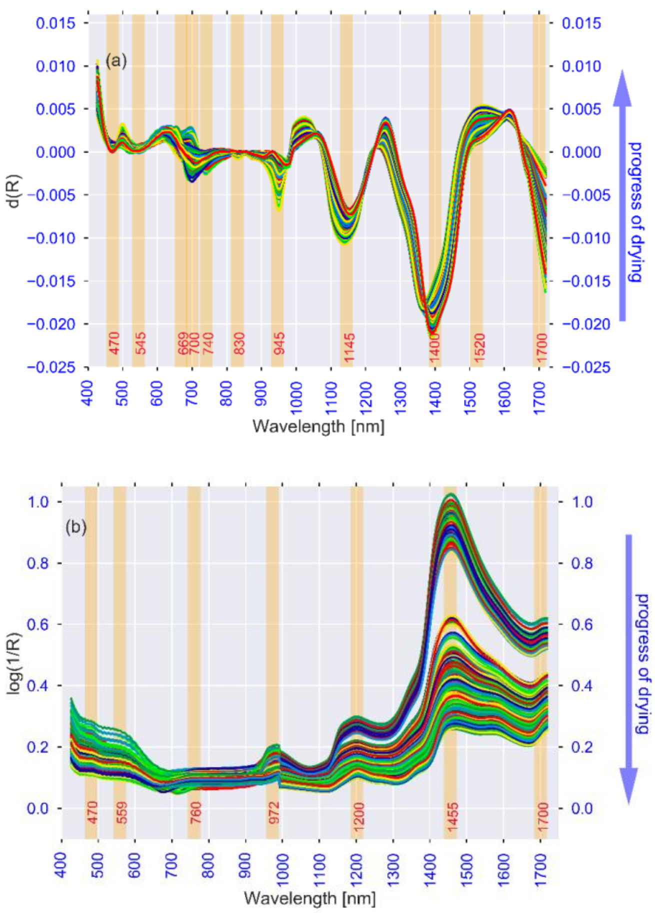


Figure 4.30: Cocoyam spectral signatures. a). the first derivative of reflectance, b). absorbance spectra

The spectral information was observed to be greater in the range above 900 nm as compared to 400 – 900 nm. Generally, absorbance was lower in the lower end of the spectrum but higher in the upper end with the highest values in the region 1200 – 1700 nm. Previous studies have shown that certain wavelengths have special importance in providing information on the physicochemical properties of the material under consideration. For purple-speckled cocoyam, these wavelengths are highlighted and labelled in Figure 4.30. Shift or drifts in peaks of the expected locations of informative wavelengths occurred possibly due to spatial variations in chemical composition, drying temperature changes, interactions of hydrogen bonds with sample components and possibly minor changes in the alignment of the material surface to the optical path of the cameras (Magwaza et al., 2012; Rongtong et al., 2018; Zude et al., 2008).

There is a small but perceptible absorption peak in the vicinity of ~760 nm which is associated with the stretching of the third overtone of O-H and the fourth overtone of CH in its vicinity (Clément et al., 2008; Sturm et al., 2020). The region 950 - 1000 nm is significant in the prediction of moisture content in tubers (Amjad, Crichton, Munir, Hensel, & Sturm, 2018; Jun, Ning, Ngadi, & Singh, 2005). This region coincides with the absorbance peak at 972 nm and the dip at 945 nm in the first derivative plot. In the second overtone region, the absorbance at 1200 nm and 1400 nm has also been associated with moisture content in biological materials (Pu et al., 2003). Independent analysis revealed relatively higher values of absorbance at these bands in the initial stages of drying (i.e., at 0, 30 and 60 min) because the high moisture content caused higher light absorption as a result of stretching and bending of O-H bonds within the water molecules (Amjad et al., 2018; Sturm et al., 2020; Workman & Weyer, 2012). The total amount of moisture in a food matrix can be segregated into free and bound water. Free water supports food spoilage microorganisms and chemical reactions (Gowen, 2012; Velazquez et al., 2003). It, therefore, is a significant indicator of food quality and is manifested in the matrix as water activity (Caurie, 2011). According to Gowen, Tsenkova, Esquerre, Downey, & O'Donnell (2009), the informative bands for free water are in the vicinity of ∼950 and ∼1398. This is consistent with the troughs of the first derivative plots in the same region. These bands could be useful for the prediction of water activity.

Bound water is unavailable for chemical reactions but has a great influence on material structure. The migration of bound water within a material causes the formation of pores, cellular shrinkage and collapse of cellular walls thereby contributing to overall structural deformation (Khan et al., 2016; Prothon et al., 2003). The rehydration ratio is commonly utilised as a structural deformation assessment index during food drying (Ashtiani, Sturm, & Nasirahmadi, 2018; Lewicki, 1998; Ndisya et al., 2020; Ratti, 2001). In this study, the change in slice structural attributes including rehydratability, volumetric shrinkage, percentage pore area and pore circularity are therefore theorized to be influenced by the removal of bound water. Wavebands in the vicinity of 1174 nm, 1454 nm, 1496 nm are reported to depict absorption of water with a higher number of strong hydrogen bonds which is representative of bound water (Gowen et al., 2009; Segtnan et al., 2001; Tsenkova et al., 2004). These bounds could be significant in the prediction of material structural behaviour.

The flesh of a cocoyam tuber contains about 12.2 – 36.0 g of carbohydrates per 100 g of dry matter where 70 – 80 per cent is starch (Ndabikunze et al., 2011; Temesgen & Retta, 2015). Sugars are another component of carbohydrates with sucrose as the largest proportion (Temesgen & Retta, 2015). The absorption bands related to starch and sugars are in the third overtone of the stretching of O-H bonds in the region 720 – 920 nm and C-H bonds at 750 – 910 nm (Malegori et al., 2017; Miyamoto & Kitano, 1995; Wang et al., 2015). The wavelengths in the vicinity of 1593 nm have also been applied in predicting sucrose in sugar beet (Roggo et al., 2004). However, sucrose forms strong hydrogen bonds with water, and therefore its informative bands overlap with the region of strong moisture absorbance thereby making them difficult to visualize (Delwiche et al., 2008; Malegori et al., 2017).

Cocoyam contains various bioactive compounds with a strong antioxidant potential, a characteristic that makes it attractive as an important food and ethnomedical item (Eleazu, 2016; Pereira et al., 2015). Phenolic compounds in cocoyam, in particular, anthocyanins contribute to red, purple or blue pigmentation in various accessions (Champagne et al., 2011; Ferreres et al., 2012; R. F. Gonçalves et al., 2013; Khoo et al., 2017; Prasad et al., 2018). The fresh material utilised in this study contained an average of TPC 3.94 ± 0.68 μg GA/g DM and TFC 1.57 ± 0.14 mg/g DM. These compounds when combined with the rich vitamin content contribute to the high antioxidant activity of the tuber (Eleazu, 2016; Vivek Kumar & Sharma, 2017). In this study, the average TAA was 77.4 ± 4.99 % RSA. Sturm et al. (2020) observed a decline in the prominence of absorption peaks in the region 700 – 1000 nm due to variation in the concentration of polyphenolic compounds as drying progressed. Phenolic compounds are also reported to absorb at bands in the spectral ranges 1415 – 1512 nm and 1650 – 1750 nm (Albanell et al., 2021; Cozzolino et al., 2008; Dykes et al., 2014; C. Zhang et al., 2008). The dip in the first derivative plot at 1700 nm and the absorbance peak observed at the same wavelength is indicative of a possible informative band for bioactive compounds.

The colour exuded by materials is a result of the interaction of light at certain wavelengths with chemical compounds and organic materials (Kusumiyati et al., 2019). Bands in the range of 400 – 700 nm are important in the assessment of colour (Munera et al., 2017; Xie et al., 2018). Respectively, the blue, green and red components of colour are detectable in the regions 400 – 500 nm, 500 – 600 nm and 600 – 700 nm (Kohl et al., 2006). However, these colours tend to overlap at certain wavelengths thereby exuding a wide range of mid-tones and colour differences (Macdougall, 2010). Ndisya et al. (2020) reported an increase in the browning index and a decline in the whiteness index of cocoyam slices with the progress of hot-air drying due to enzymatic browning. This could explain the absorbance peaks at 545 nm and 559 nm attributable to the relative contribution of green and red pigments in the brown compounds. Moreover, previous studies have correlated the absorbance peaks in the region 516 – 560 nm to anthocyanins in plant materials (Y. Liu et al., 2014; Rustioni et al., 2013).

4.3.7.2 Selection of optimal PLS Latent Variables

In this study, the optimal number of LVs was considered to be the value where no statistically significant improvement in RMSE, r^2 and RPD was observed when additional LVs were included in the model during cross-validation. The maximum number of LVs tested was 15. As shown in Figure 4.31, the red line shows that the optimal number of LVs for TFC.

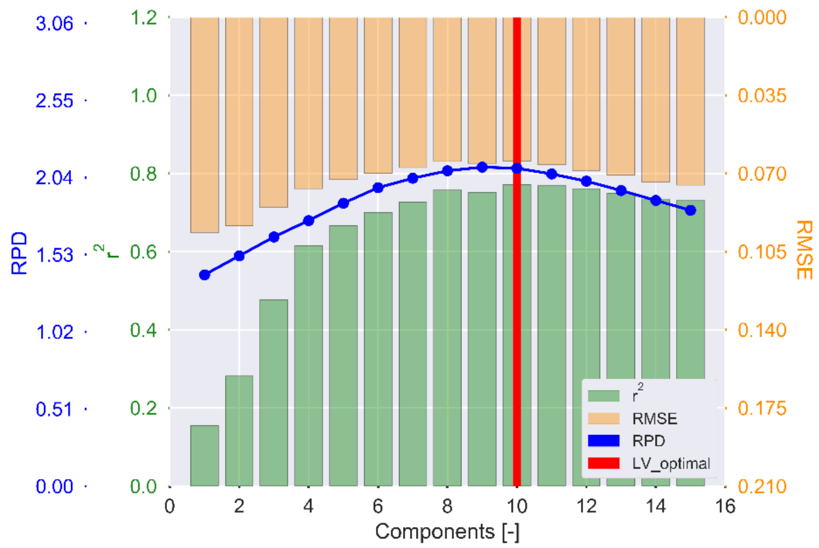


Figure 4.31: RMSE, r^2 and RPD vs PLS components for TFC

Table 4.12 provides the performance metrics of the PLSR models at calibration and prediction. As it can be seen in the table, better model performance was obtained from the spectra preprocessed by applying Multiplicative Scatter Correction to reflectance spectra followed by applying the second derivative. Moreover, the optimal latent variables obtained ranged from 5 for PC to 15 for WI and RR.

Table 4.12: Performance metrics of PLSR calibration models

Response	Pre-processing	No. of LVs	Calibration [n = 362]			Prediction [n = 241]		
			$RMSE_C$	r^2_C	RPD_C	$RMSE_P$	r^2_P	RPD_P
Moisture attributes								
MC	MSC+d^2(R)	13	1.698	0.99	13.1	1.978	0.99	11.2
MR	MSC+d^2(R)	10	0.026	0.99	12.6	0.030	0.99	10.8
a_w	MSC+R	11	0.059	0.93	3.8	0.065	0.92	3.5
Colour attributes								
CIELAB L*	MSC+d(R)	15	0.821	0.64	1.8	0.907	0.53	1.6
CIELAB a*	MSC+d^2(R)	6	0.303	0.75	2.1	0.460	0.50	1.4
CIELAB b*	MSC+d(R)	13	0.335	0.79	2.3	0.343	0.78	2.3
BI	log (1/R)	14	0.489	0.81	2.5	0.491	0.78	2.4
WI	MSC+d.(R)	15	0.109	0.76	2.1	0.134	0.65	1.7
Chroma	log (1/R)	11	0.313	0.80	2.4	0.343	0.76	2.2
Hue angle	MSC+d.(R)	7	0.043	0.75	2.2	0.049	0.72	1.9
Chemical attributes								
TAA	MSC+d^2(R)	13	7.100	0.70	2.0	7.600	0.69	1.9
TFC	MSC+d^2(R)	12	0.063	0.77	2.2	0.063	0.76	2.2
TPC	MSC+d^2(R)	9	0.239	0.46	1.5	0.280	0.45	1.3
Structural attributes								
V_s	MSC+d^2(R)	9	0.039	0.97	5.5	0.042	0.96	5.2
RR	MSC+d(R)	15	0.017	0.99	8.4	0.021	0.98	7.0
PPA	MSC+d^2(R)	9	1.774	0.82	2.4	2.347	0.64	1.8
PC	MSC+d^2(R)	5	0.020	0.85	2.7	0.022	0.84	2.4

4.3.7.3 Selection of optimal wavelengths

Analysis of data from a large number of hypercubes is computationally demanding. Therefore, the selection of a subset of wavelengths with high information value and reduced co-linearity and redundancy is important (Gao et al., 2020). PLS-BETA and PLS-VIP are some of the most frequently used methods for feature selection because of their simple implementation, less computational demand, and few parameters requiring tuning (Dai et al., 2015; Galindo-Prieto et al., 2015; Z. Wang et al., 2015). Additionally, the two techniques have been reported to be complementary (Chong & Jun, 2005). In the PLS-BETA method, PLSR coefficients are ranked and the ones with the largest contribution to the model are selected (Chong & Jun, 2005; Dai et al., 2015; Wang et al., 2015).

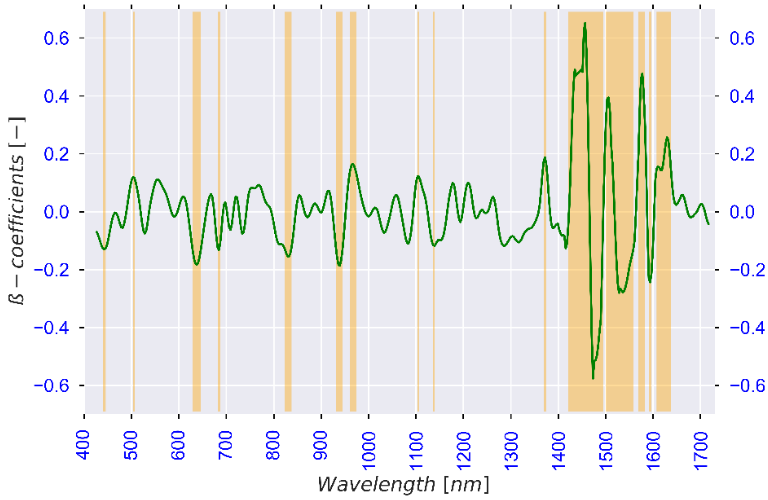
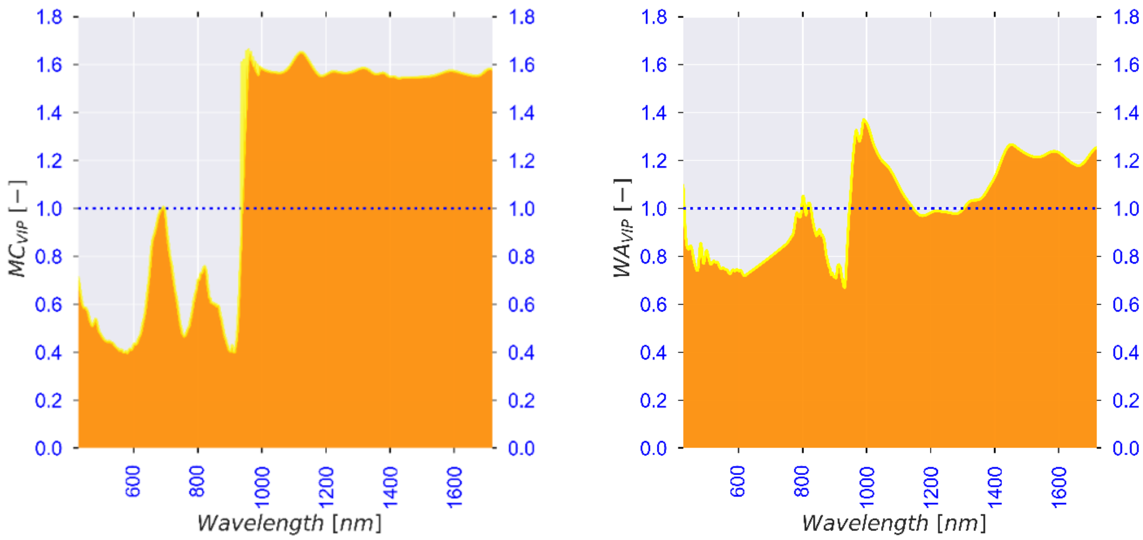


Figure 4.32: Features selected using PLS-BETA for moisture content (highlighted)

Figure 4.32 highlights the features selected using the PLS-BETA method for MC. It can be observed from the magnitudes of the ß-coefficients that the most influential features are in the upper end of the spectrum in the range 1380 – 1650 nm. The PLS-VIP method assigns VIP scores to each variable based on the weighted sum of squares of the PLS weights. The `greater than one´ rule is the standard utilised as the cut-off value to decide the features to be selected (Afanador et al., 2014; Jun, Lee, Park, & Lee, 2009). Figure 4.33 – Figure 4.36 present PLS-VIP plots of the quality attributes under consideration.

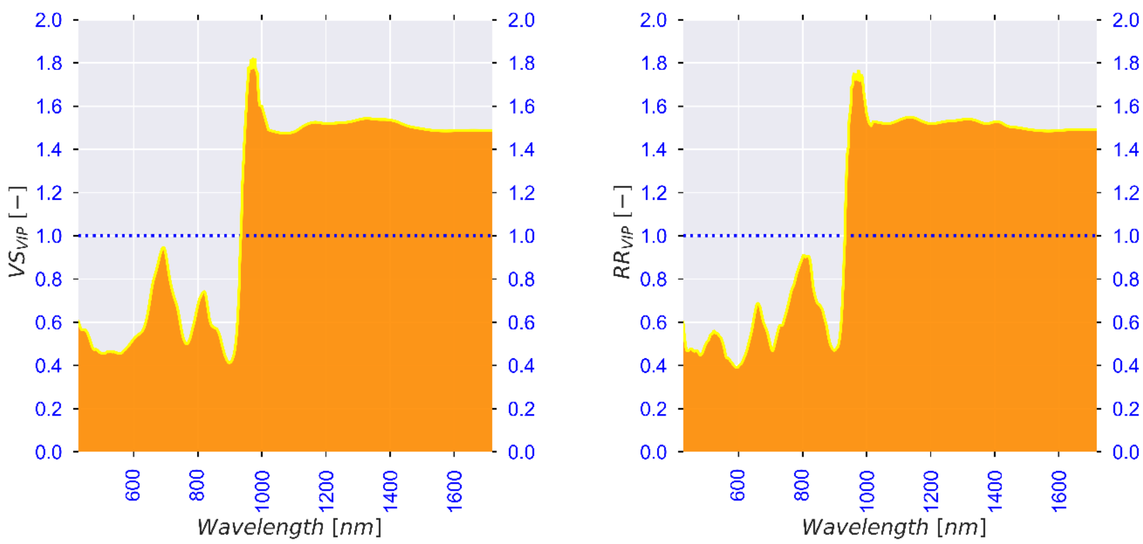


a). VIP plot for moisture content

b). VIP plot for water activity

Figure 4.33: VIP plot for moisture content and water activity

In Figure 4.33a, wavelength bands in the region of 700 – 760 nm and 951 – 999 nm have high VIP scores owing to the third overtone of O-H indicating their importance in predicting moisture content. The viability of these bands is well documented in previous studies (Amjad et al., 2018; Q. Jun et al., 2005; Pu et al., 2003; Shrestha, Crichton, et al., 2020). As shown in Figure 4.33b, the region 962 – 990 nm exhibits a high VIP score peak (approx. 1.4) for water activity. A broad peak is also exhibited at 1448 nm but with a relatively lower VIP score. This could be attributed to the huge quantity of free water in the material, especially in the initial stages of drying. With free water as a proxy indicator of water activity (Caurie, 2011; Gowen et al., 2009), the bands in these regions are viable for future prediction of water activity.

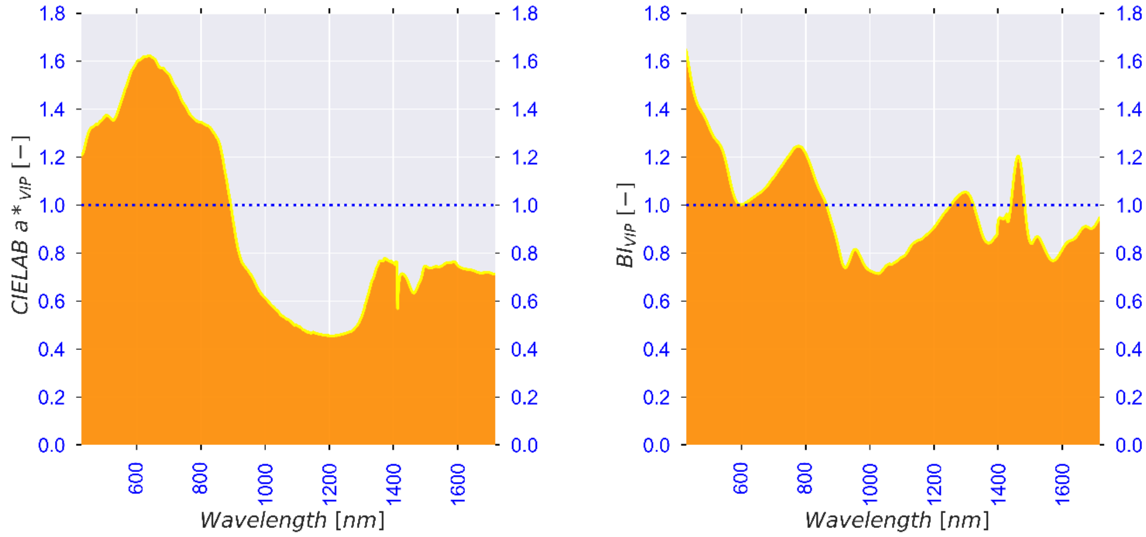


a). VIP plot for volumetric shrinkage

b). VIP plot for rehydration ratio

Figure 4.34: VIP plots for volumetric shrinkage and rehydration ratio

VIP scores for volumetric shrinkage and rehydration ratio are presented in Figure 4.34a and Figure 4.34b respectively. The wavebands at 977 nm and 975 nm for volumetric shrinkage and rehydration ratio respectively were found to depict VIP scores higher than in moisture content and water activity in the same region. Similarly, high VIP scores were obtained for percentage pore area and pore circularity. The application of heat during drying diminished the amount of free water in the cocoyam matrix. With less free water available, further application of heat mobilized bound water into extracellular space thereby enabling its removal through the normal channels. Structural attributes could therefore be envisaged as proxies for the combined free water and bound water. Since bound water does not exert vapour pressure, it theoretically has zero influence on water activity (Joardder et al., 2019). However, small but perceptible peaks are depicted in the vicinity of 1150 nm and 1400 nm. Previous studies have associated the regions with bound water (Büning-Pfaue, 2003; Gowen et al., 2009; Khan et al., 2016; Prothon et al., 2003; Segtnan et al., 2001; Tsenkova et al., 2004). The bands in these regions could therefore be utilised to predict structural changes in cocoyam material during drying.



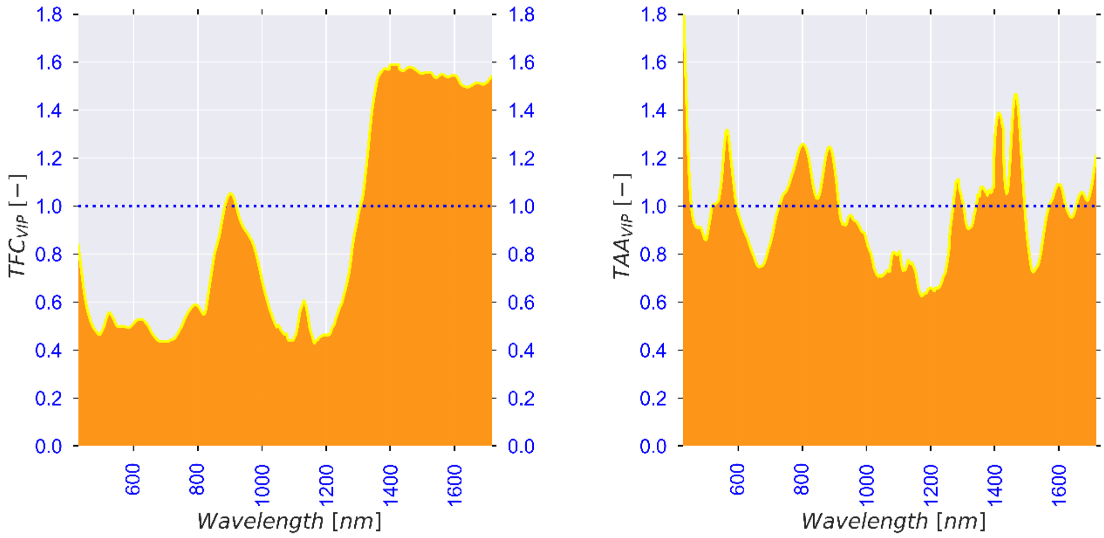
a). VIP plot for CIELAB a*

b). VIP plot for browning index

Figure 4.35: VIP plot for CIELAB a* and browning index

Figure 4.35a and Figure 4.35b present the VIP scores of CIELAB a* and browning index (BI). As shown in Figure 4.35a, the dominant wavebands for CIELAB a* are in the vicinity of 520 nm and 624 – 640 nm which is consistent with the findings of Kohl, Landmark, & Stickle (2006). This could be attributed to the purple-red pigmentation of speckles on the cocoyam slices associated with anthocyanins (Y. Liu et al., 2014; Rustioni et al., 2013). While the importance of this waveband region in the detection of chlorophyll in green plant material is well documented (Sturm et al., 2020; J. Zhang et al., 2019), limited information is available on its utility in predicting red pigments in plant materials. Red and green form an opponent colour pair in the CIELAB colour space (Berezhnoy et al., 2007). The high VIP scores in the region 520 nm and 624 – 640 nm could therefore indicate the utility of these wavelengths in the detection of anthocyanins in cocoyam. Figure 4.35b presents the VIP scores for the BI, the most prominent peak is exhibited at 775 nm in the fourth overtone zone of C-H. This peak could be indicative of the degradation of phenolic compounds to brown coloured compounds like malvidin 3-O-glucoside as a result of drying (Francis & Markakis, 1989; Ndisya et al., 2020; Ziabakhsh et al., 2016).

Figure 4.36a and Figure 4.36b present the VIP scores of the total flavonoid content and total antioxidant activity respectively. The informative waveband for TFC is at 903 nm in the third overtone zone of C-H. Smaller peaks in the VIP plot were observed at 1407 – 1600 nm in the first overtone combination zone for C-H. These regions have been associated with phenolic compounds (Cozzolino et al., 2008; Dykes et al., 2014; C. Zhang et al., 2008). Phenolic compounds combined with the vitamins in cocoyam tubers contribute to its high antioxidant activity (Eleazu, 2016; Vivek Kumar & Sharma, 2017). The peaks in the TFC VIP plot also appear in the TAA VIP plot at similar wavebands as shown in Figure 4.36a and Figure 4.36b. However, the TAA VIP plot has additional peaks at 522, 558, 802, 884, 1273, 1360, 1412, 1465 and 1600 nm. These peaks could be related to other bioactive compounds not quantified in this study.



a). VIP plot for TFC b). VIP plot for TAA

Figure 4.36: VIP plots for TFC and TAA

4.3.7.4 Modelling and method comparison: Moisture attributes

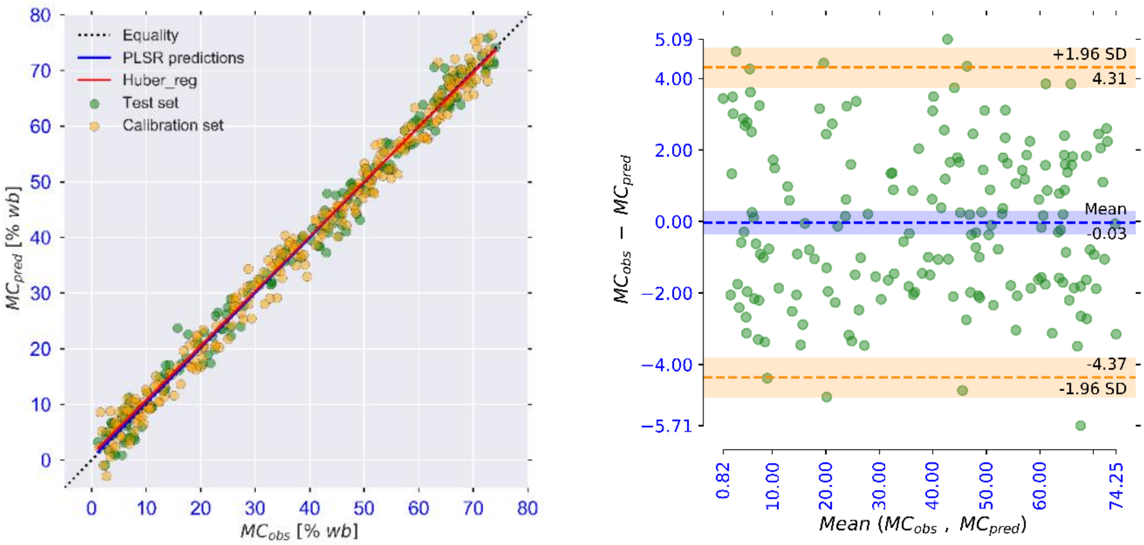
The fresh purple-speckled cocoyam material utilised in this had an initial moisture content of 68.8±3.0% on a wet basis. The water activity of the material measured at 25°C was 0.976±0.002. MC, a_w and MR were adequately modelled with 13, 11 and 10 LVs respectively. Good prediction performance was observed with low values of $RMSE_P$ (i.e., 1.978, 0.030, 0.065), high values of r^2_P (i.e., 0.99, 0.99, 0.92) and high values of RPD_P (i.e., 11.2, 10.8, 3.5). Considering these values of RPD_P and the recommendation of Williams & Sobering (1993), the models for MC and MR are equivalent to their standard methods of measurement. Table 4.13 provides the method comparison metrics for MC, a_w and MR while Figure 4.37 and Figure 4.37 provide the regression plot and Bland-Atman plot respectively for MC.

The results reveal a high degree of agreement between the predictions and observations for MC and MR with values of regression coefficients ($ß_0$ and $ß_1$) not significantly different from 0 and 1 respectively. The Bland-Altman plot shows few points outside the LOA but the confidence interval for the mean difference includes zero. However, the degree of agreement of predictions and observations for a_w was inadequate as deduced from the slope and intercept of the regression line and CCC. This is because the PLSR model slightly underestimated water activity values at the initial stages of drying and considerably overestimated water activity as the drying process approached the end thereby diminishing the slope and increasing the value of the intercept of the regression line.

Table 4.13: Method comparison metrics for moisture attributes

Response	Huber Regression				CCC	Bland-Altman		
	β_1	β_1 - 95% C.I [LCL, UCL]	β_0	B_0 - 95% C.I [LCL, UCL]		*Mean diff.*	LOA_u	LOA_l
MC [% w.b]	0.99	[0.98, 1.01][b]	0.12	[-0.56, 0.80][b]	0.96	-0.02	4.31	-4.37
a_w [-]	0.87	[0.82, 0.92][a]	0.13	[0.08, 0.17][a]	0.73	0.00	0.15	-0.15
MR [-]	0.99	[0.97, 1.01][b]	0.01	[-0.01, 0.02][b]	0.96	0.00	0.08	-0.08

Statistical significance: H_0: $\beta_1.LCL < 1 < \beta_1.UCL$ / $\beta_0.LCL < 0 < \beta_0.UCL$, $^a p < 0.05$ = significant, $^b p$ = non-significant



a). MC regression plot b). MC Bland-Altman plot

Figure 4.37: MC regression plot and Bland-Altman plot

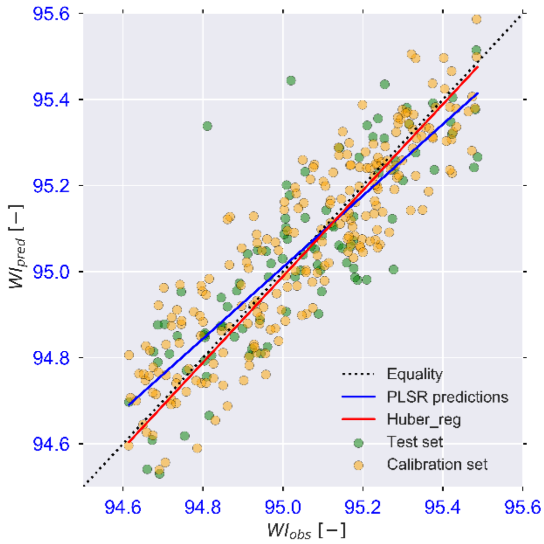
4.3.7.5 Modelling and method comparison: Colour attributes

In this study, the CIELAB colour values (L*, a* and b*) of fresh cocoyam slices were measured to be 86.28±1.18, 1.69± 0.39 and 7.51±0.70 respectively. The best model results for colour attributes were obtained using absorbance spectra for BI and chroma, the first derivative of reflectance for CIELAB L*, b*, WI and hue and the second derivative of reflectance for CIELAB a*. The best prediction performance was obtained for BI ($RMSEP_P$ = 0.491, r^2_P = 0.78, RPD_P = 2.4). Table 4.14 provides the method comparison metrics for colour attributes while Figure 4.38 provides the regression plot and Bland-Atman plot for WI. The metrics reveal a good agreement between predictions and observations for BI, WI, CIELAB b*, chroma and hue angle. This was corroborated by the Bland-Altman plots which exhibited only a few differences outside the 95 per cent limits of agreement. Further, irregular patterns associated with heteroscedasticity were absent and the confidence intervals for the respective mean differences included zero.

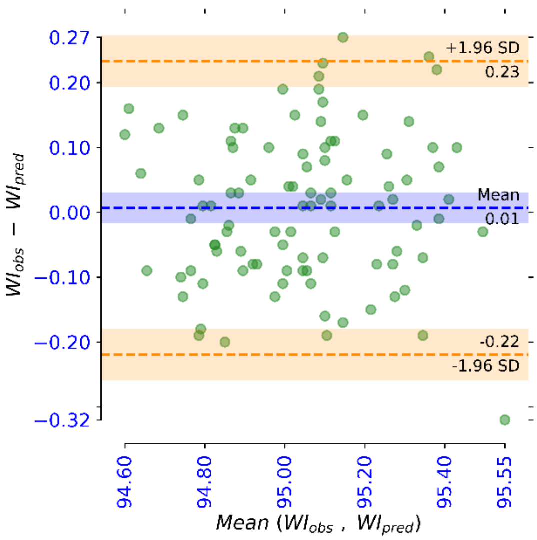
Table 4.14: Method comparison metrics for colour attributes

Response	Huber Regression				CCC	Bland-Altman		
	β_1	β_1 - 95% C.I [LCL, UCL]	β_0	B_0 - 95% C.I [LCL, UCL]		*Mean diff.*	LOA_u	LOA_l
BI [-]	0.99	[0.89, 1.08][b]	0.14	[-0.90, 1.18][b]	0.86	0.00	0.96	-0.96
WI [-]	0.85	[0.64, 1.05][b]	14.41	[-5.06, 33.87][b]	0.83	0.01	0.23	-0.22
CIELAB L* [-]	0.84	[0.73, 0.96][a]	13.33	[3.73, 22.93][a]	0.80	0.01	1.84	-1.82
CIELAB a* [-]	0.84	[0.73, 0.95][a]	0.34	[0.06, 0.63][a]	0.81	-0.01	0.75	-0.78
CIELAB b* [-]	0.92	[0.81, 1.04][b]	0.56	[-0.26, 1.38][b]	0.84	-0.01	0.70	-0.71
Chroma [-]	0.95	[0.84, 1.05][b]	0.40	[-0.41, 1.22][b]	0.84	0.00	0.67	-0.67
Hue angle [°]	0.93	[0.74, 1.12][b]	0.09	[-0.14, 0.33][b]	0.85	0.00	0.09	-0.09

Statistical significance: H_0: $\beta_1.LCL < 1 < \beta_1.UCL$ / $\beta_0.LCL < 0 < \beta_0.UCL$, $^a p < 0.05$ = significant, $^b p$ = non-significant



a). WI regression plot



b). WI Bland-Altman plot

Figure 4.38: WI regression plot and Bland-Altman plot

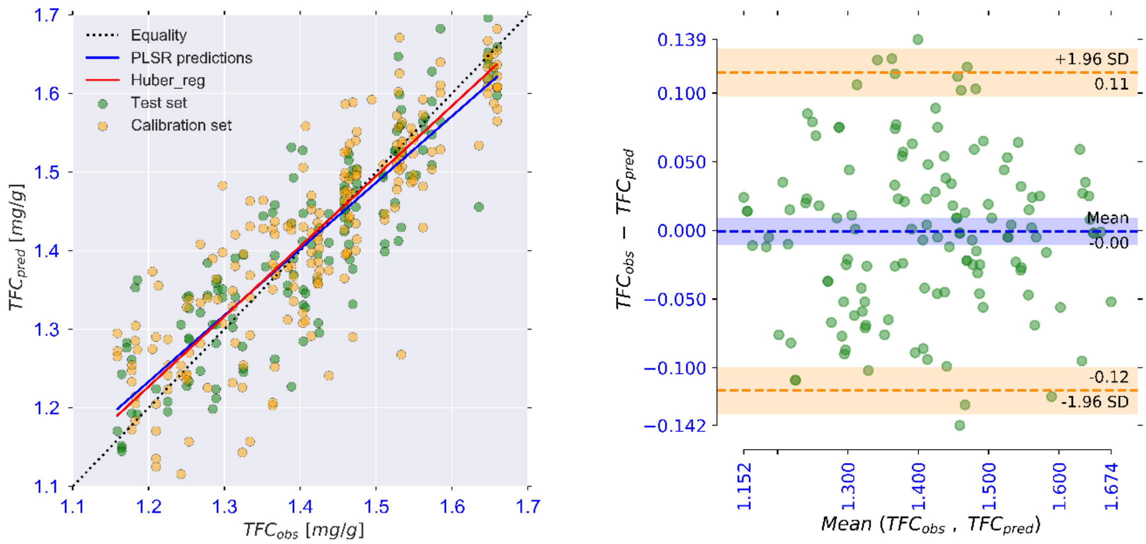
4.3.7.6 Modelling and method comparison: Chemical attributes

The cocoyam tubers utilised in this study contained on average, TPC of 4.75±0.23 µg GA/g_{DM}, TFC of 1.43±0.04 mg/g DM and TAA of 80.98±0.18% RSA. TAA, TFC and TPC were adequately modelled using the second derivative of reflectance with 13,12 and 9 LVs respectively. A good prediction performance was obtained for TAA ($RMSEP_P$ = 7.600, r^2_P = 0.69, RPD_P = 1.9) and TFC ($RMSEP_P$ = 0.063, r^2_P = 0.76, RPD_P = 2.2). However, poor prediction performance was obtained for TPC ($RMSEP_P$ = 0.280, r^2_P = 0.45, RPD_P =1.3). This could be as a result of unevenness in TPC assessed at each point of drying leading to an underfitting problem. A similar finding was reported by Arefi, Sturm, von Gersdorff, Nasirahmadi, & Hensel (2021). As provided in Table 4.15, good agreement between the predictions and observations was observed for TAA and TFC with regression coefficients ($ß_0$ and $ß_1$) not significantly different from 0 and 1 respectively. Satisfactory values of CCC were also obtained for the two attributes. This is confirmed by the method comparison metrics in Table 4.15 and Figure 4.39. The Bland-Altman plots for TAA and TFC also indicated good agreement between the methods, with a few outlying differences, absence of a noticeable trend in the scattered differences and the line of zero mean difference lies within the confidence interval of the mean difference.

Table 4.15: Method comparison metrics chemical attributes

Response	**Huber Regression**				**CCC**	**Bland-Altman**		
	β_1	***β_1* - 95% C.I [LCL, UCL]**	***β_0***	***B_0* - 95% C.I [LCL, UCL]**		***Mean diff.***	***LOA_u***	***LOA_l***
TAA [% RSA]	0.92	[0.83, 1.01][b]	5.19	[-0.04, 10.42][b]	0.84	0.17	13.97	-13.62
TFC [mg/g]	0.95	[0.88, 1.01][b]	0.08	[-0.02, 0.17][b]	0.85	0.00	0.11	-0.12
TPC [µg/g]	0.77	[0.60, 0.95][a]	0.81	[0.17, 1.45][a]	0.77	-0.01	0.50	-0.52

Statistical significance: H_0: $\beta_1.LCL < 1 < \beta_1.UCL$ / $\beta_0.LCL < 0 < \beta_0.UCL$, [a]p < 0.05 = significant, [b]p = non-significant



a). TFC regression plot b). TFC Bland-Altman plot

Figure 4.39: TFC regression plot and Bland-Altman plot

4.3.7.7 Modelling and method comparison: Structural attributes

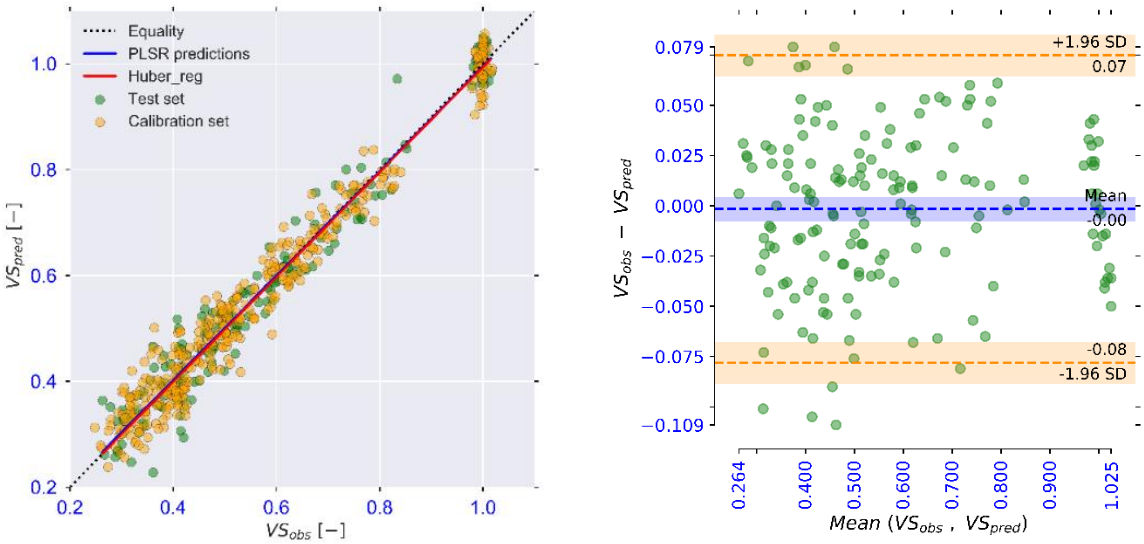
The best model results for volumetric shrinkage (V_s), percentage pore area (PPA) and pore circularity (PC) were acquired from the second derivative of reflectance data with 9, 9 and 5

LVs respectively while the rehydration ratio was best modelled using the first derivative of reflectance with 15 LVs. Excellent prediction performance was obtained for V_s ($RMSEP_P$ = 0.042, r^2_P = 0.96, RPD_P = 5.2), RR ($RMSEP_P$ = 0.021, r^2_P = 0.98, RPD_P = 7.0) and pore circularity ($RMSEP_P$ = 0.022, r^2_P = 0.84, RPD_P = 2.4) while a good performance was obtained for PPA ($RMSEP_P$ = 2.347, r^2_P = 0.64, RPD_P = 1.8). Table 4.16 provides the method comparison metrics for the structural attributes under consideration. The regression coefficients ($ß_0$ and $ß_1$) obtained for all the attributes were not significantly different from 0 and 1 respectively. It can be observed from Figure 4.40 that the regression line for V_s overlaps the identity line. This is corroborated by the values of CCC and the Bland-Altman plots for the attributes. The Bland-Altman plot shows only a few points lie outside the 95% limits of agreement, the absence of a trend in the scattered points and that the confidence interval for the mean difference includes zero.

Table 4.16: Method comparison metrics for structural attributes

Response	**Huber Regression**				**CCC**	**Bland-Altman**		
	β_1	***β_1* - 95% C.I [LCL, UCL]**	***β_0***	***B_0* - 95% C.I [LCL, UCL]**		***Mean diff.***	***LOA_u***	***LOA_l***
V_s [-]	0.98	[0.93, 1.04][b]	0.01	[-0.02, 0.05][b]	0.92	0.00	0.08	-0.09
RR [-]	0.98	[0.93, 1.03][b]	0.02	[-0.04, 0.09][b]	0.80	0.00	0.05	-0.05
PPA [%]	0.85	[0.67, 1.03][b]	2.31	[-0.79, 5.42][b]	0.84	-0.17	4.82	-5.15
PC [-]	0.86	[0.69, 1.02][b]	0.09	[-0.01, 0.18][b]	0.87	0.00	0.05	-0.05

Statistical significance: H_0: $\beta_1.LCL < 1 < \beta_1.UCL$ / $\beta_0.LCL < 0 < \beta_0.UCL$, [a]$p < 0.05$ = significant, [b]p = non-significant



a). V_s regression plot   b). V_s Bland-Altman plot

Figure 4.40: V_s regression plot and Bland-Altman plot

4.4 General discussion

4.4.1 Baseline survey

At the inception of this study, a baseline survey was conducted to evaluate the cocoyam value chain in Kenya for information on materials flows, handling operations and key actors as cocoyam tubers moved from the farm to storage or processing plants to the final consumer. The baseline survey collected and compiled information that formed the basis for comprehensive investigations on preservation, storage and value addition of cocoyam. The cocoyam value chain was observed to be fairly well developed in the selected study location with the key players including farmers, farmer groups, community-based organisations, aggregators, middlemen, transporters, agro-processors, wholesalers, retailers, hoteliers and consumers.

Cocoyam production methods include the traditional wetland production method and the improved upland method in moisture beds. The farmers interviewed understood that the optimal harvesting maturity was 4 – 6 months but this best practice was only observed when there was a need for immediate consumption or a ready market. In the absence of a ready market or need for consumption, the Cocoyam tubers were either left infield or harvested and stored using various methods. On-farm preservation and storage methods included open sun drying on tarpaulins which is not only weather-dependent but also exposes the product to contamination. Fresh tubers were observed to be stored in poorly designed stores without proper consideration of environmental factors including temperature, relative humidity and air circulation. This shortened the storage duration of fresh tubers with a majority of the farmers losing the whole harvest within 3 weeks of storage. The estimated financial loss associated with this loss in comparison to the farmers' monthly incomes was found to be substantial. The introduction of proper preservation and storage technologies could help in preventing losses due to late harvesting and poor storage.

Harvested cocoyam tubers were transported to destinations including open-air markets, local shops, hotels and restaurants and supermarket outlets using various means of transport. The final consumer purchased fresh tubers directly from these points of sale for household consumption or as prepared meals in hotels and restaurants. Various methods of preparation before cooking were reported but preparation boiling in water was by far the most popular. Water boiled and seasoned chunks of the tubers are consumed as a breakfast food item or a main meal within the day. The popularity of this method of preparation provides a market possibility for dried tubers which could be marketed as instant food. This study established an existing contract farming arrangement between farmer groups in the study location and a local agro-processing organisation and a national supermarket chain. These entities engaged farmers in the area to farm the cocoyam crop with the assurance of ready buyers which minimised marketing and financial risks for the farmers.

The agro-processing plant processed the raw tubers into finished and semi-finished products such as flour for baking, making porridge and baby food. The processing operations include peeling with kitchen knives, size reduction to chips and slices, cleaning, optional blanching and seasoning, drying in a solar greenhouse dryer, milling, preparation of composite flour, branding and packaging. The products would then enter the retail market or be sold to other plants for further processing. However, processing operations during the peak of the harvesting season were hampered by the drying operation because fluctuations in weather conditions caused unpredictable drying temperatures and relative humidity. As a result, drying operations often extended to several delays and this negatively affected the quality of the product. Moreover, non-uniform chip and slice dimensions, drying temperature and relative humidity caused inter-batch variations in moisture content which encourage the proliferation of spoilage biotic elements. Therefore, operations in the agro-processing plant could benefit from improved drying technologies, knowledge of the optimal drying settings for cocoyam and mathematical or numerical tools to accurately predict the length of drying operations.

4.4.2 Forced convection cooling

Fresh food products deteriorate rapidly immediately after harvest and therefore require immediate preservation to prevent qualitative and quantitative losses. Postharvest management of temperature by forced convection cooling is commonly practised for on-farm precooling and storage of fresh agricultural products. Cooling preserves the natural quality of products by suppressing physiological, biochemical, and microbiological processes (Dehghannya et al., 2010). This study investigated the influence of air velocity, tuber size and tuber orientation on airflow on the cooling behaviour of whole cocoyam tubers. Information on the cooling behaviour of whole cocoyam tubers is vital in the design and optimisation of forced convection cooling systems to precool tubers immediately after harvest and for long-term storage.

Information on forced convection cooling kinetics provides important design information for the prediction of the amount of time required to cool a product to its target temperature (Carroll et al., 1996). In turn, the cooling time helps in the estimation of the corresponding cooling loads

(Becker & Fricke, 2004). The cooling kinetics of whole cocoyam tubers depicted an exponential decay behaviour with a rapid cooling rate at the start of the cooling process which levels off towards the end of cooling. Rapid cooling both at the centreline and under the skins of the tubers was observed at the higher air velocity setting. Additionally, smaller sized tubers cooled faster than large-sized tubers but the orientation of the tubers to the direction of airflow did not influence the cooling time. At the cooling settings investigated, the influence of tuber size on the cooling time was greater than that of air velocity. While it could be possible to control the size of the tubers to a certain degree through selective breeding and proper timing of harvesting operations, it is impossible to predict the actual sizes expected from a farm. The challenge of developing a cooling solution to accommodate differences in tuber sizes could be handled by sorting the tubers before storage.

The development of a cooling solution requires the knowledge of how the physical and thermophysical properties of the product interact with those of the cooling medium (Korese et al., 2017; van Gogh et al., 2017). In this study, forced convection cooling of whole cocoyam tubers was modelled as a transient state heat transfer process using a modified lumped systems analysis approach with effective heat transfer coefficients and Biot numbers. The cocoyam tubers were idealised as short cylinders which exhibited multidimensional heat transfer. The solution to the multi-dimensional heat transfer was then solved using a product solution approach as described by Çengel & Ghajar (2015). Method comparison techniques were applied to assess the agreement between prediction from the transient heat transfer model and experimental data. An examination of the data using the Student's t-test revealed that the slope and intercept were not significantly different from 1 and 0 respectively at the 0.05 level of significance. Moreover, the maximum values of MAPE and SMDAPE between predictions and observations were 3.73% and 2.91% while the values of CCC obtained were notably all greater than 0.99, some are equal to 1.0. This indicates an almost perfect or perfect strength of agreement between the model predictions and the experimental observations. This finding was also confirmed by results from Bland-Altman analysis which showed mean biases were less than the tolerable maximum variation of ±2 °C and were also statistically insignificant at the 0.05 level of significance. This variation could therefore be disregarded in practice and the model could therefore be utilised to reliably predict the forced convection cooling time and field heat content to be removed.

4.4.3 Hot-air drying

In this study, hot-air drying was investigated as a potential method to extend the shelf life and as a first step in the value addition process of cocoyam tubers. The drying process of cocoyam slices exhibited a two-stage falling rate behaviour with kinetics best modelled by the Two-term Exponential, Peleg and Midili models. Therefore, these models provide an understanding of the drying behaviour of cocoyam tubers and this information will be important in the design and optimization of drying equipment (Onwude, Hashim, Janius, et al., 2016; Ratti, 2001). Investigations on the influence of pretreatments, slice thickness and drying temperature revealed pretreatment with blanching and blanching followed by the application of sodium metabisulfite resulted in increased drying time, total colour change, browning and specific energy consumption but not rehydratability at all levels of drying temperature and slice thickness. This is because swelling and gelatinisation of starch during the blanching step caused case hardening that prevented moisture migration to the slice surface thereby increasing the drying time accompanied by increased browning and energy consumption. Therefore, starchy materials such as cocoyam are better dried without the specific pretreatments utilised in this study. The drying rate, drying time, colour retention, rehydration ratio and specific energy consumption were found to benefit from the smaller slice thickness and higher temperature settings. These settings resulted in decreased residence time of slices in the dryer which is linked to better outcomes of the quality attributes considered. These findings exemplify the significance of the selection of optimal drying settings on improving both process and quality outcomes.

Drying is a complex process involving simultaneous heat and mass transfer in the differential structures of different biological materials (Erbay & Icier, 2010). Additionally, physical, chemical, and biochemical changes occur during the drying process thereby influencing sensory, textural, structural and nutritional quality attributes. Mathematical and numerical models can help in the monitoring and prediction of these changes and therefore guide the design and optimisation of drying processes. In this study, the feasibility of utilising Vis-NIR hyperspectral imaging to assess quality changes in purple-speckled Cocoyam slices during hot-air drying was studied. The quality attributes studied included moisture content water activity, CIELAB Lab, browning index, whiteness index, chroma, hue angle, total phenolic content, total flavonoid content, total antioxidant activity, volumetric shrinkage, rehydration ratio, percentage pore area, and pore circularity. Spectral pre-processing by applying multiplicative scatter correction (MSC) followed by the second derivative ($d^2 \cdot (R)$) to the reflectance spectra resulted in good model performance for MC, CIELAB a*, TAA, TFC, TPC, V_s, PPA, and PC. Additionally, the application of MSC and the first derivative (d·(R)) to the reflectance spectra resulted in the best model performance for CIELAB L*, CIELAB b*, WI, hue angle, and RR. BI and chroma were best predicted directly from absorbance spectra and a_w from underived reflectance spectra.

PLS-BETA and PLS-VIP were applied for spectral feature selection. While the PLS-BETA method was found to be useful in significantly reducing the spectrum to a smaller subset of informative features, the PLS-VIP was found to be more effective at pinpointing the specific wavelengths relevant to each quality attribute considered. In this study, PLSR models were developed on the data sampled in durations of 30 min. However, new PLSR models based on reduced spectra offer the possibility to collect smaller datasets. This would simplify the data acquisition process, decrease data acquisition times and reduce the computational demand as compared to utilising full spectrum PLSR models (Arefi et al., 2021; Gao et al., 2020; von Gersdorff et al., 2021). The simplification of the data acquisition and computation process provides the possibility to implement real-time data acquisition to control the drying process.

Spectral analysis was conducted to identify and correlate specific wavelengths to the quality attributes under consideration. Table 4.17 provides a summary of spectral analysis. Wavelength regions 950 – 999 nm and 977, 1150, 1400 nm for moisture and structural attributes respectively and 624 – 775 nm and 903, 1407 – 1600 nm for colour and chemical attributes yielded high VIP scores. The bands in these regions could therefore be utilised to predict quality attributes in purple-speckled Cocoyam material during drying.

Table 4.17: Summary of spectral analysis results

Observed λ [nm]	**Literature λ [nm]**	**Association**	**Reference**
972, 1400	950 – 1000, 1400	Moisture content (free water, water activity)	• Amjad, Crichton, Munir, Hensel, & Sturm (2018) • Jun, Ning, Ngadi, & Singh (2005) • Pu, Ge, Kelly, & Gong (2003)
1200, 1455, 1520	1174, 1454, 1496	Moisture content (bound water, structure)	• Gowen, Tsenkova, Esquerre, Downey, & O’Donnell (2009)

Observed λ [nm]	Literature λ [nm]	Association	Reference
			• Segtnan, Šašić, Isaksson, & Ozaki (2001) • Tsenkova, Iordanova, Toyoda, & Brown (2004)
740, 760, 830, 900, 1590	720 – 920, 1593	Carbohydrates (starch and sugars)	• Malegori et al. (2017) • Miyamoto & Kitano (1995) • Wang, Li, Copeland, Niu, & Wang (2015) • Roggo, Duponchel, & Huvenne (2004)
700, 740, 760, 830, 945, 1455, 1700	700 – 1000, 1415 – 1512, 1650 – 1750	Bioactive compounds	• Sturm et al. (2020) • Cozzolino, Cynkar, Dambergs, Mercurio, & Smith (2008) • Dykes, Hoffmann, Portillo-Rodriguez, Rooney, & Rooney (2014) • Zhang, Shen, Chen, Xiao, & Bao (2008)
545, 559	516 – 560	Colour (browning and anthocyanins)	• Liu et al. (2014) • Rustioni, Di Meo, Guillaume, Failla, & Trouillas (2013)

In this study, the agreement between the data obtained using laboratory techniques and the data predicted using the developed PLSR models was assessed using various method comparison techniques. The degree of agreement between methods is an indicator of the possibility of replacing one method with the other, especially when one of the methods is a reference method (Shrestha, Crichton, et al., 2020; von Gersdorff et al., 2021). Excellent agreement between observations and predictions was observed for MC, BI, WI, CIELAB b*, chroma, hue angle, TAA, TFC, V_s, RR, PPA, and PC. The values of Huber regression intercept and slope observed for these quality attributes were significantly not different from 0 and 1 respectively. Additionally, these attributes returned high values of CCC and the majority of the differences in the Bland-Altman plot laid within the 95% LoA. The mean differences were also not significantly different from 0. This finding indicates that differences between the results from the routine laboratory methods and the models based on the non-invasive hyperspectral imaging technique are statistically insignificant (Barnhart et al., 2007; Giavarina, 2015; Piñeiro et al., 2008). Therefore, the hyperspectral imaging technique could replace or be used interchangeably with laboratory measurements.

4.4.4 Summary of research findings

The findings from this study are summarised as follows;

1. **Cocoyam value chain in Kenya;**
    - Key components of the value chain include; crop production using the traditional method or the upland moisture bed method, harvesting, storage, transportation, value addition, marketing and consumption.
    - Key actors include; farmers, farmer groups, community-based organisations, aggregators, transporters, agro-processors, wholesalers, retailers or supermarket outlets and the final consumer.
    - Operations are enabled by; family labour, casual labour and permanent labour.
    - Tubers are harvested at 4 – 6 months maturity. The reported yields per harvest are less than 0.1 tons (11% of farmers), 0.1 – 0.499 tons (23.1% of farmers), 0.5 – 0.999 tons (18.7% of farmers), 1.0 – 2.5 tons (38.5% of farmers) and greater than 2.5 tons (11% of farmers).
    - Means of transportation include; motorcycles, vehicles, ox and donkey carts.
    - Market channels include; open-air markets and local shops, intermediaries, hotels and restaurants, and supermarket chains.
    - On-farm storage methods for fresh tubers include; infield storage, ventilated stores, and in gunny bags crates and boxes inside residential houses.
    - Direct observation of the storage methods revealed incidences of tuber rot due to poor control of storage environmental factors including temperature, relative humidity and air circulation.
    - A majority of the farmers (82.3%) lost the whole harvest within the first three weeks of storage.
    - Open sun drying was reported to be a common preservation method.
    - Contract farming arrangement between farmers and local agro-processing plants reported.
    - Processing operations in the agro-processing plant included; peeling, size reduction, cleaning and optional blanching/seasoning, drying in oven or solar greenhouse

dryers, machine milling, blending with other flours (dried cocoyam leaves, banana, sweet potato, pumpkin, cassava and wheat flour), branding and packaging.

- Milled cocoyam flour was further sold to other plants for further value addition operations including production of baked goods.
- Cocoyam puree is produced in a different processing plant. The puree is blended with wheat before production of baked products, branding, packaging and retailing at the supermarket chain outlets.
- Methods of preparation before consumption include; boiling, frying, baking, roasting, mashing and stewing.
- Boiling is by far is the most popular method of preparation with 99.2% and 72.7% of rural and urban consumers respectively preferring the method.

2. **Forced convection cooling;**

- Forced convection cooling kinetics of whole cocoyam tubers are best described by the Two-term model.
- Cooling time is strongly influenced by air velocity and tuber size but not the tuber orientation to air flow.
- Biot number and surface heat transfer coefficient are strongly influenced by air velocity and tuber size but not the tuber orientation to air flow.
- At the parameter space investigated, the field heat removed is influenced by tuber size but not by air velocity and tuber orientation to air flow.
- Forced convection cooling was successfully modelled as a transient heat transfer with a modified lumped system analysis approach.
- Method comparison between predictions from the transient heat transfer model and experimental data indicate that the transient heat transfer models could be utilised to reliably predict the forced convection cooling time and field heat content to be removed.

3. **Hot-air drying;**

- Thin-layer drying kinetics of cocoyam tubers are best described by the Two-term exponential model, the Peleg model and the Midili model.
- The drying of purple-speckled Cocoyam exhibits a two-stage falling rate behaviour.
- Blanching and pretreatment of cocoyam slices using sodium metabisulfite improve the rehydration ratio.
- Blanching and pretreatment of cocoyam slices using sodium metabisulfite do not improve drying time and drying rate.

- Blanching and pretreatment of cocoyam slices using sodium metabisulfite do not improve colour retention and energy consumption.
- At the parameter space investigated, the most suitable drying conditions are at a drying temperature of 75°C, slice thickness of 4 mm and without pretreatment. These drying settings resulted in a total drying time of 109 min, a total colour difference of 2.4, a browning index of 9.96, a rehydration ratio of 0.7 and specific energy consumption of 6,119.3 kJ/kg.
- Hyperspectral imaging, HSI (400 – 1700 nm) and chemometrics were successfully implemented to develop prediction models for moisture attributes [moisture content (MC), water activity (a_w)], colour attributes [CIELAB L*, CIELAB a*, CIELAB b*, browning index (BI), whiteness index (WI), chroma, hue angle], chemical attributes [total phenolic content (TPC), total flavonoid content (TFC), total antioxidant activity (TAA)] and structural attributes [volumetric shrinkage (V_s), rehydration ratio (RR), percentage pore area (PPA), pore circularity (PC)] of purple-speckled cocoyam slices subjected to hot-air drying.
- The spectral range 400 – 1700 nm was successfully reduced from 505 wavelengths to 19 optimal wavelengths using PLS-BETA and PLS-VIP feature selection methods.
- Excellent prediction performance obtained for MC ($RMSE_P$ = 1.978, r^2_P = 0.99, RPD_P = 11.2), RR ($RMSE_P$ = 0.021, r^2_P = 0.98, RPD_P = 7.0), VS ($RMSE_P$ = 0.042, r^2_P = 0.96, RPD_P = 5.2) and a_w ($RMSE_P$ = 0.065, r^2_P = 0.92, RPD_P =3.5).
- Good prediction performance was obtained for PC ($RMSE_P$ = 0.022, r^2_P = 0.84, RPD_P = 2.4), BI ($RMSE_P$ = 0.491,r^2_P = 0.78, RPD_P = 2.4), CIELAB b* ($RMSE_P$ = 0.343, r^2_P = 0.78 , RPD_P = 2.3), chroma ($RMSE_P$ = 0.343, r^2_P = 0.76, RPD_P = 2.2), TFC ($RMSE_P$ = 0.063, r^2_P = 0.76, RPD_P = 2.2), TAA ($RMSE_P$ = 7.600, r^2_P = 0.69, RPD_P = 1.9) and hue angle ($RMSE_P$ = 0.049, r^2_P = 0.72, RPD_P = 1.9).
- Average prediction performance was obtained for PPA ($RMSE_P$ = 2.347, r^2_P = 0.64, RPD_P = 1.8) and WI ($RMSE_P$ = 0.134, r^2_P = 0.65, RPD_P = 1.7).
- Poor prediction performance was obtained for CIELAB L*, CIELAB a* and TPC (r^2_P < 0.65, RPD_P < 1.5).
- Method comparison revealed the potential of the hyperspectral imaging technique to be used interchangeably or to replace laboratory measurement of quality attributes.

4.4.5 Critical review of the research approach

This section of the thesis makes a critical review of the approach adopted in this study, the challenges experienced and limitations. A comprehensive review of literature was undertaken to establish the current state of art and to anchor the study into the existing body of research. Secondary sources were analysed to establish background information on the taxonomy, production, nutritional composition, harvesting, post-harvest handling and consumption of cocoyam tubers. Literature sources on forced convection cooling, hot-air drying, energy consumption, non-invasive quality evaluation and process modelling were also reviewed in the context of the preservation and value addition of cocoyam to identify the research gaps to be filled. However, limited information on the cocoyam value chain in Kenya, harvesting and post-harvest handling of cocoyam is documented. Therefore, this presented challenges to the literature review undertaking which were overcame by conducting interviews with subject matter experts and triangulation with literature sources for similar well-researched roots and tubers such as sweet potatoes, white potatoes and cassava.

The baseline survey was conducted using a mixed methods approach integrating both qualitative and quantitative data. Qualitative data was collected through KIIs, FGDs, direct observation and analysis of available literature materials on cocoyam production in Kenya while quantitative data was acquired using a household questionnaire. However, the data collected from oral reports is susceptible to recall bias whereby the source might not accurately and completely recollect past experiences. Therefore, the mixed methods approach proved useful in reducing information gaps in the collected data and in crosschecking the information received from the different sources for consistency, accuracy and completeness. The baseline survey formed a strong background against which an understanding of the cocoyam value chain and points at which technological interventions including forced convection cooling and hot-air drying could be implemented. The baseline survey provided a strong justification for this study.

Forced convection cooling experiments utilised a replicated and completely randomised full factorial experimental design. The experimental design selected provided a possibility to completely explore the main effects air velocity, tuber size and tuber orientation to airflow, all possible factor interactions and quadratic effects. However, forced convection cooling experiments were constrained relative long cooling durations especially for the large-sized tubers at the lower air velocity setting. Conversely, hot-air drying experiments utilised the I-optimal experimental design in which the main effects, interactions and quadratic effects of drying temperature, slice thickness and pretreatments on the drying process were fully explored with a reduced set of experiments. The experimental design enables the execution of fewer experiments while retaining statistical integrity thereby helped reduce the time, effort and materials required for the experiments. However, hot-air drying experiments were constrained by the brittle and crumbly texture of the cocoyam material which gained prominence as moisture was progressively removed. This caused loss of some material during the drying process and as such it necessitated the utilisation of an increased quantity of materials and tests during experiment to counteract against material loss. Nevertheless, all planned experiments were successfully conducted and the data was suitable for the ensuing mathematical and numerical modelling exercises.

4.5 Contribution to knowledge and practical applications

Table 4.18 summarises the contributions to knowledge and potential areas of application of the knowledge generated by this study;

Table 4.18: Contribution to knowledge and practical applications

No.	Domain	Contribution to knowledge	Practical applications
1	Cocoyam value chain in Kenya	• Key actors and enablers identified. • Production methods, yields and post-harvest losses were established. • Harvesting and post-harvest operations identified. • Preservation, and storage methods and technologies were identified and assessed. • Processing operations and processed products identified and assessed.	• Information on the structure and functioning of the cocoyam value chain in Kenya is currently unavailable. This is the first study providing information on the characteristics of the value chain. • The information generated can guide planning and implementation of interventions to improve production, value addition, marketing and farmer incomes.
2	Forced convection cooling	• Influence of air velocity, tuber size and tuber orientation on direction of cooling air on cooling	• Future studies on forced convection cooling of cocoyam can benefit from information on the cooling behaviour presented.

No.	Domain	Contribution to knowledge	Practical applications
		time and field heat removal established. • Forced convection cooling models of whole cocoyam tubers to predict cooling time and cooling load successfully developed and validated.	• Design and optimisation of forced convection cooling systems to precool tubers immediately after harvest and for long-term storage.
3	Hot-air drying	• Influence of pretreatments, material thickness and drying temperature on quality attributes and energy consumption exemplified. • Optimal hot-air drying settings providing the best production conditions for dried and rehydratable cocoyam products identified. • Fitting thin-layer models for drying kinetics identified. • Empirical Response surface models for quality attributes and energy consumption developed. • Models based on computer vision and machine learning for monitoring and prediction of quality changes during drying developed and validated.	• Future studies on the processing of cocoyam can benefit from information on the drying behaviour and changes in quality attributes presented. • The information generated can be used for the design and optimization of hot-air drying equipment. • The PLSR models developed can be used in industry for non-invasive process monitoring and control during hot-air drying of cocoyam. • The optimal wavelengths identified can help in the implementation of process monitoring system utilising low-cost colour cameras.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study provides information on the characteristics of the cocoyam value chain in Kenya. Information on the flow of raw materials, post-harvest handling operations and key actors as cocoyam tubers move from the farm to storage or processing plants to the final consumer is documented. The study also identifies challenges in post-harvest preservation, value addition and storage of fresh tubers and proposes forced convection cooling and hot-air drying as potential interventions.

Forced convection cooling of whole cocoyam tubers was modelled as a transient heat transfer process. This study showed that the forced convection cooling models can be utilised to reliably predict the cooling time and field heat content when whole tubers are subjected to forced convection cooling. Additionally, air velocity and tuber size are highly significant factors that should be adequately controlled to optimize the cooling process. In the parameter space investigated, cooling time is strongly influenced by air velocity and tuber size but not the tuber orientation to airflow. Moreover, field heat removed is significantly influenced by tuber size but not by air velocity and tuber orientation to airflow. These findings demonstrate that increasing air velocity and utilising small-sized tubers could result in decreased cooling time and reduced field heat load. While it could be possible to control the size of the tubers to a certain degree through selective breeding, it is impossible to predict the exact sizes of tubers to expect from a farm. Therefore, an immediate solution would be to sort the tubers by size to guarantee the validity of the model.

Changes in product quality attributes and energy consumption during hot-air drying are highly dependent on the drying settings. In this study, non-pretreated purple-speckled cocoyam slices performed better than pretreated slices regarding all the quality criteria considered except the rehydration ratio at all drying settings. However, the studied pretreatments caused slice structural changes resulting in greater moisture reconstitution into the slices as compared to the non-pre-treated state. A myriad of previous studies has established the beneficial influence of pretreatments on product quality and the rate of drying without accounting for their potential negative effects. However, the combined adverse effects of both pretreatments and hot-air drying must be considered for a comprehensive account of the total changes the entire process imparts on the material. Moreover, the findings on pretreatments hold true only during the drying process and therefore the influence of pretreatments on product quality during storage needs to be studied.

The feasibility of utilising optical sensors in a narrow selection of wavelengths within the Vis-NIR hyperspectral range to non-invasively measure a wide range of food quality attributes during the processing of root and tuber crops and in particular, purple-speckled cocoyam was proved. The study derived 19 wavelengths from the range of 400 – 1700 nm correlated them to the quality attributes under consideration. The prediction performance of the PLSR models developed from these wavelengths was found to be excellent for MC, RR, V_s and a_w. Good prediction performance was obtained for PC, BI, CIELAB b*, chroma, TFC, TAA and hue angle. An assessment of the agreement between data collected using routine laboratory methods and the PLSR models based on the non-invasive hyperspectral imaging technique established the viability of using the hyperspectral imaging technique to replace or be used interchangeably with replacing laboratory measurements.

The results of this study show an unexploited potential of cocoyam as a food security crop and as a key agribusiness item. Moreover, the results show that cocoyam tubers can be preserved through forced convection cooling. Additionally, hot-air drying at optimal drying settings can be utilised to preserve the tubers and to produce better quality value-added products.

5.2 Recommendations

5.2.1 Policy recommendations

This study has generated information on the structure and functioning of the cocoyam value chain in Kenya. It is hoped that this information will inform policy and guide future interventions aimed at improving production, post-harvest loss reduction and value addition. Cocoyam is a traditional neglected crop that can be upscaled to combat food insecurity and malnutrition especially in the light of climate change and reducing productivity of mainstream crops. The national government and county governments could devote resources to the promotion of cocoyam production through the modern upland technology. Moreover, training of farmers in the traditional growing areas could assist them to gain skills in processing of cocoyam tubers to value added products. This would boost the prominence of cocoyam to be a key agribusiness item which could boost farmer incomes and reduce rural poverty.

5.2.2 Recommendations for future research

Future research will focus on the following areas;

1. Wider assessment of the willingness of consumers to pay for value-added cocoyam products to enhance commercialization
2. Generalisation of convective cooling results on single cocoyam tubers for application to bulk tuber storage.
3. Evaluation of the influence of relative humidity and air velocity on the hot-air drying process.
4. Analysis of the shelf life and stability, sensory quality and consumer acceptability of cocoyam products dried under the above conditions to support the transfer of the new knowledge to the market.
5. Assessment of the potential of other dimension reduction algorithms to reduce the selection even further for usage with multispectral systems to support the development of process monitoring and control systems based on simple and affordable camera systems. Analysis of the feasibility of utilising HSI to develop prediction models for food textural attributes.

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APPENDICES

Appendix 1: Glossary

Term	Meaning
Baseline	An initial point of reference that is used for comparison purposes.
Bioactive	A biological compound that has an effect on a living organism's tissues and cells.
Chemometrics	A discipline that applied mathematical and statistical methods to extract information from chemical and biological systems.
Climate chamber	An enclosure that is used to test the influence of environmental factors such as temperature and relative humidity on materials.
Computer vision	A sub-discipline of Artificial Intelligence (AI) used to derive insight from digital images and videos.
Convection	A heat transfer as a result of fluid motion.
Drying	A mass transfer process in which water or another solvent is removed from solid and semi-solid materials.
Empirical	Something based on observations and experience as opposed to pure logic.
Energy	A thermodynamic quantity that is transferred between different systems as a result of temperature difference.
Heat transfer	A science that deals with the determination of the modes and rates of the transfer of energy in the form of heat.
Hyperspectral Imaging	An imaging technique that collects spectral information across the electromagnetic spectrum beyond the visible light range.
Kinetics	A manifestation of the rate of physical and chemical changes in a system.
Machine learning	A subset of AI that involves development and use of computer systems to learn and adapt to human behaviour without explicit instructions.
Modelling	A process in which models are developed as abstractions of complex systems and phenomena.
Moisture content	The amount of water contained within a material.
Morphology	The form, shape, or structure of materials.
Multivariate	A statistical expression that contains two or more independent variables.
Optimisation	The process of finding the most effective system performance by adjusting the system's variables.

Pretreatment	The process of applying preparatory substances to a material in order to make the ensuing process or stage more effective.
Preservation	A process that prevents adverse changes in material to keep it in a good condition.
Rehydration	The process of reintegrating moisture into a dried material.
Shelf life	The amount of time a product may be kept in storage without becoming unfit for use, consumption, or sale.
Shrinkage	The reduction in size and deformation of shape as a result of moisture loss.
Storage	The process of keeping a product in a particular structure until it is needed.
Tuber	A fleshy underground stem that serves as a plant's food reserve.
Value addition	The process of enhancing the utility and economic value to a material.
Value chain	A set of activities performed to deliver a valuable product to the market.
Water activity	A ratio of the partial vapor pressure of water in a product to the partial vapor pressure of pure water at the same temperature.

Appendix 2: Baseline survey tools

Appendix 2.1: List of stakeholders interviewed

Category	Stakeholder
Government Institutions	• Ministry of Agriculture, Livestock and Fisheries, State Department of Crops, Nairobi. • Agriculture & Food Authority (AFA), Directorate of Food Crops, Nairobi. • Kenya Agricultural And Livestock Research Organisation (KALRO), Nairobi. • Agricultural. Technology Development Centre (ATDC), Kiambu • Meru County Department of Agriculture, Livestock Development & Fisheries, Meru. • Meru County Department of Trade, Investments, Industrialization, Tourism & Cooperatives, Meru. • Agriculture & Food Authority (AFA), Meru office. • Nkubu District Agricultural Office, Meru.
Retail outlets	• Naivas Supermarket, Capital Centre, Nairobi. • Tuskys Supermarket Head Office, Nairobi. • Chandarana Food Plus Supermarket, ABC Place, Nairobi. • Zucchini Greengrocers Limited, ABC Place, Nairobi.
Agro-processors	• Imenti Community Based Organization (ICOBO) Company Limited, Meru
Open-air Retail Markets	• Muthurwa, Kangemi, Mountain View
Farmers	• Meru County, Meru Central Sub-county
Consumers	• Nairobi City County

Appendix 2.2: Key informant interview guides

Introduction: Hello my name is [________________________]. This study aims at establishing the production and marketing techniques (i.e., planting, tending, harvesting, preservation, storage, cooking and marketing) applied to cocoyam (i.e., arrowroots/nduma/nduma ya mwanake) by farmers in this area. This study will support the development of improved preservation and storage methods to improve the storage duration/ shelf-life of cocoyam in this area. Your responses will be strictly confidential and will be used for this study only.

Government Institutions

1. Which are the leading areas/ counties of cocoyam production in Kenya?
2. Do you have any statistics on the production quantities?
3. Which are the challenges related to the production, value addition and marketing of root and tuber crops in Kenya? Which ones are specific to cocoyam?
4. Do you have any statistics on root and tuber crop post-harvest losses? Do you have any specific to Cocoyam?
5. There are reports of a new high yielding, early maturing variety of cocoyam that farmers report having been recently introduced from Rwanda (the highland variety). What is its level of adoption? What advantages does it offer over the other varieties?
6. A recent report by FAO and KALRO has identified cocoyam to be one of the neglected and underutilized indigenous crops in the country that have the potential to boost food and nutritional security in the face of climate change. What is the government plan in supporting the production and marketing of neglected and underutilized crops?
7. Are there specific plans/interventions under the current Big 4 agenda on food security to support the production and marketing of particular indigenous crops?
8. Challenges related to production, value addition and marketing of cocoyam
9. To what extend to you think new technologies for reducing post-harvest losses (i.e. by preservation, storage and value addition) could improve production, marketing and consumption of cocoyam?
10. Small-scale farmers are known to reject technologies, particularly new ones that have not been tried elsewhere, due to the initial cost, running costs and maintenance among other factors. What are some of the business models (new or that have been applied in other value chains) that you think would succeed in marketing new value addition technologies and new value-added products based on Cocoyam?

Research Institutions

1. Challenges related to storage both at the farmer level and at the retail level.

2. Which are the challenges related to the production, value addition and marketing of root and tuber crops in Kenya? Which ones are specific to cocoyam?
3. Do you have any statistics on root and tuber crop post-harvest losses? Do you have any specific to Cocoyam?
4. There are reports of a new high yielding, early maturing variety of cocoyam that farmers report having been recently introduced from Rwanda (the highland variety). What is its level of adoption? What advantages does it offer over the other varieties?
5. A recent report by FAO and KALRO has identified cocoyam to be one of the neglected and underutilized indigenous crops in the country that have the potential to boost food and nutritional security in the face of climate change. What are your suggestions towards improving the production and marketing of neglected and underutilized crops?
6. To what extend to you think new technologies for reducing post-harvest losses (i.e. by preservation, storage and value addition) could improve production, marketing and consumption of cocoyam?
7. Small-scale farmers are known to reject technologies, particularly new ones that have not been tried elsewhere, due to the initial cost, running costs and maintenance among other factors. What are some of the business models (new or that have been applied in other value chains) that you think would succeed in marketing new value addition technologies and new value-added products based on cocoyam?

Retailers/ Supermarket Chains

1. What variety of fresh cocoyam do you sell in your outlets? Where do you source the fresh cocoyam from?
2. Would you be willing to divulge the quantity and price of cocoyam that you purchase from your suppliers? At what interval do you do the purchase? What pre-conditions have you set for the supply of the fresh unprocessed cocoyam products?
3. How popular is cocoyam with your customers compared to other products such as sweet potatoes and cassava? Would you be willing to divulge what volumes of cocoyam (kg or bags or pieces) you sell regularly (i.e., daily/ weekly/ monthly)?
4. What are the challenges of dealing in fresh cocoyam? (i.e., availability of adequate materials from source, preparation, transportation, storage)
5. From your experience, what is the average shelf-life of cocoyam while in your stores (in days or weeks)?
6. Value-added (i.e., baked) products containing sweet potatoes and cassava components are currently available for purchase on supermarket shelves. Where do you source these

tuber components from? What agreements do you have with your suppliers/ farmers (i.e., how do they consistently meet your demand for the raw materials? For example, have you engaged any contract farmers?)

7. Do you have a production plant for bread production capable of producing bread derived from blended flour? If not, who bakes the products for you?
8. How are the fresh tubers prepared/ transported and stored before being milled into flour?
9. Would you be willing to sell baked products (e.g., bread, biscuits, cakes etc.) incorporating cocoyam flour? What is the reason for your answer?
10. What do you think would be the attitude of the final consumer on new value-added products such as dried cocoyam cubes, slices or chips/ crisps that would require minimal preparation before eating?
11. Would your outlet be willing to buy such products from farmers or mid-tier value addition facilities for final retail in your outlets? What would be some of your important considerations before buying such value-added products?

Hotels and Restaurants

1. What variety of fresh cocoyam do you sell in your outlets? Where do you source the fresh cocoyam from? What agreements do you have with your suppliers/ farmers (i.e., how do they consistently meet your demand for the raw materials? For example, have you engaged any contract farmers?)
2. Would you be willing to divulge the quantity and price of cocoyam that you purchase from your suppliers? At what interval do you do the purchase? What pre-conditions have you set for the supply of the fresh unprocessed cocoyam products?
3. How popular is cocoyam with your customers compared to other products such as sweet potatoes and cassava? Would you be willing to divulge what volumes of cocoyam (kg or bags or pieces) you sell regularly (i.e., daily/ weekly/ monthly)?
4. What are the challenges of dealing in fresh cocoyam? (i.e., availability of adequate materials from source, preparation, transportation, storage)
5. From your experience, what is the average shelf-life of cocoyam while in your stores or shelves (in days or weeks)? What storage challenges do you have?
6. What do you think would be the attitude of your customers on new value-added products such as dried cocoyam cubes, slices or chips/ crisps that would require minimal preparation (i.e., soaking in hot water) before serving?

7. Would your outlet be willing to buy such products from farmers or mid-tier value addition facilities for final retail in your outlets? What would be your minimum product quality, packaging and price pre-conditions that you would from suppliers?

Open Air Market Retailers

1. What variety of fresh cocoyam do you deal in? Where do you source the fresh cocoyam from? What agreements do you have with your suppliers/ farmers (i.e. how do they consistently meet your demand for the raw materials? For example, have you engaged any contract farmers?)
2. Would you be willing to divulge the quantity and price of cocoyam that you purchase from your suppliers/ farmers? At what interval do you do the purchase? What pre-conditions have you set for the supply of the fresh unprocessed cocoyam products?
3. How popular is cocoyam with your customers compared to other products such as sweet potatoes and cassava? Would you be willing to divulge what volumes of cocoyam (kg or bags or pieces) you sell regularly (i.e. daily/ weekly/ monthly)?
4. What are the challenges of dealing in fresh cocoyam? (i.e., availability of adequate materials from source, preparation, transportation, storage)
5. From your experience, what is the average shelf-life of cocoyam while in your stores in days or weeks? What storage challenges do you have?

Agro-processors

1. The legal name of the entity:
2. Type of legal entity (Company, NGO, CBO, Self-help group etc.):
3. Year of establishment:
4. Which crops does your facility deal in/process?
5. How many months per year does the plant operate?
6. Which variety of nduma do you process? (nduma, nduma ya mwanake):
7. At what radius do you source your raw materials? (Within 5km, 10km, 20km, 50km, 100km, More than 100km)
8. Where do you source your nduma raw materials from? (individual farmers, own farm, other places – specify)
9. What is the quantity of nduma supplied? (Please fill in the column where units are applicable)

Frequency	**Bags (50kg or 90kg?)**	**Kilograms**
Daily Weekly		

Monthly Annually Other (please specify)		

10. How is the nduma harvested?
11. At how many months of maturity is the nduma harvested?
12. How is the nduma packaged and transported?
13. How is the nduma stored before processing?
14. What is the duration of storage before processing? (days, weeks etc.)
15. Is the supply of raw nduma materials regular or erratic? If erratic, how do you plug the deficits in supply?
16. What agreements do you have with your suppliers/ farmers (i.e., how do they consistently meet your demand for the raw materials? For example, have you engaged any contract farmers?)
17. What quality and price pre-conditions have you set for the supply of the fresh unprocessed cocoyam products?
18. What type of cocoyam derived products do you produce in this plant? (dried chips, cubes, pure flour, blended flour, starch, others – please specify)
19. What is your average production per day?
20. What is your design production capacity? Do you consistently meet this capacity? Please state the reasons for your answer.
21. Please describe how nduma processing is done (i.e., the unit operations)
22. Unit operations for nduma in the processing facility.
23. Number of staff in the facility during peak operation.
24. Number of staff with specialised skills.
25. Do you hold regular training sessions for your staff? How frequently?
26. Approximate monthly plant running costs.
27. How do you market your processed products?
28. Who are the key consumers of your products? (i.e., customers)
29. How did you first introduce your product to the market? Did you conduct a customer needs assessment survey? If yes, what were the results?
30. What do you think would is the attitude of the final consumer on new value-added products such as dried cocoyam cubes, slices or chips/ crisps that require minimal preparation before eating?

31. What is the value of sales of nduma products compared to other products every month?
32. What are the challenges of dealing in fresh cocoyam? (i.e., availability of adequate materials from source, preparation, transportation, storage etc.)

Appendix 2.3: Consumer questionnaire

SECTION A: BACKGROUND INFORMATION

Personal Introduction: Hello my name is [__________**XYZ**________]. This study aims at establishing the consumer attitudes towards cocoyam (i.e., arrowroots/ nduma) products. This study will support the development of new innovative products and preservation methods to improve the storage duration/ shelf-life of nduma. Your responses will be strictly confidential and will be used for this study only.

SECTION B: PRIOR INFORMED CONSENT

Respondents must answer 'yes' to all screening questions before progressing:

- I confirm that I have been given and have read and understood the information sheet for the above study and have asked and received answers to any questions raised.
- I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason and without my rights being affected in any way.
- I understand that the researchers will hold all information and data collected securely and in confidence and that all efforts will be made to ensure that I cannot be identified as a participant in the study
- I agree to take part in this study
- I am over 18 years.

SECTION C: SURVEY QUESTIONS

1. Gender
    a. Male
    b. Female
2. Age[3]
    a. 18–35
    b. 36–60
    c. 61–75
    d. 75+
    e. Prefer not to say
3. What is the highest level of education that you have attained?
    a. Primary school
    b. Secondary school
    c. Polytechnic

[3] Defined by generation, Kenya constitution or the AU African Youth Charter

d. College/ University
e. Post-graduate (MSc, PhD)
f. Prefer not to say

4. Income level per month[4]
    a. Below KSh.6,179 (below poverty line)
    b. KSh. 6,180 - 12,215.00 (floating class)
    c. KSh. 12,216.00 - 30,539.00 (lower middle class)
    d. KSh. 30,540.00 - 61,079.00 (middle class)
    e. Above Ksh. 61,080.00 (upper class)
5. How many times do you eat in a day?
    a. Breakfast
    b. Lunch
    c. Supper
6. What kind of food do you consume most frequently?
    a. Kenyan food prepared the traditional way (githeri, mukimo, fish, nduma etc.)
    b. Modern food (emphasis on ambience and service/ pre-order)
    c. Fast- foods (emphasis on speed/ ready to eat)
    d. All the above
    e. Other (please specify)
7. Which attributes do you consider when buying any type of food?
    a. Price
    b. Quality
    c. Quantity
    d. Taste
    e. Perceived health benefits
    f. Visual attributes (i.e., color and shape)
    g. Convenience/ ease of preparation
    h. Availability and quality of packaging material from the food outlet
    i. Other (please specify)
8. In which state do you prefer your food?
    a. Prepared fresh from the farm
    b. Processed and packaged
    c. Another state (please specify)

[4] Calculated after AFDB 2011 Formula

9. How frequently do you consume ‘prepared - fresh from farm’[5] food?
    a. Daily
    b. Weekly
    c. Monthly
    d. Rarely
    e. Never
    f. Other (please specify)
10. How frequently do you consume ‘processed or packaged’5 food?
    a. Daily
    b. Weekly
    c. Monthly
    d. Rarely
    e. Never
    f. Other (please specify)
11. Which is your favourite root/ tuber food?
    a. Cocoyam (i.e., arrowroot, nduma)
    b. Sweet-potato (i.e., ngwaci)
    c. Cassava
    d. Irish potatoes (i.e., waru)
    e. Other (please specify)
12. How often do you consume nduma?
    a. Daily
    b. Weekly
    c. Monthly
    d. Rarely
    e. Never
    f. Other (please specify)
13. In which preparation style do you prefer your nduma?
    a. Boiled
    b. Fried
    c. Stewed
    d. Mashed
    e. Baked

[5] Protein and starch NOT vegetables

f. Roasted
g. Milled into flour
h. Other (please specify)

14. How do you store your fresh nduma before cooking and the remaining food after cooking?
    a. I/we consume all nduma at once
    b. I/we keep nduma at ambient conditions within the house
    c. I/we keep nduma in cold storage (e.g., domestic refrigerator)
    d. Other (please specify)
15. Would you be willing to try or buy processed nduma products? (i.e., chips, cubes, blended flour, bread, biscuits) – Yes/ No and why?

Reasons for the answer:

16. If the price of a 100g packet of potato chips is KSh. 100[6], at what price would you be willing to purchase a similar sized package of nduma chips or cubes?
17. Do you have any additional issues/ questions/ comments related to the production, value addition, storage and marketing of nduma?

This is the end of the Interview. Thank you for your time and participation.

[6] https://www.naivas.co.ke/product/Tropical-Heat-Potato-Crisps-Tomato-100-g

Appendix 2.4: Household questionnaire

QUESTIONNAIRE NUMBER			

A. INTRODUCTION

Personal Introduction: Hello my name is [**__________XYZ_________**]. This study aims at establishing the production and marketing techniques (i.e., harvesting, preservation, storage, cooking and marketing) applied to cocoyam (i.e., arrowroots/nduma) by farmers in this area. This study will support the development of improved preservation and storage methods to improve the storage duration/ shelf-life of cocoyam in this area. Your responses will be strictly confidential and will be used for this study only.

B. PRIOR INFORMED CONSENT

Respondents must answer ‘yes’ to all screening questions before progressing:

- I confirm that I have been given and have read and understood the information sheet for the above study and have asked and received answers to any questions raised.
- I understand that my participation is voluntary and that I am free to withdraw at any time without giving a reason and without my rights being affected in any way.
- I understand that the researchers will hold all information and data collected securely and in confidence and that all efforts will be made to ensure that I cannot be identified as a participant in the study
- I am over 18 years
- I voluntarily agree to take part in this study

C. BIODATA

Sub-county	………………………	**Name of Interviewer**	………………………
Ward	………………………	**Interviewer’s Phone No.**	………………………
Village	………………………	**Interview date**	………………………
Name of Respondent	………………………	**Time at Start of Interview**	………………………
Respondent’s Phone No.	………………………	**Location (GPS Coordinates)**	………………………

SECTION A: BACKGROUND INFORMATION

A1	A2	A3	A4	A5
Gender of the respondent? 1. Male 2. Female	Year of Birth (for example….1982, 1957, and 2003 etc.)	How is the respondent related to the household head? 1. Head 2. Spouse 3. Son/Daughter 4. Brother/Sister 5. Father/Mother 6. Grand Child 7. Another relative 8. Non-relative	What is the marital status of the respondent? 1. Married 2. Widowed 3. Divorced 4. Separated 5. Single	What is the highest level of education? 1. Never attended 2. Adult Literacy Class 3. Pre-Primary 4. Lower Primary 5. Upper Primary 6. Secondary 7. Post-Secondary (College, Polytechnic, University)

<table>
<tr><th>A6</th><th>A7</th><th colspan="2">A8</th><th>A9</th></tr>
<tr><td rowspan="5">Can the respondent read and write?
1. Easily
2. With Difficulty
3. Not at all</td><td rowspan="5">What is the main source of your income?
1. Formal employment
2. Crop farming
3. Livestock keeping
4. Sand harvesting
5. Fishing
6. Beekeeping
7. Poultry farming
8. Charcoal burning
88. Others (specify)</td><td colspan="2">What is the monthly family income? (from all sources - KSh.)</td><td rowspan="5">How many people live within this household?

Adults (Aged 18 years and above):
Male
Female

Children (Under 18 years of age):
Male
Female</td></tr>
<tr><td>Member</td><td>Amount (KSh. pm[7])</td></tr>
<tr><td>Husband</td><td></td></tr>
<tr><td>Wife</td><td></td></tr>
<tr><td>Others (specify)</td><td></td></tr>
</table>

[7] pm –per month

A10	A11	A12	A13	A14	A15	A16
How many meals do you have in a day?	What does a typical meal consist of? Breakfast Lunch Dinner	Do you think nduma[8] is an important part of your diet? 1. Yes 2. No 3. Don't Know	How many times do you consume nduma on average? 1. Daily 2. Every 2 - 3 days 3. Weekly 4. Every 2 weeks 5. Monthly	Which part of nduma do you consume? 1. Tuber 2. Leaves 3. Stem	What is your favourite method of preparing your nduma for consumption? 1. Boiling 2. Frying 3. Stewing 4. Mashing 5. Baking 6. Roasting 7. Blending flour with wheat/ maize/millet/sorghum flour	What methods do you apply to reduce the anti-nutrients (i.e. the irritation sensation associated with nduma) 1. Blanching (i.e. dipping in hot water) 2. Overnight soaking 3. Parboiling 4. Extended duration cooking 5. None 6. Other (please specify)
			Dt not available			

SECTION B : CROP PRODUCTION, YIELDS, MARKETING

B1	B2	B3	B4	B5	B6	B7
What is the size of your farmland under food crops? (acres)	Which crops do you grow on your farm? (please specify)	What size of your land is under nduma? (acres)	Under what system of cropping do you grow nduma? 1. Mono-cropping 2. Inter-cropping with other crops	How many times per year do you grow nduma? 1. Once 2. Twice 3. Thrice 4. I don't keep track	What is your source of water for growing nduma? 1. Stream/ river 2. Harvested rainwater 3. Rainfall 4. Borehole/ well 5. Piped water supply	What is the maturity duration of nduma from planting? (months)

[8] Cocoyam

B8	B9	B10	B11	B12
What volume of nduma do you harvest per harvest on average? Units Number Bags (50kg) Bags (90Kg) Kilograms Pieces	What is your average harvesting frequency? 1. Weekly 2. Fortnightly 3. Monthly 4. Bi-monthly 5. Quarterly 6. Bi-annually 7. Every 9 months 8. Yearly	How much of the harvested nduma is stored for consumption by the family? Units Number Bags (50kg) Bags (90Kg) Kilograms Pieces	How much of the harvested nduma do you sell? Units Number Bags (50kg) Bags (90Kg) Kilograms Pieces	How much of the harvested nduma is lost to spoilage due to poor harvesting, poor storage, rotting etc.? Units Number Bags (50kg) Bags (90Kg) Kilograms Pieces

B13	B14	B15	B16	B17	B18	B19
Who do you sell your nduma to? 1. Intermediaries ("Middlemen") 2. Directly to consumers in a shop/ the market 3. Hotels/ Restaurants 4. Supermarket chains 5. Agro-processors (e.g. ICOBO etc.) 6. None (Subsistence)	What is the average selling price in a good season? Selling price (Ksh.) Per bag (50kg) Per bag (90Kg) Per Kilogram Per Piece	Do the selling price and demand vary within a year? 1. Yes 2. No 3. Don't Know	How big is the variation in prices within a year for the units specified in B14? 1. < ± KSh. 100 2. ± KSh. 100 - 500 3. ± KSh. 500 - 1000 4. ± KSh. 1,000 – 2,000 5. > ± KSh. 2,000	Have you ever in the past had to sell your nduma at prices you would consider a loss? 1. Yes 2. No 3. Don't remember	Do you consider the nduma business to be profitable (worth the effort)? 1. Yes 2. No 3. Don't Know	By what means is nduma transported to the buyers/market? (please describe)

SECTION C: PRESERVATION, STORAGE, VALUE ADDITION, ATTITUDES TO VALUE-ADDED PRODUCTS

C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
Do you have a special store for nduma only? 1. Yes 2. No 3. Storage with other commodities	What type of storage is it? 1. On the farm until harvesting 2. Barn 3. Inside house 4. Boxes 5. Gunny bags 6. Underground/ in a pit 7. Field clamp (soil cover - above ground) 8. Plastic films/ wraps 9. On Tarpaulin (chandarua) 10. Cold storage 11. Ventilated storage 12. Cover with sawdust/ coffee husks/ leaves 13. Other (please specify)	What preparation methods do you apply to nduma before storage? 1. Drying 2. Peeling (>>C7) 3. Washing (>>C7) 4. Cutting to smaller pieces (>>C7) 5. None(>>C7)	What drying methods do you apply? 1. Sun drying 2. Electric/ gas drying 3. Drying in fire 4. Other (please specify)	Describe the key operations during drying (description)	How long is the storage duration of the **preserved/ dried products** in days/ weeks/ months? (specify units)	How long is the storage duration of **fresh stored products** in days/ weeks/ months? (specify units)

C8	**C9**	**C10**	**C11**
Would you be interested in processing/ adding value to your nduma i.e., by drying, slicing/ cubing, making flour? 1. Yes (>>C10) 2. No (>>C9) 3. Don't know (>>C10)	Why would you not add value to your nduma? 1. I produce small quantities that I cannot value add 2. I do not have facilities for value addition 3. I am sure people would not buy the value-added nduma 4. I don't know where I would sell the value-added nduma 5. My family or I would not consume the value-added nduma due to quality aspects (i.e. visual appearance, taste, flavour) 6. Other (please specify)	Would you buy value-added nduma from a shop, a supermarket or a restaurant for your consumption? 1. Yes 2. No 3. Don't know	What would be the most important factor you would consider in deciding to buy the value-added nduma from the shop, supermarket or restaurant 1. Price 2. Quality attributes (visual, taste, flavour) 3. Amount of work to prepare for consumption 4. Duration of storage at home after purchasing

SECTION D: CHALLENGES, CAPACITY BUILDING

D1	D2	D3	D4	D5
What post-harvest challenges do you experience concerning nduma? 1. Limited access to the market 2. Declining demand for nduma 3. Inability to produce enough for the market 4. Huge variation in nduma prices in a year/ season 5. Lack of storage facility 6. Lack of appropriate means of transportation to market 7. Post-harvest losses (rotting, insect damage, mechanical damage) 8. Lack of skills and knowledge for value addition 9. Other (please specify)	Have you sought or received information on nduma production and marketing from any of the following sources? 1. Government Officers 2. Radio station 3. Television Station 4. NGOs 5. Private companies/ Supermarket chains 6. Local area chief 7. Other (please specify the name of the source)	When was the last time you received the information? 1. Within the last year 2. Between one and two years ago 3. More than two years ago	Did the information help you to improve the production and marketing of nduma? 1. Yes 2. No 3. Hard to tell	In which areas you be interested in receiving support/ training (choose the 2 most important):- 1. Nduma farming/ agronomic practices 2. Crop protection from pests 3. Value addition (i.e. drying, slicing/ cubing, making flour) 4. Storage of nduma 5. Access to a stable market 6. Other (please specify)

Do you have any additional issues/ questions related to the production, value addition, storage and marketing of nduma?

This is the end of the Interview. Thank you for your time and participation.